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FACULTYOF TECHNOLOGY
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MASTER'S THESIS

Theme: Investigation of Isolation of vibrations transmitted in the ground.

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Chapter I: INTRODUCTION

- **1.1.** General introduction.

Ongoing development and transport related activities in cities and towns generate various sources of ground vibrations. Among these, the most prevalent are construction, rail and road traffic-induced vibrations that propagate from the source and are transmitted through the soil media to the surroundings and affect adjacent properties. Due to land scarcity in many urban areas, such sources of vibration can be near constructed facilities in which the transmitted ground vibration can be problematic as it can cause discomfort to the occupants, disturb ongoing activities undertaken in the building and result in damages to the structure. The transmitted vibration will depend on both the source producing it and the transmitting medium (path), while the acceptable levels of vibration will depend on the activities carried out in the affected building, which is also termed the receiver. Vibration received from an external source can easily affect sensitive processes undertaken in existing building structures, such as hospitals that house operating theatres and laboratories and/or cause discomfort to occupants. Moreover, historic buildings can be vulnerable to varying frequencies of ground vibration resulting in damage, possible partial collapse, and loss of architectural heritage in that area. Additionally, severe, and uncontrolled vibration can cause structural damage leading to potentially unsafe built environments.

Different vibration sources induce different types of vibration waves, which vary in amplitude, frequency, and direction. Further, vibration waves are affected by the material properties and attenuation characteristics of the path of propagation. Ground vibration generation and propagation through the soil media demonstrates a complex behavior and affected by many influential factors. The structural response to these ground vibrations becomes an important aspect that requires some control. Unlike vibration caused by seismic action, these ground vibrations induced by ongoing activities may not be strong enough to cause any severe structural damage, but the structural response of the receiver can still negatively affect the people in the building and disrupt their daily activities.

Generally, mitigation of ground vibration effects on adjacent structure can be achieved through different methods, such as controlling the source of vibration, changing the location and direction of the source, or wave barriers and vibration isolation techniques such as trenches. When the propagating ground vibration waves encounter a trench whose in-fill material has an impedance value different from that of the surrounding soil media, the waves undergo typical wave phenomena of reflection, refraction, diffraction and scattering.

This project aims to study ground vibrations, its propagation, methods of analysis and techniques for isolating the vibrations propagated in the ground.

- **1.2.** Aims and objectives

There are several sources of vibration transmitted to the ground, such as vibrating machines explosions including mines trains, etc. The accelerations induced by these sources will spread in the soil. Ground vibrations cause distress to adjacent structures and sensitive equipment, and even cause discomfort to residents. Generally, these adverse effects of ground vibration can be eliminated or avoided by installing various types of wave barriers, such as an open circuit, a filled trench, or a row of piles. This research project consists in proposing a solution for the active isolation of vibrations transmitted in the ground induced by a vibration source. Numerical models will be developed to study ground vibrations with and without insulation systems (e.g., trenches), followed by the design of vibration isolation systems as well as the study of the effectiveness of the proposed insulation systems.

- **1.3.** Thesis outline

1- Bibliographic research

The literature review focuses on:

- The principle of vibration propagation in the ground and methods of analysis.
- Techniques for isolating vibrations propagated in the ground.

2- Preliminary digital investigations

This phase consists of developing the necessary analysis models of the surrounding ground vibration source.

3- Design of the proposed insulation systems

Modeling and study of each proposed insulation method. Design, configuration, and material procedures are presented to successfully achieve the insulation criterion.

Establish an extensive parametric study to fully understand the behavior of insulation systems by varying the parameters of the system.

4- Comparative study

The aim is to illustrate the advantages and disadvantages of each system, followed by an efficiency study of the proposed insulation systems.

5- Conclusion.

Chapter II: LITERATURE REVIEW.

Vibrations from construction activities and traffic loading are important because they may cause damage to the adjacent structures as well as complaints to the neighbors. Damage of structures may be caused by the vibration induced differential settlement as well as by vibrations transmitted directly to structure [1].

- **2.1.** Vibrations.

When elastic bodies such as a spring, a beam, and a shaft are displaced from the equilibrium position by the application of external forces, and then released, they execute a vibratory motion. This is due to the reason that, when a body is displaced, the internal forces in the form of elastic or strain energy are present in the body. At release, these forces bring the body to its original position. When the body reaches the equilibrium position, the whole of the elastic or strain energy is converted into kinetic energy due to which the body continues to move in the opposite direction. The whole of the kinetic energy is again converted into strain energy due to which the body again returns to the equilibrium position. In this way, the vibratory motion is repeated indefinitely. Any motion that repeats itself after an interval of time is called vibration or oscillation.

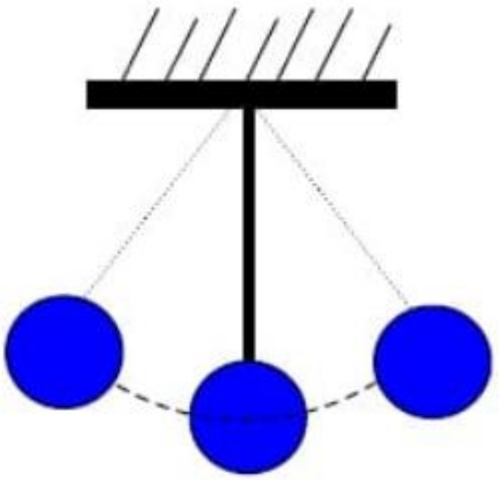

Figure 2.1. Swinging of pendulum.

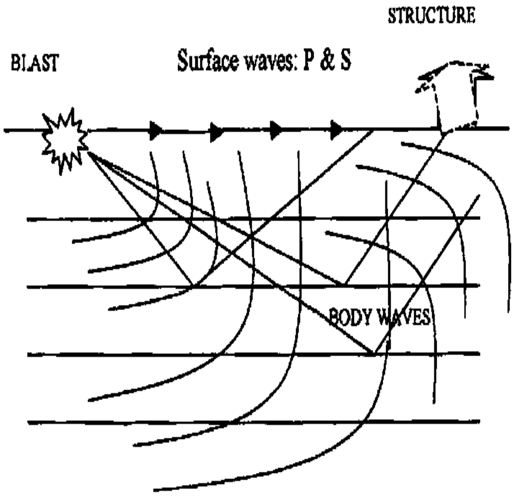

Figure 2.2. Waves of vibration.

- **2.1.1.** Terminologies of vibration.

I. Period: It is the time interval after which the motion is repeating itself. The period of vibration is usually expressed in seconds.

II. Cycle: It is the motion completed during a one-time period.

III. Frequency: It is the number of cycles described in one second. In S.I. units, the frequency is expressed in hertz (briefly written as Hz) which is equal to one cycle per second [2].

IV. Resonance: A vibration resonance occurs when a body or structure is exposed to an external forced vibration occurring at one or more of its natural frequencies. The resulting product response vibration is amplified and can be huge. Vibration resonances can cause severe damage to structures and significantly shorten their life [3].

V. Amplitude: the maximum displacement of a vibrating particle or body from its position of rest.

- **2.1.2.** Types of vibrations.

There are two main types of vibratory motion:

I. Free or natural vibration
II. Forced vibration

Free or natural vibration: A free vibration is where there is no externally applied vibration forcing. The solution to a free vibration is usually roughly sinusoidal. Of course, vibrations can occur across a whole spectrum of frequencies. There will usually be one or more frequencies where there is growing amplitude. At the limit of stability, a free vibration has constant amplitude. It neither grows nor decays. [4].

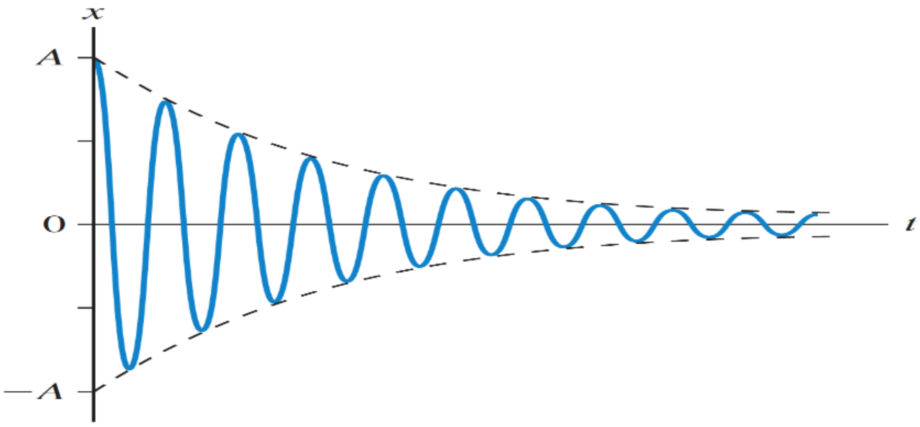

Figure 2.3. Free or natural vibration.

Types of free vibrations.

a) Longitudinal vibration
b) Transverse vibration
c) Torsional vibration

Forced vibration: When the body vibrates under the influence of external force, then the body is said to be under forced vibrations.

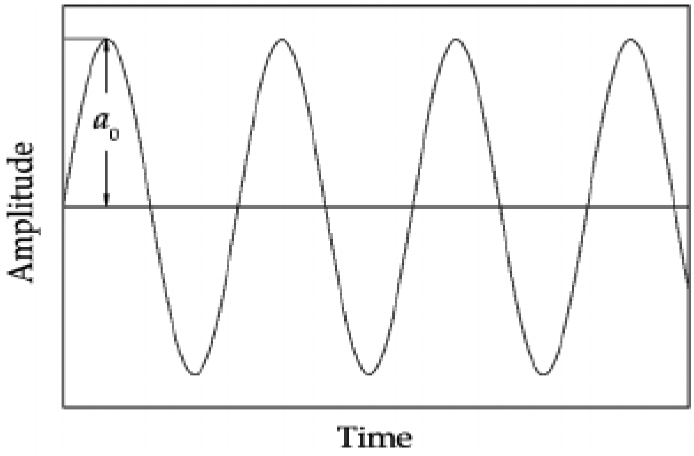

Figure 2.4. Forced vibration.

The external force applied to the body is a periodic disturbing force created by unbalance. The vibrations have the same frequency as the applied force.

Note: When the frequency of the external force is the same as that of the natural vibrations, resonance takes place.

Damped vibration: When there is a reduction in amplitude over every cycle of vibration, the motion is said to be damped vibration. This is because a certain amount of energy possessed by the vibrating system is always dissipated in overcoming frictional resistances to the motion.

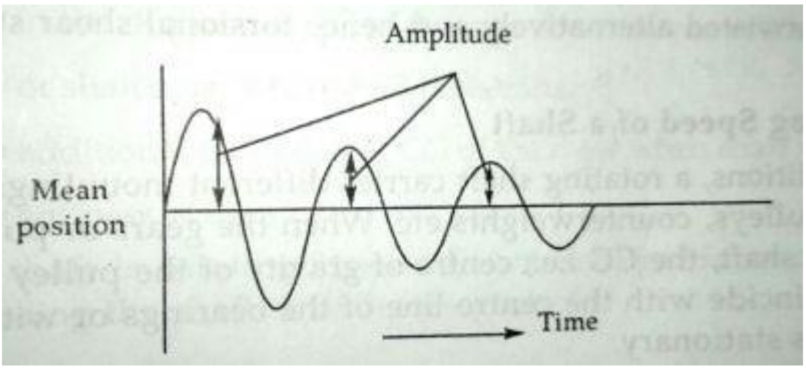

Figure 2.5. Damped vibration.

- **2.1.3.** Sources of vibration.

There are several sources of vibrations but can be grouped into two: natural sources such as earthquakes, waves washing coastal shorelines, the non-stop grind of tectonic plates, wind blowing buildings and trees, and artificial sources like HVAC (Heating, Ventilation and Air

Conditioning) systems, machinery such as trains and hydraulic water well drilling rig, street traffic, people's walks, and explosives. Impact processes such as pile driving and blasting, rotating or reciprocating machineries such as engines, compressors, and motors. Transportation vehicles such as trucks, trains, and aircraft. The flow of fluids through pipes and without pipes. Natural calamities such as earthquakes.

- **2.1.4.** Effects of vibration.

There are various effects of vibration on structures, machines, and humans. Below are a few:

(a) Excessive wear of bearings.

(b) Formation of cracks in machines, buildings, and structures, etc.

(c) Loosening of fasteners in mechanical systems.

(d) Structural and mechanical failures in machines and buildings.

(e) Frequent and costly maintenance of machines.

(f) Electronic malfunctions through the failure of solder joints.

(g) Abrasion of insulation around electric conductors, causing soots.

(h) The occupational exposure of humans to vibration leads to pain, discomfort, and a reduction in working efficiency [5].

- **2.1.5.** Measurement of vibration.

The evaluation of vibration transmitted to the site of a structure, through the ground, from external sources is imperative to aspect of building and design. Seismographs can be used to measure and record vibrations in the ground. Vibration in the ground is measured in terms of peak particle velocity (PPV) and the unit is mm/s. PPV refers to the movement within the ground of molecular particles and not surface movement.

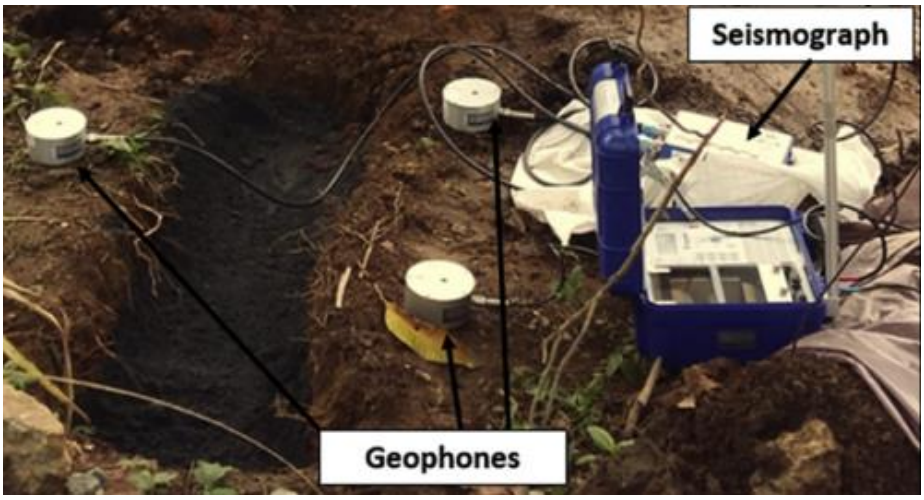

Figure 2.6. Setup to measure ground vibration.

- **2.2.** The principle of vibration propagation in the ground and methods of analysis.

To properly predict excitation levels at a building due to such sources, one must be able to predict how much vibration, in terms of both levels and spectra, is transmitted through the ground from the source. The problem of predicting the transmission of vibration through the ground is complex. The reasons for this complexity include the lack of a comprehensive understanding of soil behavior, the difficulty of determining accurate values of soil properties, and the difficulty of modeling precisely the sources of vibration and the resulting near- and far-field behavior. However, despite these and other obstacles, it is possible to make reasonable assessments of ground-transmitted vibration through a judicious use of the empirical and theoretical results that are available [6].

