EFFECTIVENESS OF A TRAPEZOIDAL TRENCH FILLED WITH EPS GEOFOAM IN REDUCING THE PROPAGATION OF GROUND VIBRATIONS

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2023

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A thesis submitted to the National University of Sciences and Technology, Islamabad

in partial fulfillment of the requirements for the degree of

Master of Science in

Structural Engineering

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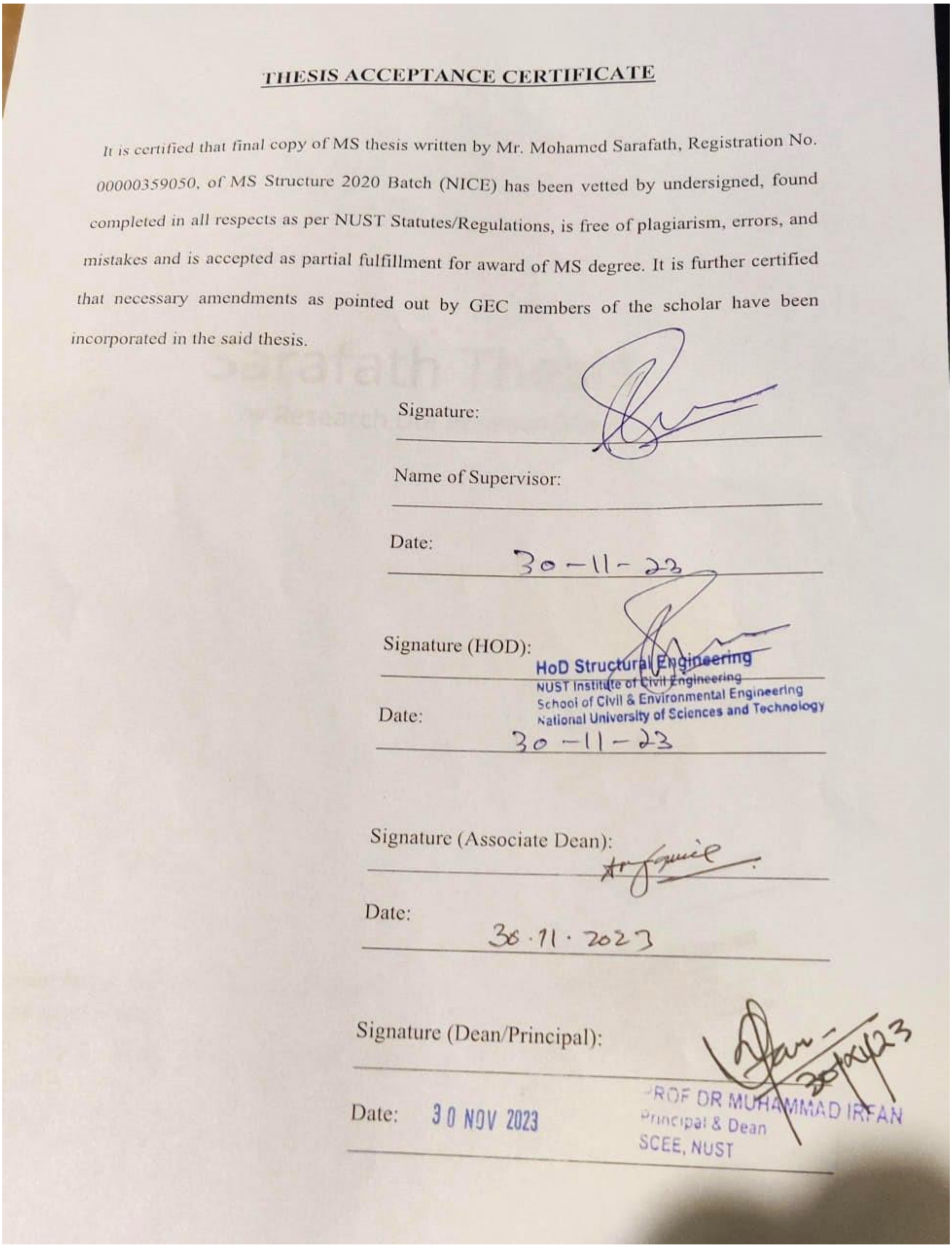