Propagation of vibration through the ground can in some cases be comparatively simple if the source is deep below ground and the soil is homogeneous and isotropic. However, the characteristics of wave propagation though an elastic medium are such that linear distance laws do not apply [7]. To effectively control vibration related problems, the development of a reliable vibration monitoring system and the proper assessment of attenuation characteristics of various vibrations are essential. For the analysis of vibration related problems, it is necessary to consider the combined effect of several factors such as the characteristics of vibration sources, the site characteristics, the propagation of surface and body waves in the ground, and response of structures. The environmental zone, which is effective to reduce the ground vibration amplitude, is often adopted to prevent the vibration damages. However, it is difficult to estimate to what degree the amplitude of vibration decreases at a certain distance. Generally, the attenuation of vibrations with distance is composed of two factors: geometric damping and material damping.

The geometric damping depends on the type and the location of vibration source, and the material damping is related with ground properties and vibration amplitude. Most of ground vibrations are currently measured only at the ground surface, not in-depth, without considering the propagation path. Propagation characteristics of vibrations generated by various sources may be dependent on the type of the generated waves, which can be assessed by measuring particle motions in three directions including vertical, longitudinal, and transverse directions. The three directional particle motion monitoring on the ground surface and in depth is important for the characterization of propagating waves [8]. The transmission of vibrations can also be analyzed based on theoretical considerations of energy propagation in an elastic medium. The energy source is assumed to be in a homogeneous, isotropic elastic material. The Swedish Standard SS 02 542 11 (SIS 1999) is one of the more elaborate standards currently available and it deals with vibrations caused by piling, sheet piling but also includes soil compaction and provides guidance levels for acceptable vibrations of buildings based on more than 30 years of practical experience in a wide range of soils [9]. In March 2012, field tests were carried out in the south-east part of Cracow city (Podgórze district), consisting in measuring vibrations propagating in the subsoil, caused by driving steel piling by means of a vibratory pile driver. Geotechnical conditions on site of measurements carried out were recognized and described in the geotechnical documentation, prepared in January 2011 by a local geological company, and based on sounding using a light driving rod performed in April 2012. According to Hölscher and Waarts, the quality of the predictions made with current vibration prediction methods is disappointingly low. They concluded that, to make an accurate prediction of the soil surface vibration, it is unavoidable to perform calculations with the Finite Element Method (FEM). The disadvantages of the FEM are that it requires a special software package, and it takes a long time for the modelling and performing the calculations. Therefore, it would be very useful to have a simple analytical method for engineering purposes, which could be used to predict geotechnical vibrations close to the source without the need of special software and long calculations [10,11].

2.3. Techniques for isolating vibrations propagated in the ground.

Vibration isolation is the process of isolating an object, such as a piece of equipment or structure, from the source of vibrations. Vibration is undesirable in many domains, primarily engineered systems and habitable spaces, and methods have been developed to prevent the transfer of vibration to such systems. Vibrations propagate via mechanical waves and certain mechanical linkages conduct vibrations more efficiently than others. Passive vibration isolation makes use of materials and mechanical linkages that absorb and damp these mechanical waves. Active vibration isolation involves sensors and actuators that produce disruptive interference that cancels-out incoming vibration [12].

- **2.3.1.** Ground vibration.

Ground vibrations is a technical term that is being used to describe mostly man-made vibrations of the ground, in contrast to natural vibrations of the Earth studied by seismology. For example, vibrations caused by explosions, construction works, railway and road transport, etc. - all belong to ground vibrations. Ground vibrations are associated with different types of elastic waves propagating through the ground. These are surface waves, mostly Rayleigh waves, and bulk longitudinal waves and transverse waves (or shear waves) propagating into the ground depth. Typical frequency range for environmental ground vibrations is 1 – 200 Hz. Waves of lower frequencies (below 1 Hz) are usually called microseisms, and they are normally associated with natural phenomena, e.g. water waves in the oceans. Magnitudes of ground vibrations are usually described in terms of particle vibration velocity (in mm/s or m/s). Sometimes they are also described in decibels (relative to the reference particle velocity of 10^{-9} m/s). Typical values of ground vibration particle velocity associated with vehicles passing over traffic calming road humps are in the range of 0.1 – 2 mm/s. Magnitudes of ground vibrations that can cause structural damage to buildings are above 10–20 mm/s. The main sources of ground vibrations generated by railway trains are dynamic forces transmitted from tracks to the ground. These forces are associated with complex processes of interaction of moving train axles with railway tracks supported by the elastic ground. The magnitudes of these forces generally increase with the increase of train speeds. Therefore, the levels of generated ground vibrations may be substantial in the case of high-speed trains. If a train speed becomes larger than Rayleigh wave velocity in the ground, an additional very large increase in generated ground vibrations takes place. This phenomenon is termed ground vibration boom, and it is similar to sonic boom generated by supersonic aircraft. The main mechanism responsible for generation of ground vibrations by moving cars and lorries is the dynamic forces associated with vehicle passage over road irregularities, such as bumps, peats, etc. These forces, and hence generated ground vibrations, can be reduced by keeping road surfaces in good condition. The main sources of ground vibrations at construction are pile driving, dynamic compaction, blasting, and operation of heavy construction equipment. These vibrations may harmfully affect surrounding buildings, and their effect ranges from disturbance of residents to visible structural damage [13].

- **2.3.2.** Ground vibration isolation.

Ground vibrations due to human activity can be reduced with the installation of vertical barriers within the soil. The efficiency of the isolation system depends on various parameters such as depth, width, distance from the source, wavelength. A centrifuge parametric study is conducted to examine the influence of the different parameters in some reduced scale models made of Expanded polystyrene (EPS) isolation barriers within Fontainebleau sand to determine geofoam isolation efficiency. Ground-borne vibrations due to high-speed trains (HST) passage strongly depend, apart from the speed of the train, on the geometry of the railways as well as the properties of the underlying soil layer(s). The main aim of this study is to investigate the effectiveness of expanded polystyrene (EPS) blocks in mitigating soil vibrations induced on railway embankments for different subsoil and railway embankment material conditions. The EPS blocks are placed in suitable locations, either as embankment's side fill material, or trench filling material, or combination of the above. An efficient three-dimensional numerical model has been developed -in conjunction with a user-developed subroutine for applying the moving loads-to accurately calculate the dynamic response of the coupled embankment-soil model. Four typical soil types - categorized as rock, dense sand with gravels, stiff and soft clay - are investigated. In addition, the mechanical properties of the embankment material have been altered to assess to what extend they can affect the HST vibrations [14].

Vibration isolation can be achieved by using materials capable of providing a combination of highly elastic behavior in conjunction with damping properties. Pneumatic, hydraulic, elastic metal, and elastomeric designs are commonly used in commercial vibration isolation applications. Elastomeric materials are arguably most common and are extensively used in the industry with a very commonly used design consisting of elastomeric material bonded to metal plates or a metal core. Such isolators are typically called elastomeric mounts. Natural rubber, neoprene, and butyl rubber are some of the commonly used elastomers in commercial vibration isolators. Elastomers provide a designer with a range of stiffness and damping characteristics as well as an ability to withstand different environmental conditions. This ability to satisfy performance requirements over a wide range of rugged conditions along with the ease of manufacturing through a molding process make elastomers a common choice for isolators during the design process. Table 1.1 lists some of the commonly used elastomers for manufacturing passive vibration isolators with a listing of some of their characteristics that can be considered during design. In addition to the commonly used elastomers, manufacturers often develop proprietary elastomeric recipes to serve the needs of a specific design that may require a combination of properties from different materials. Properties of elastomeric materials can be changed significantly by changing their composition or by using different blends. A typical manufacturing process of the raw material involves vulcanization by adding sulfur and by the addition of accelerators, fillers, and plasticizers. The raw material is then used in a molding process to produce a vibration isolator of the designed shape and size to deliver the necessary stiffness and damping properties. While there are many characteristics that are sought from the design of a vibration isolator, some of the common technical properties that a designer seeks to comprehend are damping, dynamic stiffness, environmental resistance, and some of the inherent nonlinearities.

Table 2.1. Some of the commonly used elastomers.

Material	Key characteristics
Natural rubber or polyisoprene (NR)	Good processability, high elongation, high tensile strength, relatively low damping ratio, good bonding to metals, moderate-to-low oil resistance, moderate-to-low chemical resistance, operating temperature: −34 to 71 °C.
Neoprene or polychloroprene	Good abrasion resistance, good tear strength, mechanical properties like NR, moderate oil resistance, moderate chemical resistance, flame retarding, operating temperature: −6 to 82 °C.
Nitrile or acrylonitrile butadiene	Good abrasion resistance, high oil resistance, resistance to swelling, conductor of electricity, operating temperature: −34 to 121 °C.
Styrene butadiene	High abrasion resistance, moderate-to-high oil resistance, high chemical resistance, good electrical insulator, operating temperature: −6 to 98°C
Ethylene-propylene-diene terpolymer	High abrasion resistance, relatively higher damping ratio, moderate tear resistance, low oil resistance, low chemical resistance, operating

	temperature −4 to 150 °C

Metal springs have been commonly used for vibration isolation applications as they can be designed to offer a range of stiffness properties in heavy machinery applications. Most of these designs do not allow much flexibility with damping as most metal springs offer relatively low material damping. Coil springs, disc springs, slotted springs, etc. are some examples of metal springs commonly used in vibration isolation applications.

In some cases, it is common to use a separate damper to augment damping of the vibration isolation system. Viscous dampers are designed to resist relative motion between two surfaces that are typically separated through a fluid film. Some of these dampers can exhibit nonlinear behavior due to strong temperature dependence. Since the early 1990s, magnetorheological (MR) dampers have been developed by researchers and manufacturers to provide smart damping properties that can be controlled through input current to an electromagnet that in turn governs the behavior of the damper. MR fluids consist of micron-sized particles in a carrier fluid, an MR damper allows control over the apparent viscosity of the fluid by controlling the magnetic flux of the electromagnet. Such a damper is a semi-active system that can be used for vibration isolation and control. Friction dampers and electromagnetic dampers are other examples of dampers that have been used in some vibration isolation applications.

A hydraulic mount, also called a hydro-mount, is another vibration isolator that has been used in automotive applications. Such an isolator provides properties that are amplitude dependent as well as frequency dependent. The isolator typically consists of two chambers connected through a channel that allows fluid passage from one chamber to the other. This design allows the vibration isolator to exhibit low stiffness and high damping for dynamic excitations with large amplitude and low frequency while demonstrating low damping at small amplitude and high frequency vibrations. Different designs of hydro-mounts have been used in some automotive applications to provide dynamic characteristics that can be tuned to provide a frequency-dependent behavior [15].

One would also include the applications and criteria of vibration isolation. Design of an optimal vibration isolation system is a complex problem due to the diversity of the requirements for the isolation of various objects in need of vibration isolation. Additional difficulties arise from the variety of working regimes and the internal configurations of some objects (such as cutting regimes in machine tools, position variations of heavy tables or gantries on machine tools and coordinate measuring machines (CMMs), etc.), as well as a variety of environmental conditions (dynamic characteristics of floor and foundation structures, presence of vibration producing and/or vibration sensitive equipment in the vicinity, etc.). While the development of special requirements for unique objects is warranted, a more appropriate way in many cases is to formulate generic criteria for four groups of similar objects:

a. Vibration-sensitive devices (precision machine tools, CMMs, electronic devices). The main goal of vibration isolation is to ensure that relative vibration in the ‘working’ or other critical area does not exceed permissible limits under given external and internal excitations.

b. Vibration-producing machines and devices (impact-generating machines, unbalanced rotors, reciprocating mechanisms). The main goal is to reduce intensity of dynamic exertions transmitted from the object to the supporting structure (foundation, floor, etc.).

c. General-purpose machinery and equipment, neither very sensitive to external vibratory exertions nor producing excessive dynamic forces (e.g., machine tools of ordinary precision). The main goals are to protect the object from accidental intense external shocks and vibrations; to protect the environment and adjacent precision devices, from occasional disturbances caused by the object (e.g., chatter or stick-slip vibrations); to reduce dynamic loads in bearings; to reduce noise and general vibration levels; to facilitate installation by eliminating the need to fasten or grout the objects to the floor.

d. Objects installed on nonrigid structures (upper levels of buildings, ships and surface vehicles, etc). Both internal and external dynamic excitations may be amplified due to the low dynamic stiffness of the supporting load-carrying structures. Thus, even small exciters produce severe vibrations of the supporting structures, creating the need for protection not only for precision but even for ordinary general-purpose objects [16].

- **2.3.3.** Vibration isolation methods**.**

  Since ground vibration can cause damage to adjacent structures, discomfort to the occupants, disturb the activities and the people’s way of life, studies have been conducted to investigate the methods of mitigating the adverse effects of this vibration in different ways. Conclusions were made that the methods to reduce structural response can be categorized as follows.

- Adjusting the excitation frequency of the ground vibration source.

- Changing the location and direction of the source of the vibration.
- Modifying the attenuation characteristics of the soil.
- Interrupting the propagation of waves using ground barriers.
- Isolating the target structure using a base-isolation method.

Prior to any construction project, it is required to conduct a noise and vibration assessment and provide measures to reduce the resulting detrimental effects. Under most circumstances, the following noise and vibration management techniques are suggested.

- Establishing and maintaining safe buffer distances between equipment and residences.
- Informing those likely to be affected by noisy works prior to works commencing.
- Maintaining all plant and machinery regularly to ensure optimal performance and use quieter equipment.
- Continuous monitoring of noise and vibration during construction period to ensure its compliance.

In practice, it is not always a feasible solution to control the source of vibration even though adjusting a vibration source would be the most effective and easiest method of minimizing the vibration effect. Therefore, controlling the vibration by interruption through the ground barrier or building isolation methods have become more popular in practice.

Some studies have been conducted on ground barriers and applicability and limitations of available methods have been analyzed. Ground barriers can be identified as trenches (open or in-filled), shaped landscapes, sheet piles, heavy masses placed next to the sources, etc. A properly placed ground barrier can mitigate the intensity of the transmitting wave and largely isolate the structures. This study will focus on ground vibrations screening by an in-filled trench as a ground barrier [17].

a. Shaped landscape.

b. Heavy mass next to source.

c. In-filled barrier.

Figure 2.7: Vibration isolation methods. [17]

- **2.3.3.i.** Open trenches.