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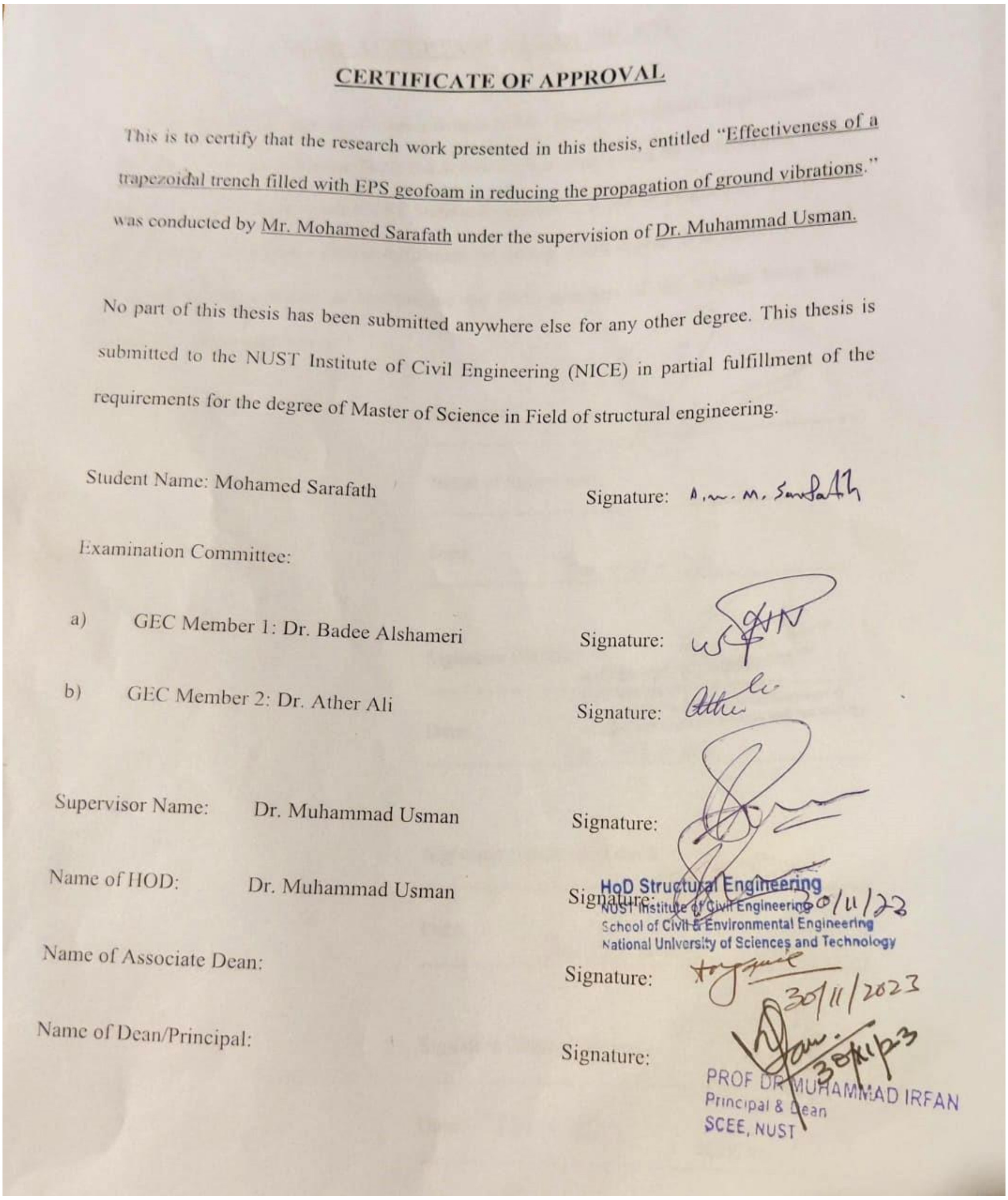