The first experimental surveys on the effectiveness of open and in-filled trenches were carried out by Barkam (1962) [18]. He showed that their effectiveness increases with increasing the depth and the distance for raising frequencies. Regarding the continuous barriers also, Woods showed the influence of the depth and the distance from the vibratory source. He also demonstrated that the passive isolation is better than the active for screening the P - body and S-body waves while the active isolation is more suitable for the screening of the Rayleigh waves; moreover, he highlighted that the most relevant geometric parameter in the screening process is the ratio between barrier depth and Rayleigh wavelength. Several experimental surveys stated that the best screening performance takes place when the depth of the trench is equal to the wavelength while the width of the trench is small. Numerous research on the effectiveness of the barriers have been carried out using FEM and BEM modelling. In 1986, Beskos et al. [19] employed boundary element method (BEM) to study open and in-filled trenches as well as pile wave barriers. In 1991, a simplified design methodology for vibration screening of machine foundations by trenches using 2D BEM was proposed. Adam and Estorff (2005) [20] inspected the effectiveness of open and in-filled trenches in reducing the six-storey building vibrations due to passing trains using a two-dimensional FEM analysis. Yang and Hung combined the finite and infinite elements to investigate the effect of trenches and elastic foundations in reducing train-induced vibration. Few works focus on the effectiveness of barriers in full scale. The most important application is based on Gas Cushion Method that consists in a vertical panel filled of gas and flexible cushion with very low impedance installed in a trench having a great depth. In Gnarp, Sweden 1984, the first application of these barriers was carried out in order to screen a sensitive building from railway ground borne vibrations. The effectiveness of this application reached an attenuation value of about 70% [21].

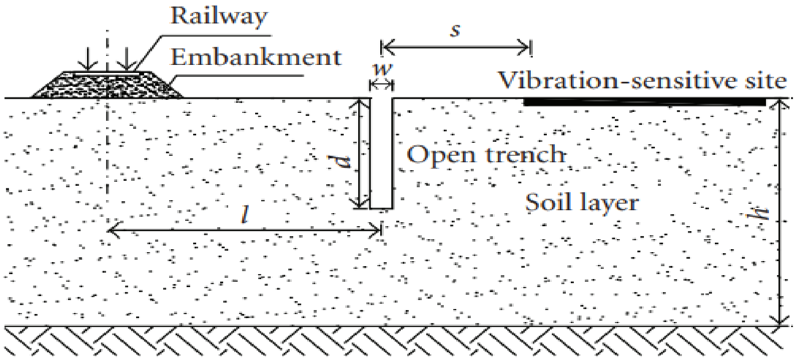

Figure 2.8: schematic representation of position of open trench [21].

- **2.3.3.ii.** In-filled trenches.

In the past, some numerical and experimental studies have been conducted to investigate the performance of ground barrier with regards to vibration screening. Numerical studies have covered a range of scenarios and have subsequently become popular, while there have been much less experimental studies due to the high costs and efforts involved. Scaled experiments under laboratory conditions may not be appropriate to extrapolate the findings. Trenches can be categorized into near-field (active) isolation or far-field (passive) isolation depending on the location of the ground barrier. Open trenches are more effective than in-filled trenches, but its practical application is limited therefore, the use of in-filled trenches has become essential in practice when ground vibration waves travel through the trench, where the two media with different impedance characteristics meet. Once vibration waves meet this interface with impedance differences, it will undergo mechanisms such as reflection, refraction, scattering, and diffraction of wave energy. Ground barriers can exist in the form of solid, fluid and void on the ground. At a solid-solid interface, both P and S waves are transmitted in solid-fluid interface, only P waves are transmitted while in solid-void interface, no waves are transmitted. Also, at a ground barrier, waves undergo mode conversion; Rayleigh waves convert into body waves. Further, it is stated that energy distribution at the mode conversion is dependent on the angle of the interface and properties of the soil and barrier. Thus, the trenches can adversely affect the wave propagation through soil.

As trenches affect the wave propagations, it is important to identify the degree of influence of each parameter such as trench geometry and in-filled material. Al- Hussaini and Ahmad (1996) [22] carried out a comprehensive numerical study and concluded that the effectiveness of an open trench is governed by the normalized depth (depth of trench/Rayleigh wavelength) while normalized width (width of trench/Rayleigh wavelength) is unimportant, except for shallow depths. Adam and vonEstorff [20] in 2005 also found that for train induced vibration, increasing the depth or the width of a trench leads to an increase in the reduction level, but increasing the depth is more effective. In 2014, Bo et al. [23] conducted a comprehensive numerical study on in- filled trenches and stated that an increase of depth causes gradual decrease of the vertical vibration component to a stable value but has less impact on horizontal vibration. However, this phenomenon is observed only for thin trenches (normalize width is 0.1m and normalized depth up to 2m). With a wide trench, (normalized width is 1m) vibration amplification is observed in both horizontal and vertical vibrations followed by a decrease until stable values are reached.

Furthermore, it was discovered in 2011 that the normalized depth should be greater than 1.2m for maximum performance of the trench while 0.25m is found to be sufficient for the width of the trench for practical construction purposes. In the case of in-filled trenches, both depth and width are equally important with properties of the in-filled material. When a trench moves outward from the structure, its vibration reduction efficiency is decreased due to increased scattered horizontal motions. It is further demonstrated by Ekanayake, et al. [24] in 2014 who used a three-dimensional finite element model and found that passive isolation is more effective compared with the active isolation, which is also stated by other researchers. However, Bo, et al. [23] found that when the distance between the trench and the vibratory source increases, reduction of horizontal and vertical vibration shows a series of maxima and minima. They concluded that active isolation is marginally better than passive isolation. Therefore, it is reasonable to assume that wall geometry and proximity to the source, has a major influence on the effectiveness of vibration screening.

Other than trench geometry, the properties of the in-filled material can affect the trench performance. A study conducted by Zoccali, et al. [25] based on the mitigation capacity of an in-filled trench for a train-induced ground vibration concluded that increment trend is strongly influenced by the properties of used in-filled material. Further, they stated that concrete is currently the best material to use, but in some frequency ranges it can increase the vibration levels, therefore this should be analyzed based on critical frequencies of the receiver. Ekanayake, et al. [24] investigated the efficiency of fill materials (water and geofoam) and summarized that geofoam is a more effective material for ground vibration attenuation. Furthermore, in active isolation, a geofoam-filled trench performs better than a water-filled trench as the depth increases. In passive isolation, a water-filled trench outperforms a geofoam-filled trench as the width of the trench increases. The characteristics of vibration also have some influence on trench performance; at lower frequencies, geofoam and water-filled trenches are similarly efficient but as the frequency increases, geofoam trenches surpass the performance of water-filled trenches. It was found in 2011 that a geofoam-filled trench (68% or higher effectiveness) can be considered as a practical alternative to the open trench (84% or higher effectiveness), when the open trench is not a feasible solution. Naggar and Chehab [26] examined the efficiency of both soft (gas-cushion and bentonite trenches) and stiff trenches (concrete), summarized that soft in-filled trenches are more effective than stiff trenches if the depth of the trench is increased by one-half of the soil layer's thickness. Furthermore, studies have been conducted to find the effectiveness of individual parameters of materials such as density, Young's modulus, shear wave velocity, Poisson's ratio and damping ratio. Bo, et al. (2014) summarized that filling materials with a smaller Young's modulus are more effective in vibration screening than those materials with larger values. Further, filling materials with large densities show better isolation while the effect of Poisson's ratio and damping ratio on vibration screening can be ignored. As the literature describes, the efficiency of a trench is not only a simple function of the in-filled material but also properties of source and trenchgeometry.

Furthermore, the existing soil profile can also influence this phenomenon. In 1996 Al-Hussaini and Ahmad [22] studied the trench performance with changing soil profiles and concluded that if the lower layer has less stiffness compared to the upper, the layering effect can be ignored. On the other hand, for a lower layer having a higher stiffness and located near the ground surface, the layering effect must be considered, and the trench should be deeper into the lower layer to be effective (normalized depth of approximately 2m achieves a reduction ratio of 0.2 or less).

- **2.3.3.iii.** Multiple trenches.

Sometimes the use of a single trench is infeasible due to necessity of unrealistic depths to achieve required vibration attenuation. As a solution, use of multiple trenches for vibration screening has been studied. Saikia in 2014 [27] conducted a comprehensive study of a pair of softer backfilled trenches and stated that multiple trenches require less depth when compared with a performance of a single trench. A recent study conducted in 2018 by Pu, et al. [28] used multiple rows of geofoam filled trenches to mitigate train induced vibration. They concluded that screening efficiency increases with an increase in the number of rows. A trench depth of up to the wavelength of the vibration enhance the trench performance significantly and further increase of depth is not effective. In 2012, Younesian and Sadri [29] studied the screening performance of multiple trenches under train-induced vibration and observed a better isolation with multiple trenches compared to a single trench (both active and passive cases). Since fewer studies have been carried out using multiple trenches, further studies are required to define design guidelines.

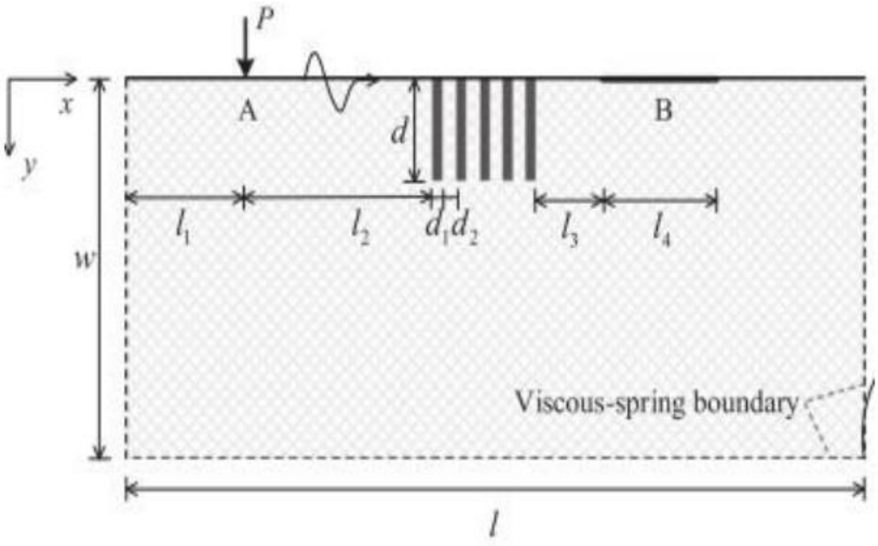

Figure 2.9: Multiple rows of infilled trenches [30].

- **2.3.3.iv.** Nonrectangular trenches.

In practice, use of rectangular trenches may be difficult to construct and maintain. As an alternative, some researches have proposed trenches with inclined slopes which is convenient to construct. Thompson et al. [31] studied four different trenches with different inclined slopes and small differences in performance were observed. This concludes that trenches with sloping sides can be used as alternative to rectangular trenches to have same performance. Effect of trench geometry on train induced vibration screening was evaluated by Younesian and Sadri [29] and rectangular, triangular, and circular cross sections were considered. Some people also studied on step-shaped and V-shaped trenches to mitigate train induced ground vibrations. Even though these numerical studies examined the use of non-rectangular trenches, experimental evaluation yet be conducted to investigate the validity of their findings [30].

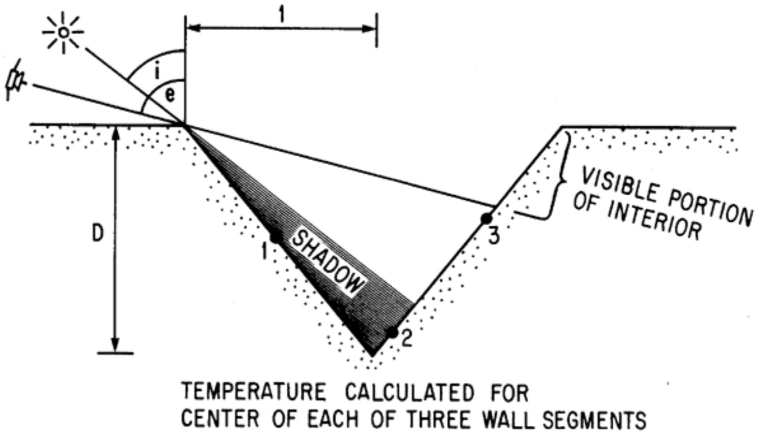

Figure 2.10: Triangular infilled trench [32].

Figure 2.11: V- shaped infilled trench [33].

- **2.3.4.** Designs and approaches of previous studies.

A numerical study conducted by Saikia and Das (2014) [27] defined simplified design formulas to design open trenches in screening steady state surface vibration. The obtained results have a good agreement with the previous studies. This formula can only be used for the design of an open trench for mitigating steady state surface vibration. However, as discussed in previous sections, vibration sources have complex behavior and open trenches are not a practical solution for this problem. Moreover, Ulgen and Toygar [34] conducted a full-scale experiment on testing the effectiveness of trenches and results are compared with previous researchers. They recommended the design charts provided by Saikia and Das in 2014 as a guideline for the practical application of open trench as it has a close agreement with the average of field test data.

Bo, et al. [23] presented an optimization design method using Python programming language which shows the amplitude reduction ratio for all possible scenarios in a limited time. This output with large data set must be analyzed to obtain results that can be used in practice. However, their study provides an optimization design method and preliminary guidelines for the design of trenches. As literature describes, a larger number of influential factors can be recognized with regards to vibration screening through trenches and, it is not feasible to study all these factors simultaneously. Furthermore, there are no developed guidelines to select trench configuration based on receiving vibration and receiver requirement due to the complex nature of the problem. This reveals the necessity of merging the research finding that investigated under various conditions to develop a generic method that can be applicable by practicing engineers.

Chapter III: Preliminary numerical modeling and parametric study.

3.1. Introduction

Numerical modeling is a mathematical representation of a physical (or other) behavior, based on relevant hypothesis and simplifying assumptions. Most usually, numerical models describe one of the experimental methods and compare the results with those measured. In this way, the model is being validated. After the validation, parametric studies can be performed, and any variability of the wavelength (λ) can be observed. The disadvantage of numerical modeling is the complexity of the model preparation, the exact description of the realistic problem and the evaluation of the results. The advantage on the other hand is that when a numerical model is being validated and is showing good correlation with experimental results, easy and fast observation of changing material parameters can be obtained [35]. Numerical modeling is at present widely used to simulate the behavior of rock-mass with or without rock-bolting in various geotechnical projects. The numerical methods used in modeling of geomaterials include finite element method (FEM), boundary element method (BEM), finite difference method (FDM), and discrete element method (DEM). No matter what type of numerical method is used, a constitutive model for rock-bolting, which describes the behavior of rock-bolts in the rock-mass, has to be included in the code. A number of studies were carried out in developing bolt models for numerical modeling in the past years [36].

This phase consists of developing the necessary analysis models of the surrounding ground vibration source to establish the artificial neural network's training and testing database. The present study involves modelling the source of vibration, ground vibration propagation, attenuation with distance and screening vibration through trenches using finite element modelling. This chapter describes the development of the numerical models and their validations to verify the finite element modelling techniques used in this study. Analyses were run for both open and in-filled trenches. The barriers were studied at 5m away from the source of vibration. 3D numerical model was used while utilizing the COMSOL Multiphysics numerical modeling software.

3.2. Open trenches.

3.2.1. Finite element model.

As already stated above, COMSOL Multiphysics was employed as the visualizing tool considering the huge number of analyses needed to be ran simultaneously. 3D conditions were used with solid mechanics as the physics and time dependent used to study the model. A field 400m long, 200m wide and 100m deep was studied with a normal mesh size as shown in Figure 3.1.