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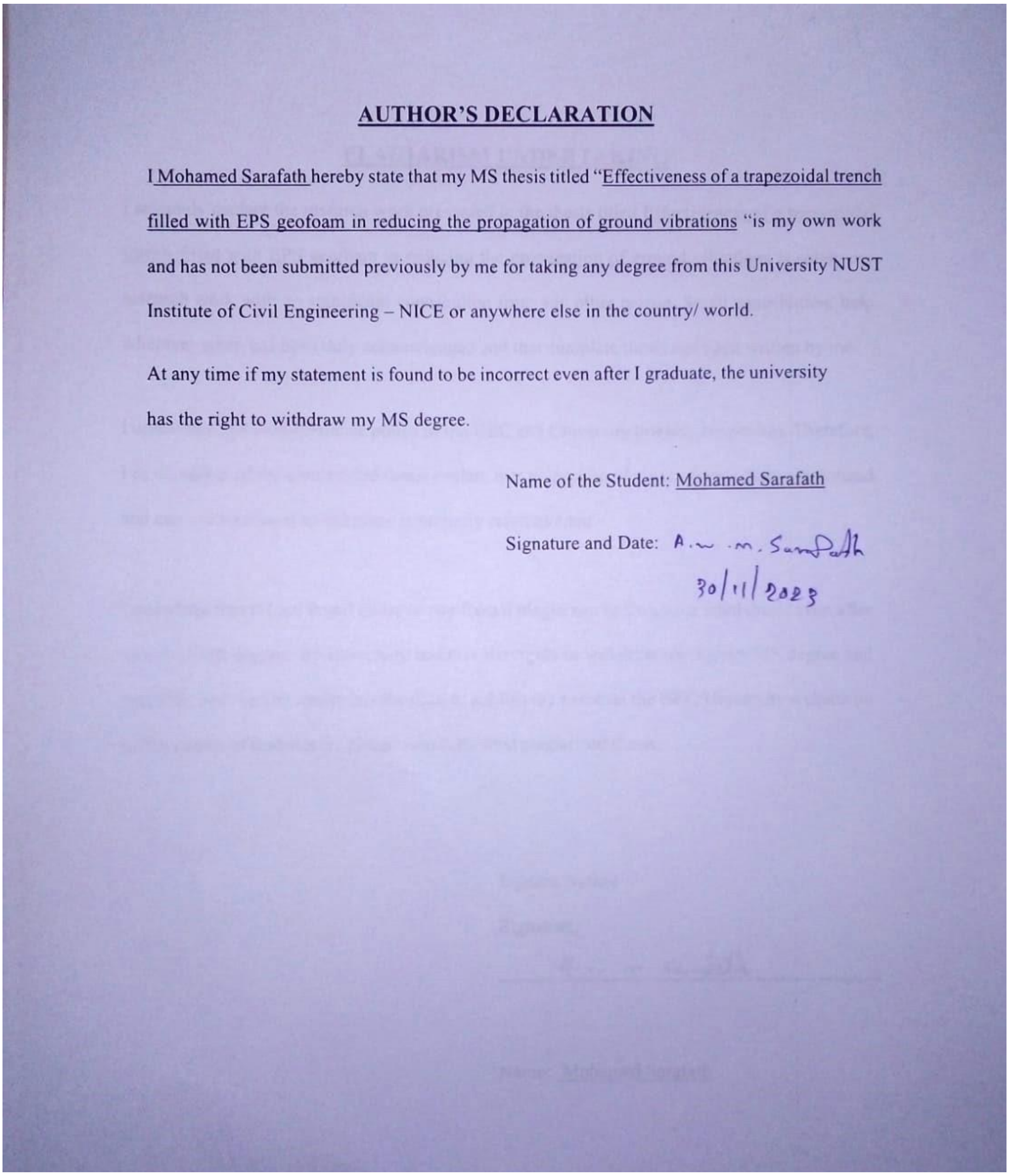

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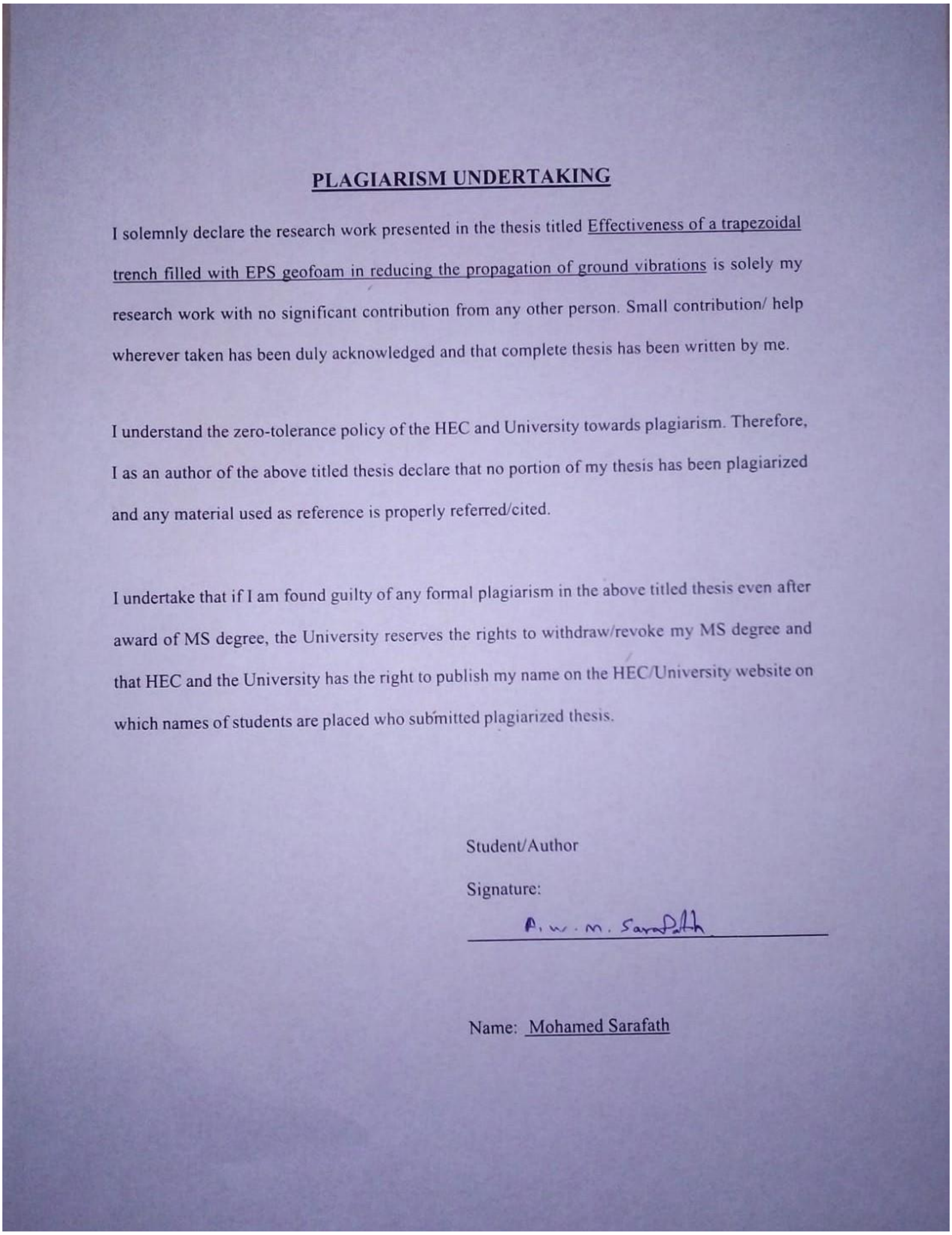

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DEDICATED TO

My Father: “**May Allah have mercy on his soul”**

My Mother: “**I am deeply indebted to this individual”**

My Beloved Wife: **Fathima Nafha**

who supported me throughout this project.

ACKNOWLEDGEMENTS

I take this opportunity to express my sincere gratitude to all the individuals who guided me in making this Master of Science Research thesis.

Firstly, I sincerely thank Dr Muhammad Usman, my supervisor and the Head of Structural Engineering at NICE, Islamabad. His steadfast guidance, encouragement, and empathy have proven priceless to me. Despite his busy schedule, he consistently made time for meaningful discussions and offered invaluable assistance to his research students.