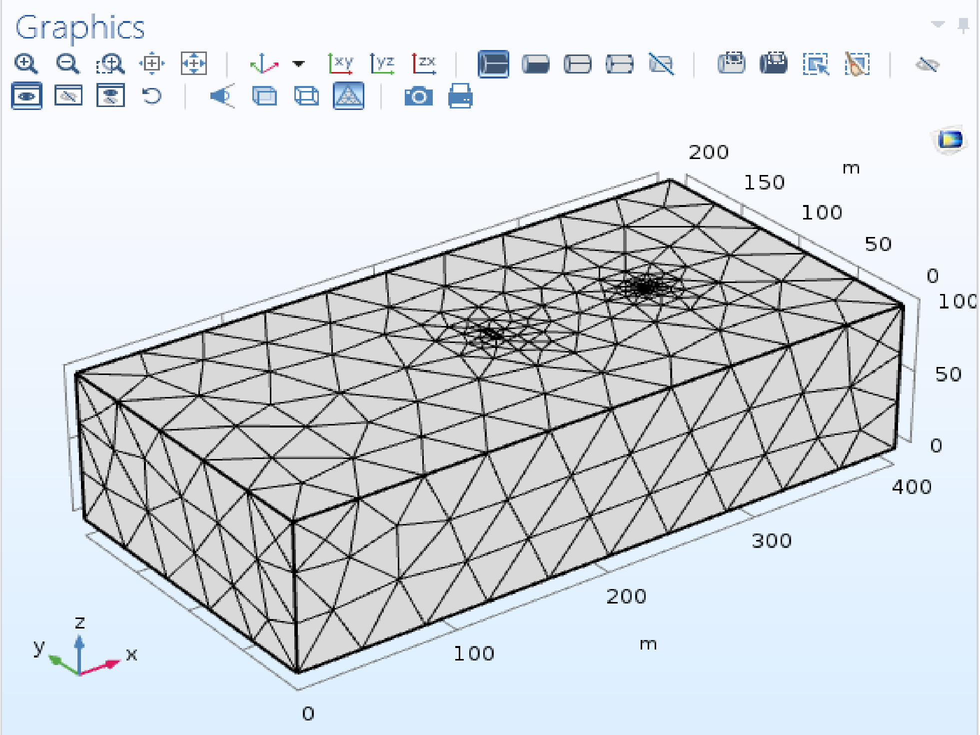

Figure 3.1: Finite element model with mesh size normal.

Damping was introduced in terms of Rayleigh damping parameters (Alpha and Beta). Mass damping parameter (α) was taken as 0 and 0.02 was taken as the stiffness damping parameter (β). Ground vibration attenuation caused by a trench 1m in width and depth of 2m at a distance of 5m away from the source was considered. A parametric sweep study was done on the dimensions of the trench. For length and width, 1.5 to 3m with a step of 0.5m and for the height, 3 to 6m with a step of 1m. The model was studied for 5s (i.e., 0 to 5s with a step of 0.01) with relative tolerance of 0.000001. For properties of the soil, Young's Modulus was taken as 25MPa and 0.4 was taken as Poisson's ratio. A Rayleigh wave with frequency of 62.5Hz was considered. With fixed constraints and prescribed acceleration on the x-axis, the model was analyzed.

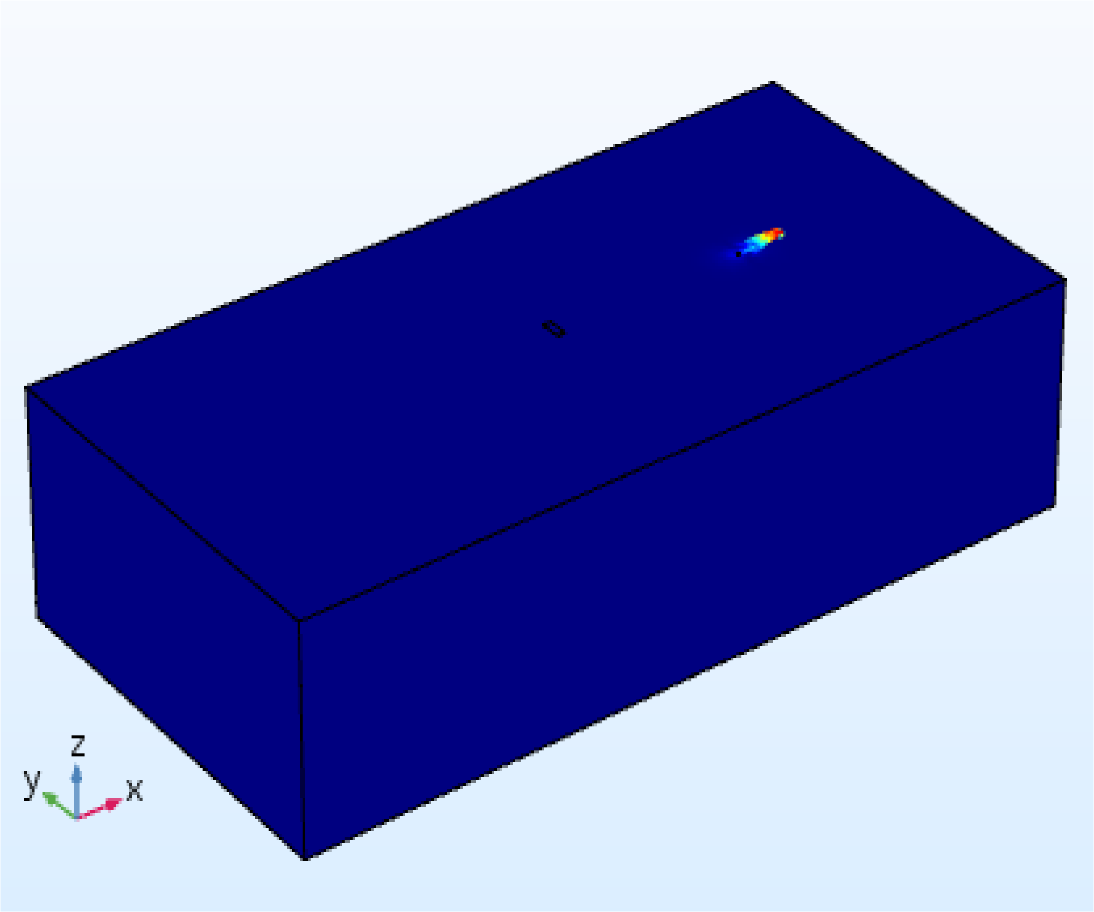

Figure 3.2: Acceleration variation in the soil.

3.2.2. Finite element model results.

The results obtained are for different or various dimensions of the trench. With no materials in the trench, the barrier was studied.

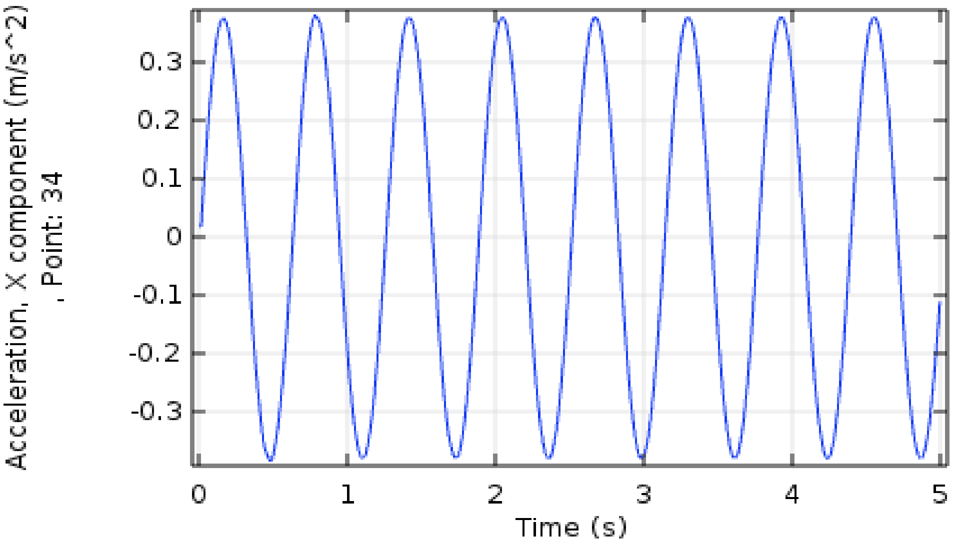

Figure 3.3. vibration attenuation 5m away from source.

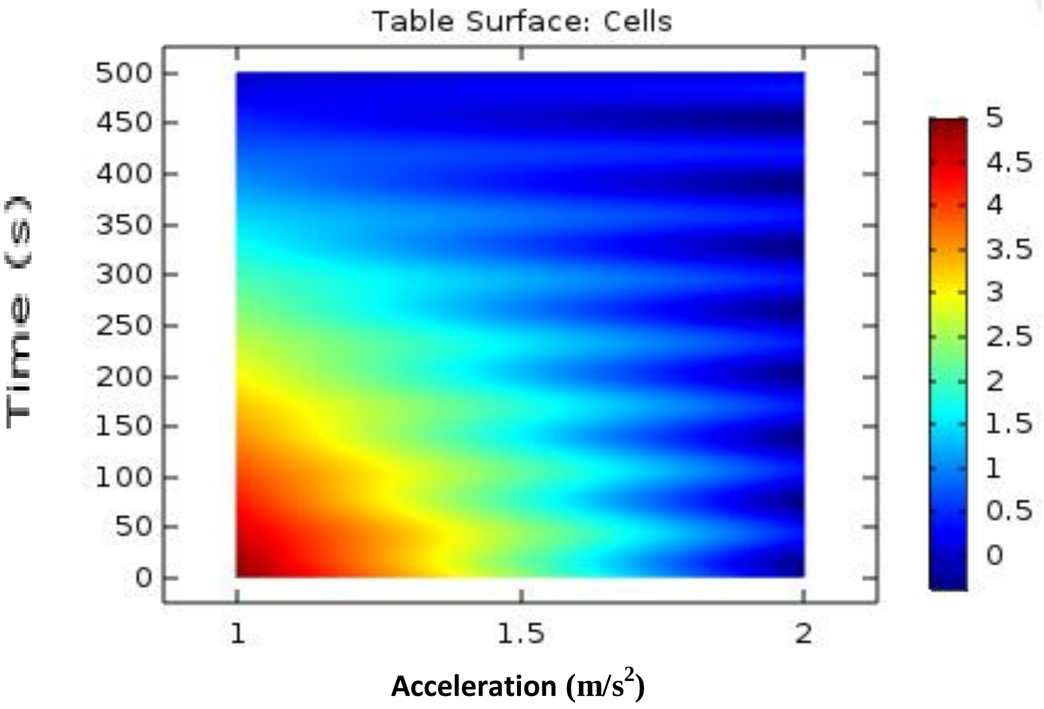

Figure 3.4. 2D image of vibration attenuation 5m away from source.

In figure 3.3, at a point 5m away from the source of vibration, we see that the acceleration of the vibration drops to 0.36 m/s^2. The 2D image shows the propagation of the waves with time.

3.3. In-filled trenches.

For in-filled trenches, a Rayleigh wave with different highest input frequencies were considered and a normal mesh size was selected. A trench was then modelled in the transmission path of the vibration to evaluate its effect on vibration mitigation. Ground vibration attenuation caused by a trench, 2m wide and a height of 3m at various distances from the source was taken into consideration. Parametric studies were done for the dimensions of the trench and the physical and mechanical properties of the materials used. The width and depth were started from 1m to 10m with a step of 1m and the height started at 3m to 12m with a step of 1m. Three types of trench materials (EPS (geofoam), concrete, and water) were used in the analysis to assess the effectiveness of the trench in vibration attenuation. Studies were done 5m away from the source of vibration.

Table 3.1. Materials properties

Material	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)	Damping ratio
EPS	10	0.1	10	5
Water	220	0.4	1000	5
concrete	25	0.23	2300	5

A parametric study was conducted by varying the properties of the materials. Table 3.2 shows the various variations of the properties of the material.

Table 3.2. Variations of infilled trench material properties.

Material	Property	Start	Step	Stop
EPS	Young's modulus	20MPa	1MPa	29MPa
	Poisson's ratio	0.1	0.05	0.5
	Density	10kg/m^3	1kg/m^3	19kg/m^3
Water	Young's modulus	200MPa	10MPa	290MPa
	Poisson's ratio	0.1	0.05	0.5
	Density	1000kg/m^3	100kg/m^3	1900kg/m^3
concrete	Young's modulus	200MPa	10MPa	290MPa
	Poisson's ratio	0.1	0.05	0.5

	Density	1000kg/m^3	100kg/m^3	1900kg/m^3

The properties of these materials were selected based on previous studies. The model was studied for a time of 10s starting from 0 with a step of 0.01s. The relative tolerance was taken to be 0.000001. Acceleration of ground vibrations were recorded for different trench configurations and different materials with different property configurations.

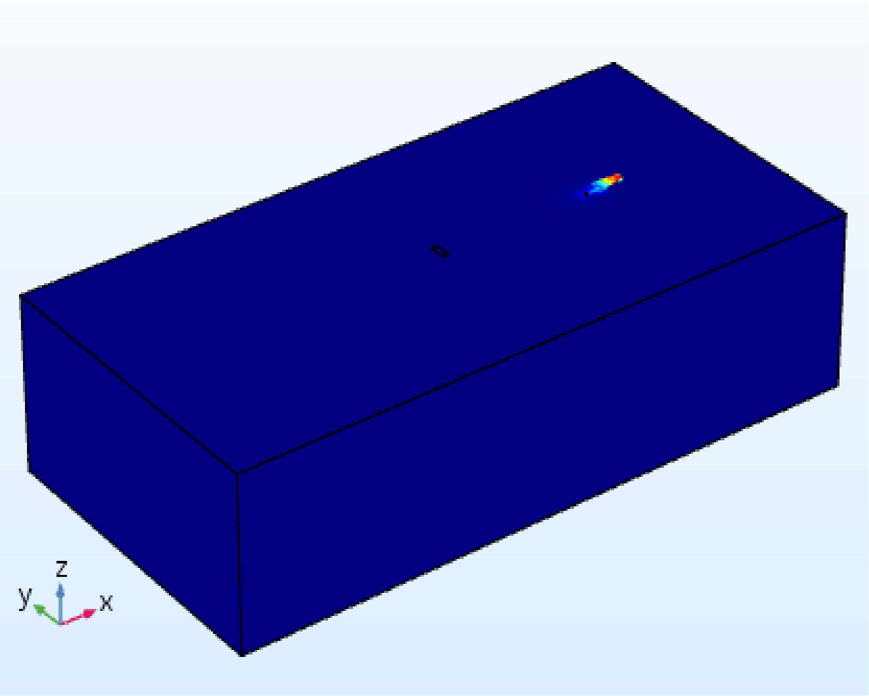

Figure 3.5. Developed FE model results.

The results are obtained for different conditions (trench dimensions, materials and properties of materials).

3.3.a. In-filled trench with EPS.