My sincere thanks go to the esteemed members of my Graduate Examination Committee, namely Dr. Badee Alshameri and Dr. Ather Ali. Their constructive suggestions and assistance were instrumental in shaping the course of my research.

Due to the multidisciplinary nature of my research, I had the opportunity to collaborate in two distinct laboratories: the Structural Lab and the Geotechnical Lab at NICE. I want to express my profound gratitude to the lab engineers and technicians who demonstrated exceptional professionalism and support throughout this work.

I owe a great deal to my friends who readily offered their assistance whenever it was needed, making significant contributions to the successful completion of my project.

Finally, I want to sincerely acknowledge my parents, wife, siblings, and well-wishers. Their consistent motivation and encouragement provided me with the resilience to overcome challenges in this undertaking. Their unwavering belief in me served as a continual source of inspiration.

ABSTRACT

Structural and serviceability health of the buildings and infrastructure are facing challenging problems due to ground-born vibration from the surrounding environment. The vibration source and transmitting soil medium are the defining parameters of the ground-born vibration propagation and the surrounding environments and buildings will define the allowable limit of vibration. This full-scale field experimental study aims to examine the two primary goals. Firstly, the characteristic of the ground-born vibration propagations through soil medium and secondly, the effectiveness of the trench barrier in minimizing the impact of the ground-born vibration for both active and passive isolation systems. Introducing a wave barrier between the vibration source and structure to be protected has been considered a cost-effective and easily applicable solution to minimize the impact of ground-born vibrations. There is no field experimental data available on the effects of trapezoidal trenches filled with EPS geofoam to screen such ground-borne vibrations. This study aims to describe a series of field experiments conducted to examine the characteristics of ground-born vibrations, the open trapezoidal trench and the effect of a trapezoidal trench filled with EPS geofoam-filled trenches. Further, available findings in past studies were compared with the experimental findings results from the series of field experimental tests. The results obtained from the field tests ensured that the geofoam-filled trapezoidal trench could be used as a higher-forming isolation system for effectively minimizing the propagation of ground-borne vibrations.

Keywords: Ground-born vibrations, Vibration isolation, Open and infilled trapezoidal trenches, EPS geofoam.

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Chapter 1: Introduction

1.1 Background

The need for infrastructure in developing cities and urban regions has increased due to the high rate of population growth and industrial development. Many cities are undergoing increased density as construction activities extend from nearby surroundings to existing buildings. Consequently, residences are susceptible to increased vibration issues arising from sources such as passing high-speed trains, machine foundations, traffic, pile driving and various construction activities. Ground-borne vibrations, generated by these sources becoming seismic waves (body and surface waves), contribute to the occurrence of these vibrational concerns.