With Rayleigh damping as the damping type, Mass damping parameter (α) was taken as 0 and stiffness damping parameter (β) = 0.05. Ground vibration attenuation caused by the trench was considered. Some properties of the soil were changed. Young's Modulus of soil was taken as 25MPa. 0.4 was taken as Poisson's ratio.

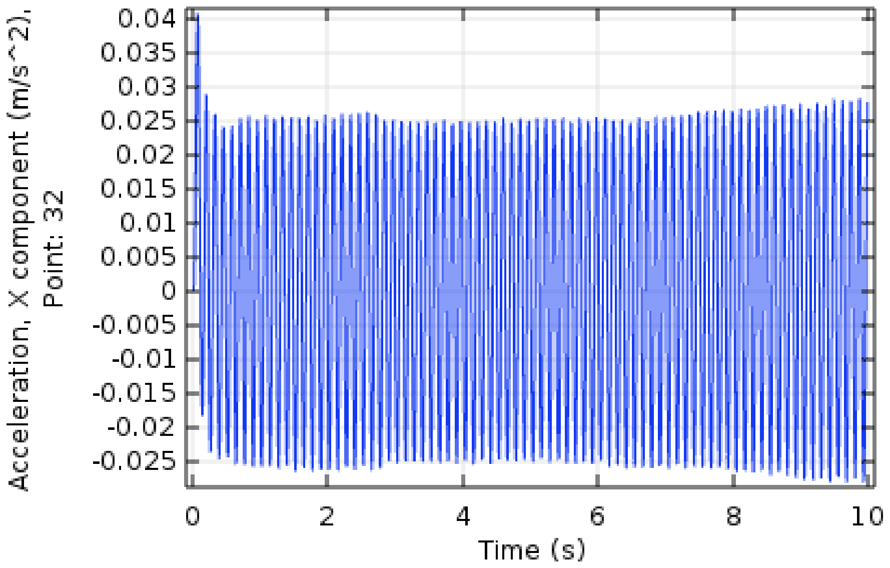

Figure 3.6. Vibration attenuation of in-filled trench with EPS

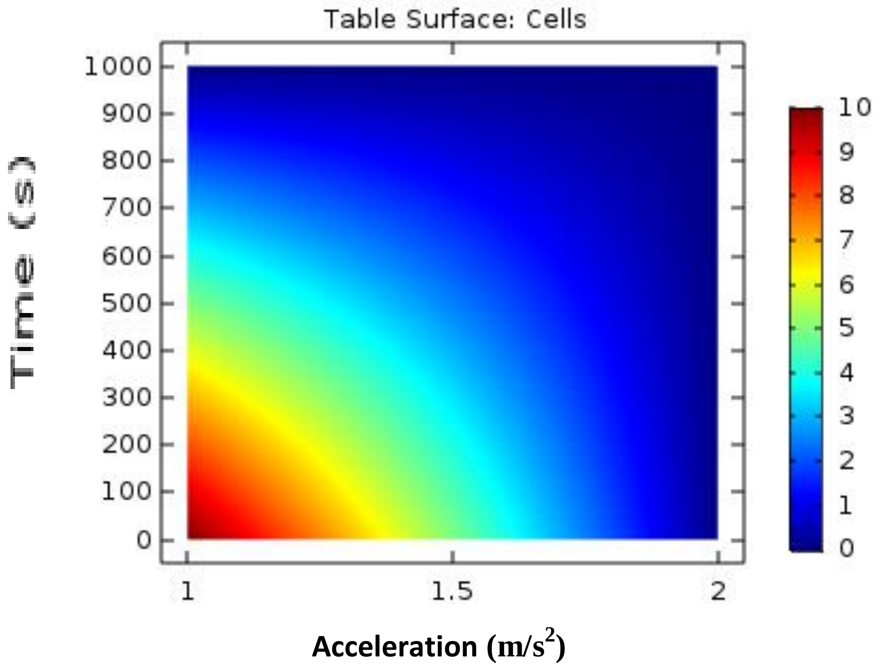

Figure 3.7. 2D image of vibration attenuation of in-filled trench with EPS.

Among the three infilled materials studied, geofoam was the best in vibration attenuation.

With this material, we recorded a reduction of the initial vibration acceleration to 0.04 m/s^2. With the red portion being the peak acceleration and the blue portion being the lowest, we could see in the 2D image that the vibration waves dissipate rather quickly.

3.3.b. In-filled trench with water.

Rayleigh damping parameters (Alpha and Beta) were maintained (i.e., α = 0 and β = 0.05). Soil properties were maintained.

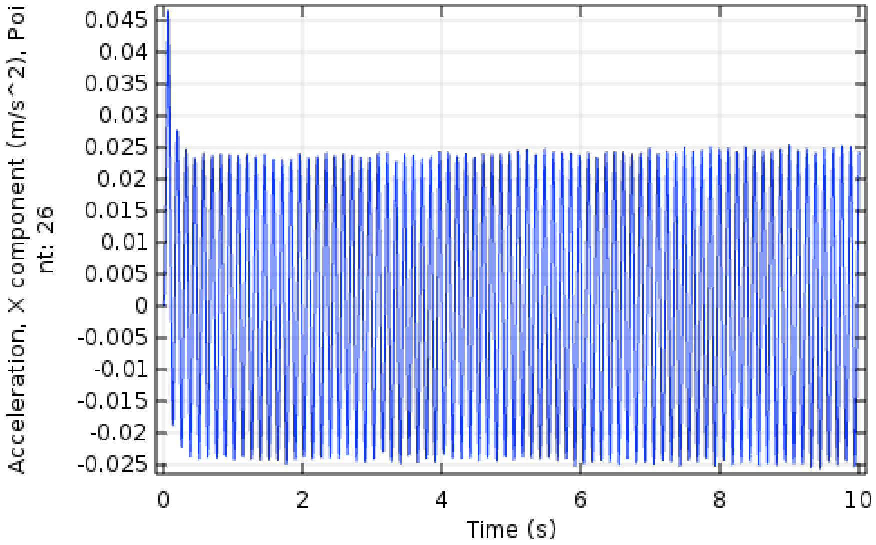

Figure 3.8. Vibration attenuation of in-filled trench with water.

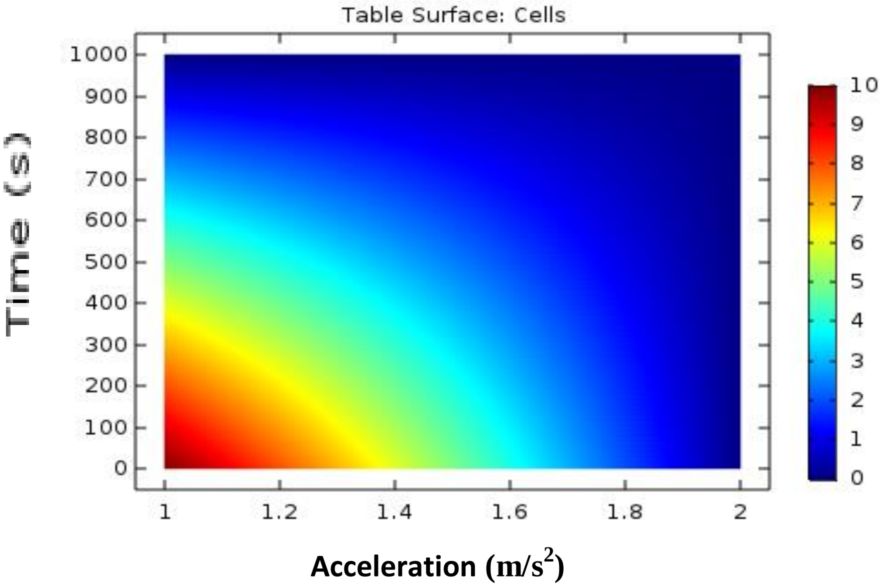

Figure 3.9. 2D image of vibration attenuation of in-filled trench with water.

Water has been known to be a fairly good material to use in infilled trenches and in this case, we recorded an acceleration of 0.045m/s^2. And just like the geofoam, we could see in the 2D image that the vibration waves dissipate rather quickly.

3.3.c. In-filled trench with concrete.

This time around, Mass damping parameter (α) was changed to 0.001 and stiffness damping parameter (β) = 0.02. Young's Modulus of soil was taken as 30MPa. 0.4 was taken as Poisson's ratio and density of the soil, 1500kg/m^3. Acceleration was recorded for distances of 5m, 10m and 20m away from the source of vibration because concrete has the lowest mitigation capacity among the three materials selected.

3.3.c.I. In-filled trench 5m away.

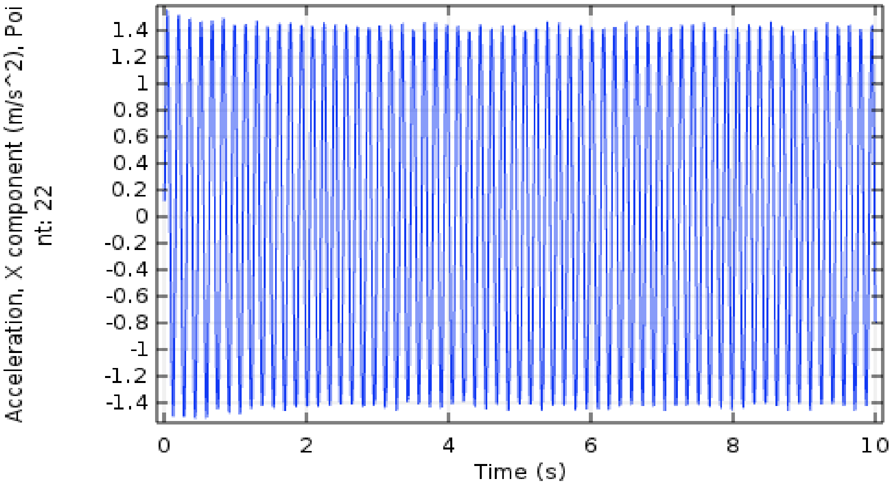

Figure 3.10. Vibration attenuation of in-filled trench with concrete 5m away.

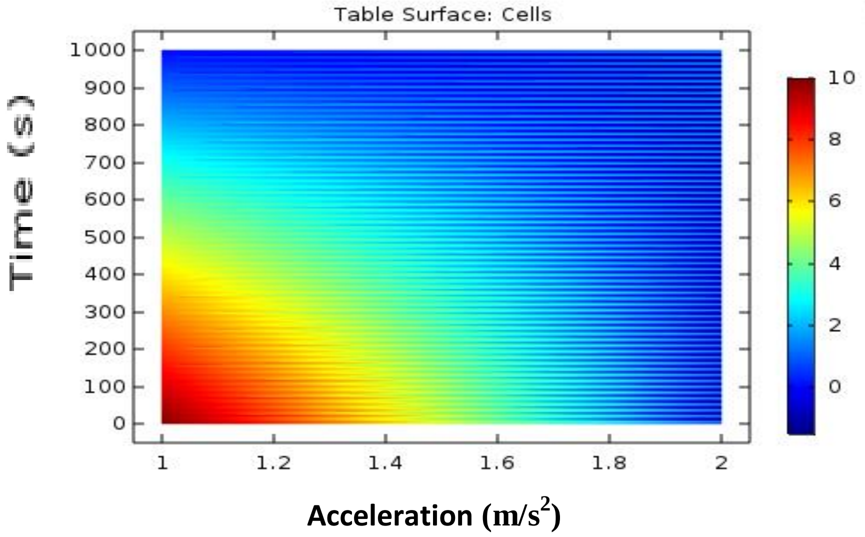

Figure 3.11. 2D image of vibration attenuation of in-filled trench with concrete 5m away.

1.4 m/s^2 was recorded as the acceleration at 5m away from the source and we could see active vibration waves in the 2D image.

3.3.c.II. In-filled trench 10m away.

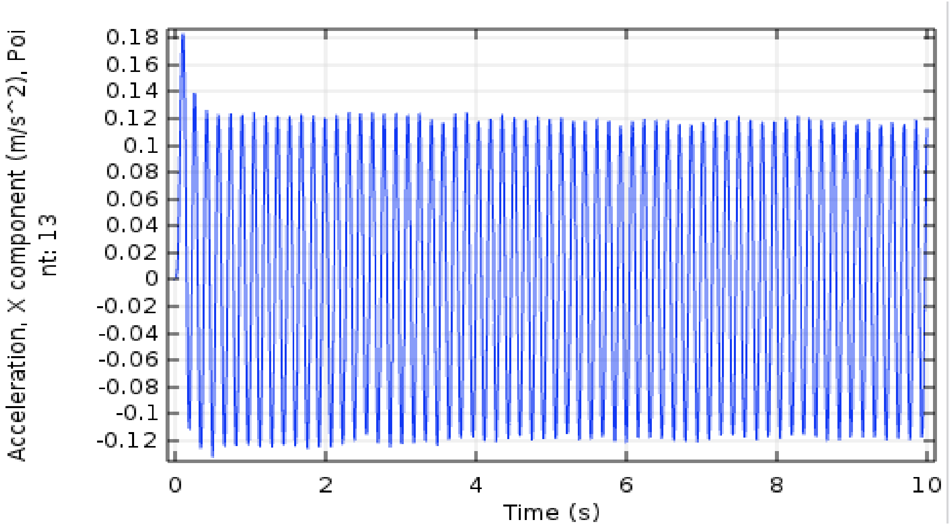

Figure 3.12. Vibration attenuation of in-filled trench with concrete 10m away.

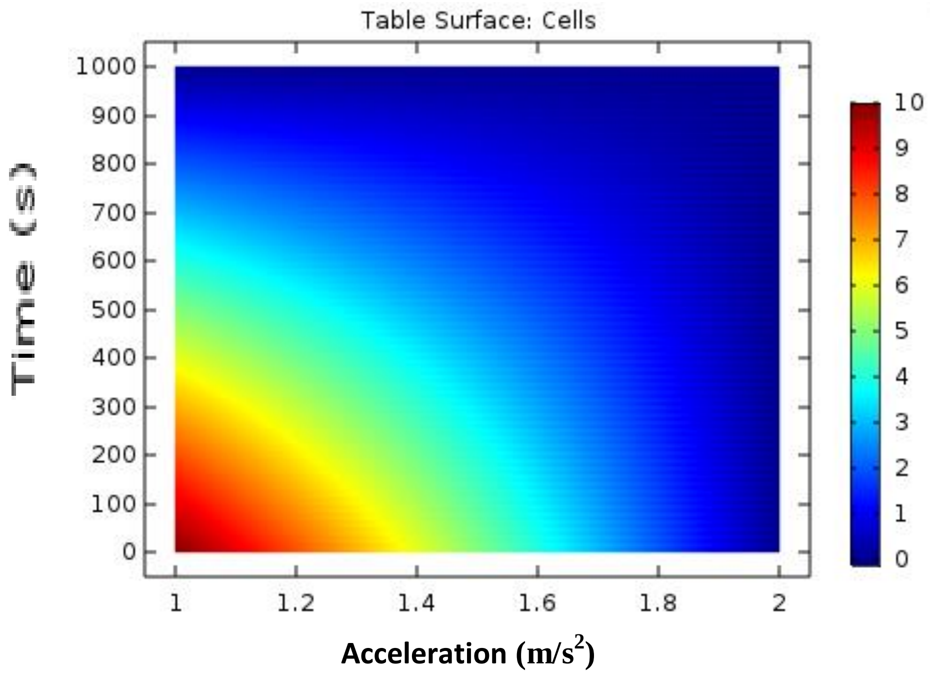

Figure 3.13. 2D image of vibration attenuation of in-filled trench with concrete 10m away.

At 10m away, vibration acceleration drops to 0.18 m/s^2. This a low acceleration for vibration waves but some waves could still be active in the ground although it may not cause any serious harm.

3.3.c.III. In-filled trench 20m away.

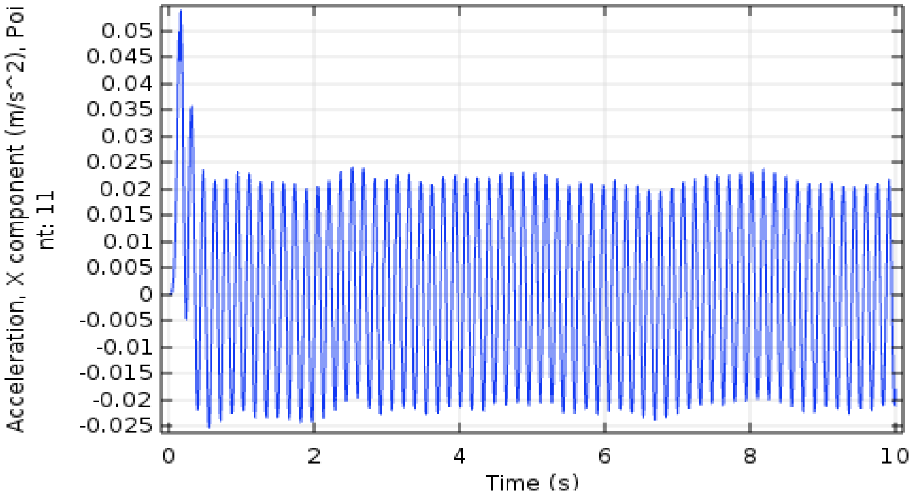

Figure 3.14. Vibration attenuation of in-filled trench with concrete 20m away.

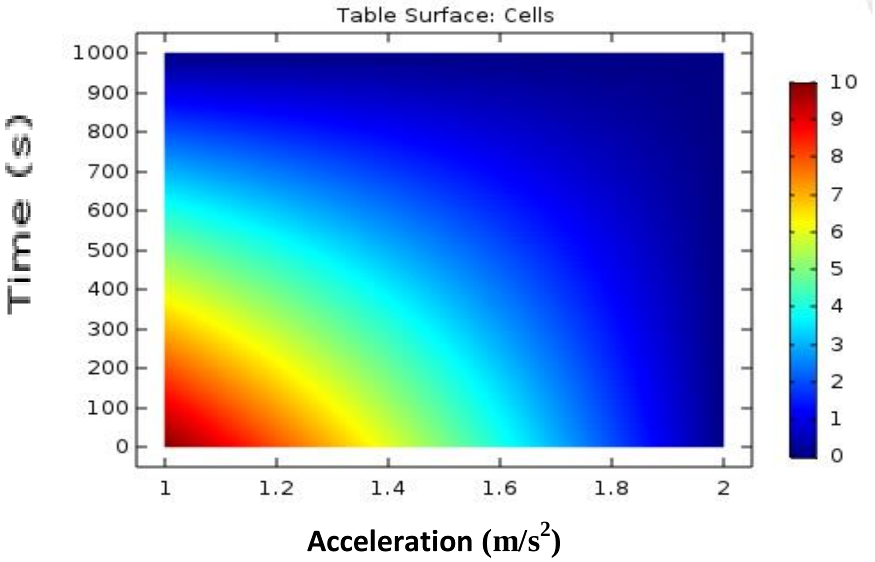

Figure 3.15. 2D image of vibration attenuation of in-filled trench with concrete 20m away.

At 20m away from the source of vibration, we recorded an acceleration of 0.05 m/s^2. This tells us that in order to use concrete as infilled material, the source to barrier distance should be relatively longer than that of other materials.

The figures above show from the numerical analysis a deceleration of the waves with time at points after the trench. This clearly shows that results obtained are in good agreement and provide confidence in the modeling techniques used in the studies.

Chapter IV: Comparative study of open and in-filled trenches

4.1. Introduction.

Ground vibrations caused by heavy machines, vehicles, blasts, trains and construction related activities have become major concerns of cities over the past few years, which, depending on their source and the distance to where they are originated can trouble both occupants and structures containing sensitive accoutrements. For this reason, vibration isolation demands considerable attention. Too much vibration distorts sensitive instrument functions, damages constructions and disturbs residents. Among isolation techniques applied in the mitigation of the inimical vibrations, active wave barriers (located close to the source of vibrations) and passive wave barriers (farther away from the source of vibrations) are of great interest. These barriers include trenches (open or infilled), piles (sheet piles, tubular piles, row of solid piles), wave-impeding blocks, soil grouting, gas-filled cushions or scrap-tire isolation walls.

Due to easy and economical construction procedure and good performance, trench barriers (open or infilled) are common ones. Wave-barrier performance is influenced by various factors, including wave and soil characteristics, as well as geometrical parameters. Released energy during mentioned activities propagates in forms of surface waves (Rayleigh waves) and body waves (including pressure (P) and shear (S) waves). Most of the energy (nearly two-third) generated by vibrations is released in the form of Rayleigh waves. Thus, we can measure barrier effectiveness through the amount of Rayleigh waves reflected, diffracted, or scattered. Alterations in the amplitude of Rayleigh waves’ components with depth are directly affected by the source of vibrations and dynamic features of the soil.

To address vibration isolation trenches barriers, numerous analytical as well as laboratory and field tests have been conducted on both open and infilled trenches. Laboratory and field studies are limited; thus, investigations employing numerical methods are most frequently utilized. Open trenches bear the probability of instability, therefore requiring constant maintenance and care, whereas for infilled trenches, this is not the case. Trench effectiveness is measured by the reduction in horizontal and vertical components of surface displacements. Factors influencing the measurement include soil characteristics, trench geometry, and infill material properties

[37].

The acceleration of vibratory waves at a point 5m away from the source was recorded without a trench. This was taken as the reference acceleration and used to calculate the reduction factor and attenuation percentage of various parameters and materials of the trenches as shown in the tables below. The reference acceleration = **2.26m/s^2.**

Table 4.1. Attenuation percentage of various depths of an open trench.

Depth (m)	Acceleration (a) (m/s^2.)	Reduction factor (R) a/2.26	Attenuation percentage (%) [100 – (100*R)]
Before trench	1.73	0.76	24
1	1.02	0.45	55
2	0.75	0.33	67
3	0.52	0.23	77
4	0.36	0.16	84
5	0.31	0.137	86.3
6	0.23	0.101	89.9
8	0.09	0.04	96
10	0.027	0.011	98.9

The trench depth was maintained at 4m for all materials of the infilled trench and just like it was done for the open trench, reduction factor and attenuation percentage were calculated for each material.

Table 4.2. Attenuation percentage of various parameters of an in-filled trench.

Material	Acceleration (a) (m/s^2.)	Reduction factor (R) a/2.26	Attenuation percentage (%) [100 – (100*R)]
EPS	0.42	0.185	81.5
Water	0.78	0.34	64
concrete	1.4	0.62	38

4.2. Ground vibration mitigation using open trenches.

Many vibration countermeasures have been developed to reduce the vibration effects from various sources. Various types of isolation are discussed in the literature, e.g., open and filled trenches, concrete walls or piles, and flexible gas cushions. Among these types of isolation, the open trench has been demonstrated as an effective intervention, and it is the most common intervention in practical traffic applications. The main reasons why open trenches can be an effective way to mitigate ground-borne vibrations are:

1) They are one of the lowest cost isolation measures
2) They are faster to put in place
3) They provide better vibration reduction capacity

In the past, efforts were made to use open trenches to solve vibration reduction problems analytically and experimentally. Closed-form solutions were obtained, and model tests for particular cases were conducted, but they were restricted to simple geometries and idealized problems. To complement the analytical and experimental studies, numerical simulations have been used extensively to investigate the performance of open trenches because they can be used to analyze complicated geometries and conditions. Hence, it is possible to provide design guidelines for practical traffic applications. 2D and 3D Finite Element (FE) models were established to analyze the influence of open trenches on various types of incident waves.

The three main defining variables that influence the performance of an open trench are the width, the depth and the distance of the trench away from the source of vibration [38].

4.2.1. Trench depth.

Trench depth is recognized as the most important factor affecting trench performance in the majority of studies. In a research in 2014, Bo et al. [23] demonstrated that in not excessively thin trenches (with relatively small width to depth ratio), adding more depth to trenches strengthens vibration amplitude reduction; this proved to be right especially when dealing with vertical vibrations. On the other hand, wide shallow (superficial) trenches exhibit unfavorable results and actually magnify vibrations. So, in an average range of width, by increasing the depth of trench, its performance becomes better. Also, Emad and Manolis [39] investigated shallow trenches and mentioned that presence of shallow trenches results in an amplification along the surface of half-space up to 200%. Increasing the depth, however, slows vibrations down until they eventually reach a rather steady value where the further addition to depth yields no considerable effect on amplitude reduction. One reason explaining the finite reduction effect resulted by deepening the trenches could be a drastic decrease in Rayleigh wave amplitude with depth. Some researchers have mentioned that Rayleigh wave components' amplitude fall by 90% in trenches that 1.5 times deeper than the wavelength of the vibration waves. Saikia and Das back in 2014 stated that the trench depth can decrease both vertical and horizontal vibrations. For instance, in an open passive trench (with the source to barrier distance, L = 5) with a normalized width of 0.2m, vertical vibrations reduction factor falls from 0.62 to 0.14 when the depth rises from 0.3m to 1.5m. A deeper trench reflects waves of greater depth, resulting in a better isolation.

The depth of the trench is the most important parameter in an open trench because deepening the trench increases the performance of the trench in vibration attenuation and as the trench deepens, varying the width has none or little effect on reducing the waves.

Figure 4.1. A deep trench at residential construction site [40].

4.2.2. Trench width

The majority of studies indicate little amplitude reduction effect for normalized trench width. For example, in 2014, Saikia and Das back pointed out that obtaining specific results from amplitude reduction with respect to normalized width is rather difficult, because actually no clear trend can be extracted. However, given a shear-wave velocity ratio (the ratio of shear wave velocity of barrier to the surrounding soil) in range of 0.1–0.2, which is the recommended scope for practical purposes, the effect is relatively small and can be neglected.

Research conducted in the past shows that excessive normalized width values (over 0.6) for active trenches that are relatively shallow (with depth values smaller than 0.6) result in unfavorable effects. Adding depth and distance from the source can diminish these effects, however. Others also observed that for shallow trenches, the wider trench performed worse but as the trench becomes deeper, varying the width of the trench does not make much difference. We can say the explanation behind the issue is that when a trench is located near the source of vibration, body waves play a more dominant role with respect to surface waves, and thus a shallow trench would allow greater amounts of body waves to underpass the trench. A wider trench, however, provides a greater free surface that converts body waves to surface ones, yielding unfavorable outcome. As we move further away from the source of vibration, surface waves gain dominance over body ones, this, in turn, explains the reason for rather less unfavorable effects that shallow passive trenches with greater width have. Finally, when the trench is deep enough, most surface waves will be reflected by the trench and effect of width becomes minor.

Centrifuge model tests conducted by Murillo et al. in 2009 also supported the idea that width effect is more considerable in shallow trenches, and it decreases as depth increases. Having studied a wide range of the normalized trench width (stretched from 0.1 to 2.0), it was concluded that expanding the trench width to some specific extent can yield improved performance; however, further expansion results in an undesired outcome. Trenches with width values greater than depth are actually another breed of wave barriers known as wave-impeding block whose behavior varies and have not received much attention yet. Briefly, the results obtained from most of the research insists on the negligible effects of width, some researches, for active trenches that are relatively shallow, show that excessive normalized width results in vibration amplification. To diminish these effects, depth and distance from the source should be added. So, when designing active trenches to prevent undesired performance, the minimum depth of the trench should be 0.6m.

4.2.3. Source to barrier distance.

Most of the researchers reported the negligible effect of this parameter in trench performance. In their centrifuge experiments, Murillo et al. [14] found no considerable traces of the effects caused by source-barrier distance. However, results indicated that at distances below 1m, some subtle magnification is observed in front of the trenches, which was due to wave reflection. In numerical studies, also the amplification before the trench was seen. There is no clear trend towards trench distance from the vibration source in experiments conducted by Bo et al. [23]. Not much influence on amplitude reduction coefficient is observed with changes in distance, and no certain pattern can be extracted for the alterations. It can be concluded from various researches mentioned above that the source-barrier distance has a low effect on barrier's performance except in shallow trenches. But for optimal isolation, the farther away the trench is from the source, the better it is in vibration attenuation [37].

One negative side of open trenches is the instability of waves in the trench. Depending on the load impact force, initial amplitude of the vibration wave or source to trench distance, the wave may still find its way to the other side of the trench and continue its propagation in a phenomenon known as the butterfly effect.

In chaos theory, the butterfly effect is the sensitive dependence on initial conditions in which a small change in one state of a deterministic nonlinear system can result in large differences in a later state. The term is closely associated with the work of mathematician and meteorologist Edward Norton Lorenz. He noted that the butterfly effect is derived from the metaphorical example of the details of a tornado (the exact time of formation, the exact path taken) being influenced by minor perturbations such as a distant butterfly flapping its wings several weeks earlier. Lorenz originally used a seagull causing a storm but was persuaded to make it more poetic with the use of butterfly and tornado by 1972 [41]. Lorenz discovered the effect when he observed runs of his weather model with initial condition data that were rounded in a seemingly inconsequential manner. He noted that the weather model would fail to reproduce the results of runs with the unrounded initial condition data. A very small change in initial conditions had created a significantly different outcome [42].

The idea that small causes may have large effects in weather was earlier recognized by French mathematician and engineer Henri Poincaré. American mathematician and philosopher Norbert Wiener also contributed to this theory. Lorenz's work placed the concept of instability of the Earth's atmosphere onto a quantitative base and linked the concept of instability to the properties of large classes of dynamic systems which are undergoing nonlinear dynamics and deterministic chaos [43].

The butterfly effect concept has since been used outside the context of weather science as a broad term for any situation where a small change is supposed to be the cause of larger consequences. Hence, we acknowledge that this is a possibly in this type of trenching system.

4.2.4. Frequency

Geometrical parameters in studies concerned with wave barrier trenches are generally expressed as ratios of Rayleigh wavelength; therefore, the frequency influences trench performance indirectly. Briefly, with an increase in frequency, the wavelength decreases and the normalized dimension of the trench will increase, so this will result in improvement of trench performance. The generated wave frequencies in different investigations are variant. According to previous investigations, the frequency range of most of the environmental and civil construction vibrations is below 100 Hz. Therefore, most of the researchers conducted their investigations in the frequency range of below 100 Hz. In addition, the resonant frequency of domain is variant too, because the properties of the domain are not constant in different investigations. However, the point is the presence of the trench in the domain does not make a noticeable change in the resonant frequency value and models with and without the trench have almost the same resonant frequency. So, the effect of the resonant phenomenon is omitted because it has almost the same effect on models with and without the trench [37].

4.3. Ground vibration mitigation using in-filled trenches.

Open trenches are the most efficient way to mitigate or reduce ground-borne vibrations, but in-filled trenches are also a very efficient and reliable method for ground vibration attenuation. Open trenches cut down the medium through which vibration waves travel while in-filled trenches reduce vibrations by reducing the shear velocity of the waves. It is hence necessary to consider in-filled trenches. In-filled trenches with appropriate sizes have been found to be effective, but in no case as effective as an open trench of the same size. When ground vibration waves travel through the trench, two media with different impedance are met. The materials used to fill the trench are of utmost importance as they play the primary role of vibration amplitude reduction and hence the performance of the trench. The material type and mechanical properties of these materials must be studied and taken into consideration.

4.3.1. Type of trench material.

Many researchers in the past have studied and investigated the use of many materials in trenches to reduce the transmission or propagation of vibration waves. Some of these materials include geofoam, water, soil, concrete, rubber, bentonite and rocks. After numerous experiments and investigations, it was concluded that some materials were more effective in vibration attenuation than others. Expanded polystyrene (geofoam) was found to be the most effective material to use in in-filled trenches. It was also concluded the depending on the source to barrier distance, water can also be used. In this case, the trench must be more 5m away from the source of vibration. In 2015, Ulgen and Toygar [33] performed field tests and concluded that water had a vibration reduction percentage of 60% at a distance >5m from the source. Also, they found out that geofoam had a reduction percentage of 75% with a trench depth of 1.5m. Celebi et al in [44] also performed field tests and concluded that with excitation frequency varying from 10 to 100Hz, concrete filled trenches have a 36% vibration reduction percentage. This relatively too low for trenches less than 5m away from the source of vibration. Murillo et al performed centrifuge test in the lab and found out that EPS in a trench 2m deep had a reduction percentage of 60% [14]. Sakai[27], Yang and Hung[45] and Bo et al [23] all performed numerical case studies with soft elastic material as the infilled trench material. Sakai worked an excitation frequency of 31Hz, an impedance ratio ranging between 0.1 and 0.15 and concluded that the material had reduction percentage of 80%. Yang and Hung had the same excitation frequency and an impedance ratio less than 0.2. they concluded that the material had 70-80% reduction percentage. With a frequency of 50Hz and impedance ratio 0.17, Bo et al came out with a vibration reduction percentage of 65%. As stated above, among all the materials that can be used in infilled trenches, geofoam has the higher vibration reduction percentage. The downside of the geofoam is that it has a low shear strength.

a) [46]

b) [47]

c) [48]

Figure 4.2. Trench with various materials. a) geofoam. b) concrete. c) water.

4.3.2. Young’s modulus

Young’s modulus or modulus of elasticity is a mechanical property that measures the tensile or compressive stiffness of a material (mostly solid) when the force is applied lengthwise. It quantifies the relationship between tensile/ compressive stress (force per unit area) and axial strain (proportional deformation) in the linear elastic region of a material. [49].

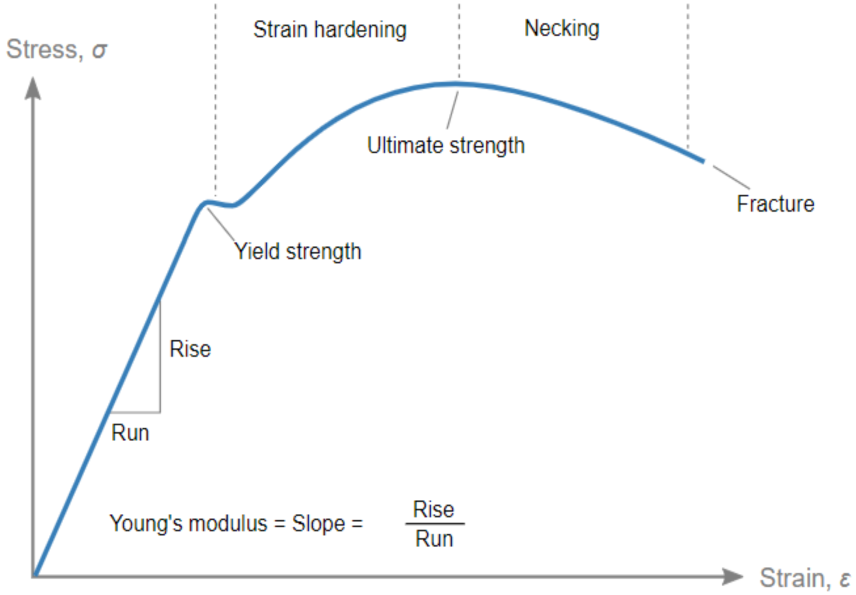

Figure 4.3. Stress-strain curve for a material under tension or compression.

E = $\frac{\sigma}{\varepsilon}$; but $\sigma = \frac{F}{A}$ and $\boldsymbol{\varepsilon} = \frac{\Delta L}{L}$ => E = $\frac{FL}{\Delta LA}$

Where:

E = Young’s modulus

σ = tensile stress

$\boldsymbol{\varepsilon}$ = strain

F = force exerted

L = length of the object

ΔL = change in length

A = cross sectional area of the object

A solid material will undergo elastic deformation when a small load is applied to it in compression or extension. Elastic deformation is reversible, meaning that the material returns to its original shape after the load is removed. At near-zero stress and strain, the stress–strain curve is linear, and the relationship between stress and strain is described by Hooke's law that states stress is proportional to strain. The coefficient of proportionality is Young's modulus. The higher the modulus, the more stress is needed to create the same amount of strain; an idealized rigid body would have an infinite Young's modulus. Conversely, a very soft material (such as a fluid) would deform without force and would have zero Young's modulus. Not many materials are linear and elastic beyond a small amount of deformation [50]. Materials with higher Young’s modulus tend to perform better when facing oscillatory or vibratory waves. For these reasons, materials with high elasticity modulus must be prioritized in trench material selection.

4.3.3. Material damping.

Damping which basically means reduction in vibratory or oscillatory motion is one very important factor to consider in when selecting materials for infilled trenches. Damping is a unitless measure that indicates the rate at which vibration waves in systems run out in the face of obstacles or hindrances. It is not the same as friction, which is a force that hinders of solid surfaces, fluid layers and material elements sliding against each other. Friction can cause damping or can be an underlying factor of damping. Damping ration can be denoted by the symbol ζ known as zeta. There are four types of damping:

1) Undamped; $\zeta = 0$
2) Underdamped; $\zeta < 1$
3) Critically damped; $\zeta = 1$
4) Over damped; $\zeta > 1$

Extensive studies must be done on materials before they are selected to be used in trenches to know and understand their absorbing capabilities. Materials with higher absorbing capabilities have been known to perform very well in vibration attenuation. The higher the damping coefficient of the material, the better it performs in oscillatory motion reduction which in turn indicates elevated levels of trench performance.

4.4. Sizing of barriers

Calculations were made manually for the dimensions and compared to results of previous results.

Previous studies have shown that the width of a trench does not have a very significant role on the performance of the trench, so we focused mostly on the depth of the trench. We know that the trench depth shouldn’t be less than 1.5 times the wavelength of the wave, so we set out to calculate the wavelength. As previously stated, the frequency was taken as 62.5Hz. Angular frequency was input as 10rad/s and with an angular change per unit space of 8, the wave velocity was calculated.

$$V = \frac{\omega}{k} = \frac{10}{8} = 125\text{m/s}$$

Where : V = wave velocity

ω = angular frequency

k = angular change per unit space

$$\lambda = \frac{v}{f} = \frac{125}{62.5} = 2\text{m}.$$

where : λ = wavelength

f = frequency of the wave.

We know that the trench depth (h) = 1.5* λ

⇨ h = 1.5 * 2

⇨ h = 3m

This means that for a wave with a PPV of 125m/s the minimum depth of a trench to sufficiently attenuate the waves should be 3m. the width of the trench cannot be less than 0.3 times the height so we can take a minimum width of the trench to be 0.9m.

In 1970, Richard et al investigated and concluded that with a trench depth 1.5 times the wavelength, vibration amplitude falls by over 80%.[46]. Sakai and some other researchers confirmed this so we can also conclude that results found are in agreement with previous studies hence are approved.

Chapter V: Conclusion.

Due to the fast growing structural and mechanical developments going on in the world today, ground vibrations transmitted through the soil from external sources have become an important aspect to look at. If not properly checked, these vibrations can and may cause irreparable havoc to structures, sensitive equipment and even to the health of nearby habitants. Vibrations are sourced from various machines and activities including trains, cars, machines at construction sites to HVACs. It is imperative therefore to come up with efficient, tried, tested, and approved methods to limit the transmission of these such vibrations in the ground. To limit these vibrations, we need to study and know the amplitude and transmission paths. Soil character also must be studied analytically. In this thesis, numerical models were made using COMSOL Multiphysics to predict the amplitudes of vibratory waves before and after putting trenches in the propagation path. This research involved a comprehensive but inconclusive study on the use of trenches (both open and in-filled) in ground vibration limitation.

Open trenches have been found to be the most efficient method in ground vibration mitigation. They come cheaper and easier to construct but do the job perfectly. Their only inconvenience is the instability of waves in the open space. To optimize the performance of open trenches, diverse parameters that affect the trench's vibration attenuation capabilities were studied. We concluded that the height or depth of the trench is the most important parameter. We noted that having a trench depth 1.5 times the wavelength of the oscillatory motion was the best minimum depth of every open trench. After various studies and investigations, we also concluded that trench width can be neglected or ignored since it has little or no effect on elevation of the performance levels of open trenches. The explanation being that when a trench is located near the source of vibration, body waves play a more dominant role with respect to surface waves, and thus a shallow trench would allow greater amounts of body waves to underpass the trench. A wider trench, however, provides a greater free surface that converts body waves to surface ones, yielding unfavorable outcome. So, widening the trench has a more negative effect on the trench than positive. There is no clear trend towards trench distance from the vibration source in investigations and studies conducted. Not much influence on amplitude reduction coefficient is observed with changes in distance, and no certain pattern can be extracted for the alterations. It can be concluded from various researches mentioned above that the source-barrier distance has a low effect on barrier's performance except in shallow trenches but for optimal isolation, the farther away the trench is from the source, the better it is in vibration attenuation.

The use of infilled trenches would never have been considered in ground-borne vibration mitigation if not for the instability issues of open trenches. And after extensive studies and investigations, they have been found to attenuate vibration sufficiently. The performance of these such trenches depends highly on the materials used in them. For this reason, various materials have been studied and investigated in the past. To complement the investigations and findings of previous researchers, numerical studies were done to see the effects of various materials on the performance of the trench. Among all of them, extended polystyrene (geofoam) was found to be the most efficient because of its high damping capabilities. Water was found to be a material than can also be used but in this case the barrier to source distance would be a key factor. Meaning the trench would have to be sufficiently far away from the source of vibration; minimum 5m away. Material damping is one very important factor that was considered in material selection. Materials with higher absorbing capabilities have been known to perform very well in vibration attenuation. The higher the damping coefficient of the material, the better it performs in vibration reduction which in turn indicates elevated levels of trench performance. The modulus of elasticity of the materials was considered too. The harder it is for a material to deform, the better it would be at reducing vibratory waves. Materials with higher Young's modulus tend to perform better when facing vibratory waves. For these reasons, materials with high elasticity modulus must be prioritized in trench material selection.

There's much to be learned from the information provided in this thesis but it remains insufficient. Further research would have to be done to fully or let me say get close to fully understand and predict the behavior of vibratory waves. Years of extensive and definitive research and studies must be done to be able to properly mitigate ground-borne vibrations.

REFERENCES

[1] D. S. Kim, J.-S. Lee, Propagation and attenuation characteristics of various ground vibrations, Soil Dynamics, and Earthquake Engineering 19 (2000) 115–126, Korea Advanced Institute of Science and Technology, Taejon, 305-701, South Korea, December 1999.

[2] S. Thorat. Theory of machines, https://learnmech.com/vibrations, 2022.

[3] Delserro engineering solutions. 3900 Broadway Road, Easton, PA 18040, Vibration & Shock Testing, June 2015.

[4] W. Brian Rowe, in Principles of Modern Grinding Technology (Second Edition), 2014.

[5] S. Thorat. Theory of machines, https://learnmech.com/vibrations, 2022.

[6] T. G. Gutowski and C. L. Dym, Propagation of ground vibration: A review, Journal of Sound and Vibration (1976) 49(2), 179-193, 1976.

[7] R.M. Thornely-Taylor, Ground vibration prediction and assessment.

[8] D. S. Kim, J.-S. Lee, Propagation and attenuation characteristics of various ground vibrations, Soil Dynamics, and Earthquake Engineering 19 (2000) 115–126, Korea Advanced Institute of Science and Technology, Taejon, 305-701, South Korea, December 1999.

[9] K.R Massarsch and B.H Fellenius, Ground vibrations induced by impact pile driving. The Sixth International Conference on Case Histories in Geotechnical Engineering, Edited by S. Prakash, Missouri University of Science and Technology, Arlington, Virginia, 38 p, August 2008.

[10] D. Macijauskas[1], S. Van Baars[2]. A Simple Engineering Soil Surface Vibration Prediction Method. [1]ArcelorMittal Commercial RPS, Luxembourg [2]Professor in Foundation Engineering and Soil Mechanics, Faculty of Science, Technology and Communication, University of Luxembourg, Luxembourg, March 2018.

[11] P. Hölscher, P.H. Waarts, Reliability of vibration prediction and reducing measures. Report Delft Cluster, Delft, 2003.

[12] Vibration isolation - https://en.wikipedia.org/wiki/vibtation_isolation.

[13] Wikipedia contributors, Ground vibrations. In Wikipedia, The Free Encyclopedia, from https://en.wikipedia.org/w/index.php?title=Ground_vibrations&oldid=1072119698, 2022.

[14] C. Murillo[1], L. Thorel[1], B. Caicedo[2], Geotextiles and Geomembranes, Pages 423-434, [1]Laboratoire Central des Ponts et Chaussées, Centre de Nantes, Point 87, Route de Bouaye, BP4129, 44341 Bouguenais Cedex, France, [2]Civil and Environmental Department, Universidad de los Andes, Cr 1 #18a-10 Bogotá, Colombia, December 2009.

[15] S. Kaul, Modeling and Analysis of Passive Vibration Isolation Systems, 2021.

[16] E. Rivin, Encyclopedia of Vibration, 2001.

[17] D. J. Pubudu W. Arachchillage, B.Sc. in engineering, mitigating ground vibration using in-filled trenches and predicting performance through artificial neural network, School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, 2019.

[18] D. D. Barkam, Dynamics of Bases and Foundations, McGrawHill, New York, USA, 1962.

[19] D. E. Beskos, B. Dasgupta, and I. G. Vardoulakis, Vibration isolation using open or filled trenches; part 1: 2D homogeneous soil, Computational Mechanics, vol. 1, no. 1, pp. 43–63, 1986.

[20] M. Adam and O. von Estorff, Reduction of train-induced building vibrations by using open and filled trenches, Computers and Structures, vol. 83, no. 1, pp. 11–24, 2005.

[21] G. Di Mino[1], M. Giunta[2], and Ciro Maurizio Di Liberto[1], Assessing the Open Trenches in Screening Railway Ground-Borne Vibrations by Means of Artificial Neural Network, [1]Department DIIV, University of Palermo, Parco D'Orleans, 90100 Palermo, Italy, [2]Department DIMET, University Mediterranea of Reggio Calabria, Via Graziella Feo di Vito, 89100 Reggio Calabria, Italy, 13 October 2009.

[22] S. Ahmad & Al-Hussaini, Simplified Design for Vibration Screening by Open and In-Filled Trenches. Journal of Geotechnical Engineering, 117(1), 67-88, doi: doi:10.1061/(ASCE)0733- 9410(1991)117:1(67), 1991.

[23] Q. Bo, L. Ali, & D.M. Irini, Numerical study of wave barrier and its optimization design. Finite Elements in Analysis and Design, 84, 1-13, 2014.

[24] S. D. Ekanayake, D. S. Liyanapathirana, & C. J. Leo, Attenuation of ground vibrations using in-filled wave barriers. Soil Dynamics and Earthquake Engineering, 67, 290-300. doi:10.1016/j.soildyn.2014.10.004, 2014.

[25] P. Zoccali, G. Cantisani, & G. Loprencipe, Ground-vibrations induced by trains: Filled trenches mitigation capacity and length influence. Construction and Building Materials, 74, 1-8, 2015.

[26] M. H. E. Naggar, & A. G. Chehab, Vibration barriers for shock-producing equipment. Canadian Geotechnical Journal, 42(1), 297-306, doi:10.1139/t04-067, 2005.

[27] A. Saikia, Numerical study on screening of surface waves using a pair of softer backfilled trenches. Soil Dynamics Earthquake Engineering, 65:206–213, 2014.

[28] X. Pu, Z. Shi, & H. Xiang, Feasibility of ambient vibration screening by periodic geofoam-filled trenches. Soil Dynamics and Earthquake Engineering, 104, 228-235, 2018.

[29] D. Younesian, & M. Sadri, Effects of the trench geometry on vibration mitigation level in high-speed railway tracks, Journal of mechanical science and technology, 26(8), 2469-2476, 2012.

[30] D. J. Pubudu, W. Arachchillage, B.Sc. in engineering, mitigating ground vibration using in-filled trenches and predicting performance through artificial neural network, School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, 2019.

[31] D. J. Thompson, J. Jiang, M. G. R. Toward, M. F. M. Hussein, E. Ntotsios, A. Dijckmans, G. Degrande, Reducing railway-induced ground-borne vibration by using open trenches and soft-filled barriers. Soil Dynamics and Earthquake Engineering, 88, 45-59, 2016.

[32] fig43.gif (603×344) (swri.edu)

[33] https://www.agric.wa.gov.au/sites/gateway/files/Digging deep drain_27June08 004.JPG.

[34] D. Ulgen, & O. Toygar, Screening effectiveness of open and in-filled wave barriers: A full-scale experimental study. Construction and Building Materials, 86, 12-20, 2015.

[35] C. Brischke, M. Humar, Performance of Bio-based Building Materials, pp. 249-333. 2017.

[36] C. L. Chunlin, Department of Geoscience and Petroleum, The Norwegian University of Science and Technology, Available online 26 May 2017, Version of Record 26 May 2017.

[37] E. Mahdavisefat, A. Heshmati, H. Salehzadeh, H. Bahmani & M. Sabermahani Vibration screening by trench barriers, a review, Iran University of science and technology, Tehran, Iran, article in Arabian Journal of Geosciences · November 2017.

[38] W. Yang[1], R. Yuan[1], J. Wang[2], Vibration Induced by Subway Trains: Open-Trench Mitigation Analysis in the Time and Frequency Domains. 1 Key Laboratory of Transportation Tunnel Engineering, Southwest Jiaotong University, Ministry of Education, Chengdu, China 2 Ningbo Nottingham New Materials Institute, University of Nottingham Ningbo, Ningbo, China, September 2018.

[39] K. Emad, G. D. Manolis, Shallow trenches and propagation of surface waves. J Eng Mech 111:279–282, 1985.

[40] J. Smith, Plumbing contractor faces $57K in fines after trench cave in, Bloomberg News, 2019.

[41] Wikipedia contributors, Butterfly effect. In Wikipedia, The Free Encyclopedia, from https://en.wikipedia.org/w/index.php?title=Butterfly_effect&oldid=1093904572, 2022

[42] Lorenz, N. Edward, "Deterministic Nonperiodic Flow". Journal of the Atmospheric Sciences. **20** (2): 130–141. Bibcode:1963JAtS...20..130L. doi:10.1175/1520-0469(1963)020<0130:dnf>2.0.co;2, March 1963

[43] R. Nicolis, Catherine; Nicolis, Gregoire, "Butterfly effect - Scholarpedia". Scholarpedia. **4** (5): 1720. doi:10.4249/scholarpedia.1720, 2009

[44] E. Çelebi, S. Firat, G. Beyhan, I. Çankaya I. Vural, O. Kirtel, Field experiments on wave propagation and vibration isolation by using wave barriers. Soil Dynamics Earthquake Engineering, 29:824–833, 2009.

[45] Y. B. Yang, H. H. Hung, A parametric study of wave barriers for reduction of train-induced vibrations. Int J Numer Methods Eng 40:3729–3747, 1997.

[46] R. Bygness, S. O'Keefe, Wetlands restoration at San Pablo Bay, August 2016.

[47] Jason and Tina Coleman, concrete trenches, May 2008.

[48] L. Greyling, Trench filled with putrid water, 2007.

[49] D. Jastrzebski, Nature and Properties of Engineering Materials (Wiley International ed.). John Wiley & Sons, Inc, 1959.

[50] Wikipedia contributors, Young's modulus. In Wikipedia, The Free Encyclopedia, from https://en.wikipedia.org/w/index.php?title=Young%27s_modulus&oldid=1093823286, 2022.

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ABSTRACT

The world is fast growing in terms of structural developments and machinery. The constructions of these structures and the use of these machines cause vibrations in the ground. These vibrations have adverse effects on adjacent structures, their occupants and sensitive equipment used in them. Ground-borne vibrations have become very important aspects to be considered in the fast-developing world we live in. To check these vibrations, we can control the source (which is nearly impossible) or make necessary advances to limit the propagation of the waves. To limit the transmission of ground vibrations, wave barriers are put in the transmission path of the waves.

In this thesis, we investigated and studied some of the isolation methods for these ground-borne vibrations. A field of soil 400m in length, 200m wide and 100m deep was taken as the field of study. A cube block of length 2m was taken as the source of excitation with a frequency of 62.5Hz and vibration variations were recorded.

Finite element method developed by researchers in the past was adopted to investigate the effectiveness of two types of wave barriers (open and infilled trenches) in ground vibration mitigation. COMSOL Multiphysics numerical modelling software was used to model the field, trench, and cube block.

The acceleration of vibrations at a point 5m away from the source of vibration (without a trench) was recorded and taken as the reference acceleration and used to calculate the reduction factor and attenuation percentage of various depths and materials of the trenches. A trench was then modeled in the transmission path. Various depths were studied in the case of open trenches and for infilled trenches, we studied three different materials: (geofoam (EPS), water and concrete). We recorded vibration acceleration at the different depths and different materials and divided it by the reference acceleration to get the reduction factor. With these, we could easily calculate the attenuation percentage of every parameter ((1-reduction factor)*100). For open trenches, trench depth of 3m yielded an attenuation percentage of 77. At 5m, we noticed 86.3% of vibration attenuation and 10m yielded 98.9% vibration reduction. For infilled trenches, EPS had the highest attenuation percentage of 81.5, followed by water with 64% and concrete showed a reduction of 38%.

The results from this thesis can be used to develop design guidelines for wave barriers.

Keywords

Artificial Neural Network

Vibration

Isolation

Barriers

Trench

List of Symbols and Abbreviations

ANN : Artificial Neural Network

HVAC : Heating, Ventilation and Air Conditioning

PPV : Peak Particle Velocity

FEM : Finite Element Method

EPS : Expanded Polystyrene

HST : High-Speed Trains

NR : Natural Rubber

MR : Magnetorheological

CMM : Coordinate Measuring Machines

BEM : Boundary Element Method

2D : Two Dimensional

3D : Three Dimensional

FDM : Finite Difference Method

DEM : Discrete Element Method

α : Mass Damping Parameter

β : Stiffness Damping Parameter

ζ : Zeta

Table of Contents

ACKNOWLEDGEMENTS ……….………………..………………………………i

ABSTRACT ..……………………………………..…………………...…ii

KEYWORDS ..…………………………………………………………...iii

LIST OF SYMBOLS AND ABBREVIATIONS ………………...……….……….iii

TABLE OF CONTENTS……………………………………………………iv

LIST OF FIGURES………………………………………………………vi

LIST OF TABLES ……………………………………………..……….viii

CHAPTER I : INTRODUCTION ……………………………….……..........1

1.1. General introduction ………………………………………………………1

1.2. Aims and objectives …………………………...…………………………..2

1.3. Thesis outline ……………………...……………………………………...2

CHAPTER II : LITERATURE REVIEW ..………………….……… ………………3

2.1. Vibrations ……………………………………………….………………..3

2.1.1. Terminologies of vibration ……………………………………………..3

2.1.2. Types of vibrations …………………………………………………….4

2.1.3. Sources of vibrations …………………………………………………...5

2.1.4. Effects of vibrations ………………………………..……………….6

2.1.5. Measurement of vibrations ……………………………………………6

2.2. The principle of vibration propagation in the ground and methods of analysis…7

2.3. Techniques for isolating vibrations propagated in the ground…………………..8

2.3.1. Ground vibration …………………………………………………....8

2.3.2. Ground vibration isolation ……………………………………………….9

2.3.3. Vibration isolation methods ……………………………………………13

2.3.3.i. Open trenches …………………………………………………...15

2.3.3.ii. In-filled trenches ………………….…………………………16

2.3.3.iii. Multiple trenches ………………………………………………18

2.3.3.iv. Nonrectangular trenches ……………………………………….19

2.3.4. Designs and approaches of previous studies ……………………………21

CHAPTER III: Preliminary numerical modelling and parametric study …...22

3.1. Introduction… ……………………………………………………………………….22

3.2. Open trenches…………………………………………………………………..23

3.2.1. Finite element model ……………………………………………………………23
3.2.2. Finite element model results …………………………………………………….24
3.3. In-filled trenches ………………………………………………………………….26
3.3.a. In-filled trench with EPS ……………………………………………………...28
3.3.b. In-filled trench with water …………………………………………………….30
3.3.c. In-filled trench with concrete …………………………………………………31
3.3.c.I. In-filled trench 5m away …………..………………………………...........31
3.3.c.II. In-filled trench 10m away ……….…..……………………..….............32
3.3.c.III. In-filled trench 20m away …………..……………………………...........33
CHAPTER IV: COMPARATIVE STUDY OF OPEN AND IN-FILLED TRENCHES ….34
4.1. Introduction ……………………………………………………………………….34
4.2. Ground vibration mitigation using open trenches ………………………………..36
4.2.1. Trench depth ……………………………………………………………………36
4.2.2. Trench width ……………………………………………………………………38
4.2.3. Source to barrier distance ………………………………………………………39
4.2.4. Frequency ………………………………………………………………………40
4.3. Ground vibration mitigation using in-filled trenches ……………………………41
4.3.1. Type of trench material …………………………………………………………41
4.3.2. Young's modulus ……..…………………………………………………………43
4.3.3. Material damping ……..…………………………………………………………44
4.4. Sizing of barriers ……...………………………………….……………………....45
CHAPTER V : CONCLUSION …….………………………………………..…......46
REFERENCES …………………………..…………………….………………………48

List of figures

Figure 2.1. Swinging of pendulum …………………..…..…………………….……….………..…………3

Figure 2.2. Waves of vibration ……………..……………...…………………………………..…………3

Figure 2.3. Free or natural vibration ……………………...……………………………….………..4

Figure 2.4. Forced vibration ………………………...……………………………….………..5

Figure 2.5. Damped vibration ……….……………….…………………………………….…………5

Figure 2.6. Setup to measure ground vibration ……………………….……..………….………6

Figure 2.7. Vibration isolation methods …………………………………………………..……….14

Figure 2.8. schematic representation of position of open trench …………………..…………15

Figure 2.9. Multiple rows of infilled trenches ………….………..…………………………..………19

Figure 2.10. Triangular infilled trench ……………………………………………………....20

Figure 2.11. V- shaped infilled trench ……………………………………………………………20

Figure 3.1. Finite element model with mesh size normal …………………………………...23

Figure 3.2. Acceleration variation in the soil ……………………………………………………..24

Figure 3.3. vibration attenuation 5m away from source ……………………………………….25

Figure 3.4. 2D image of vibration attenuation 5m away from source ………………..….….25

Figure 3.5. Developed FE model results ……………………………………………………….28

Figure 3.6. Vibration attenuation of in-filled trench with EPS ………………………………29

Figure 3.7. 2D image of vibration attenuation of in-filled trench with EPS …………………29

Figure 3.8. Vibration attenuation of in-filled trench with water ……………………………..30

Figure 3.9. 2D image of vibration attenuation of in-filled trench with EPS …………………30

Figure 3.10. Vibration attenuation of in-filled trench with concrete 5m away ………………31

Figure 3.11. 2D image of vibration attenuation of in-filled trench with concrete 5m away ….31

Figure 3.12. Vibration attenuation of in-filled trench with concrete 10m away ……………..32

Figure 3.13. 2D image of vibration attenuation of in-filled trench with concrete 10m away ..32

Figure 3.14. Vibration attenuation of in-filled trench with concrete 20m away ……………..33

Figure 3.15. 2D image of vibration attenuation of in-filled trench with concrete 20m away ..33

Figure 4.1. A deep trench at residential construction site ………………………………………37

Figure 4.2. Trench with various materials. a) geofoam. b) concrete. c) water ………..………42

Figure 4.3. Stress-strain curve for a material under tension or compression ……….………..43

List of tables

Table 2.1. Some of the commonly used elastomers ……………….…………..……………….11

Table 3.1. Materials properties …………..…………………..…………..…..…..…………………26

Table 3.2. Variations of infilled trench material properties ………..………………………….27

Table 4.1. Attenuation percentage of various depths of an open trench ……………………….35

Table 4.2. Attenuation percentage of various parameters of an in-filled trench ……………….35