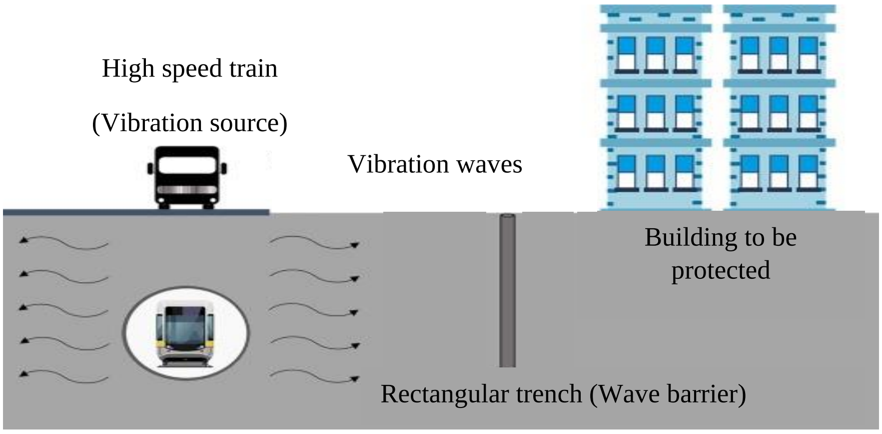


Figure 1.1: Isolation of ground born vibration by rectangular trench barrier

Ground-born vibrations are transmitted through the surface of the soil medium to a building's foundation, causing distress to both the structures and their residents[1]. A vibration isolation mechanism can be implemented either at the vibration-generated locations or the near to surrounding structures. An effective method involves installing a wave barrier such as a rectangular trench between the vibration source and the nearby structures (Figure 1.1)[2]. Wave barriers are commonly employed to disperse ground-borne vibrations, effectively managing the transmitted vibrations, and minimizing their disturbance. Implementing appropriate wave barriers proves to be an effective strategy for scattering generated seismic waves. These barriers can take various forms, including open trenches, in-filled concrete or bentonite trenches, sheet-pile walls and rows of solid or hollow concrete or steel piles[3].

This study focuses on mitigating ground-born vibrations along the transmission path by installing a trapezoidal trench barrier filled with EPS geofoam. Active isolation and passive isolation are the two categories into which vibration isolation using trench barriers can be divided according to how close they are to the source of disturbance. Often referred to as near-field isolation, active isolation describes the location of the wave barrier around or near the disturbance source. consequently, when the wave barrier is installed far from the vibration source of disturbance, it is known as passive (far-field) isolation [4] as shown in Figure 1.3[5]. Passive isolation systems are appropriate for protecting residential areas from artificially generated or manmade vibrations, while active isolation systems are effective in scenarios involving dynamically loaded foundations, such as machine foundations and high-speed train traffic where the barrier needs to be positioned near the foundation. [5].

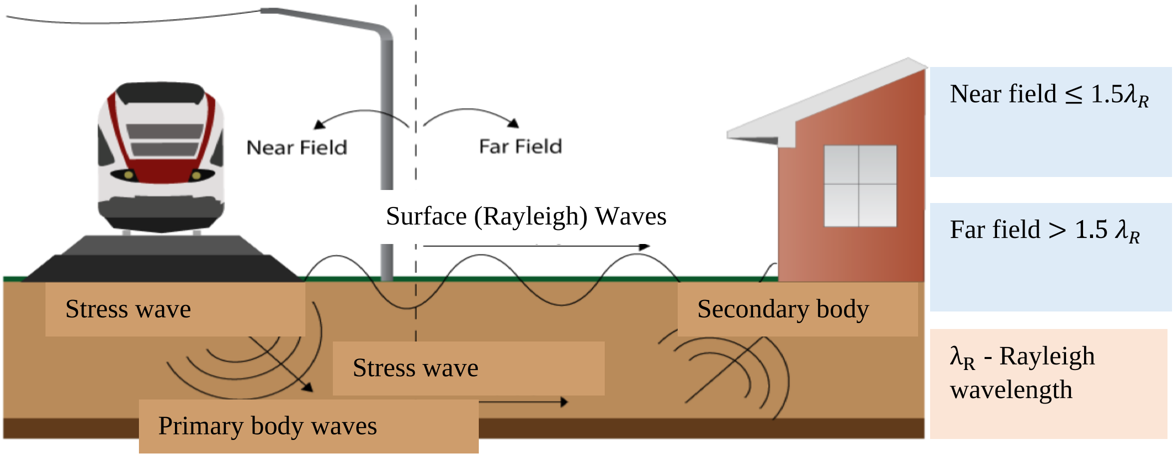


Figure 1.2: Basic seismic wave propagation mechanism

Figure 1.2[6] shows the basic seismic wave propagation and near field, far field phenomenon. It is defined by the Rayleigh wavelength. A distance less than $1.5\lambda_R$ it is defined as active isolation; if the distance is greater than $1.5\lambda_R$ it is defined as a passive region[4]. It is noted that Rayleigh wavelength depends on the excitation frequency. Therefore, field far field phenomenon is frequency dependent.

A significant amount of computational and experimental work has been done in the last seven decades to study vibration isolation over rectangular trenches as a wave barrier, which has improved our understanding of the vibration propagation and isolation phenomena. Most of this work has been devoted to improving experimental and computational techniques as vibration isolation issue analysis mechanisms. Consequently, the different characteristics associated with open trenches, in-filled concrete or bentonite trenches, sheet-pile walls, and rows of solid or hollow concrete or steel piles are now well understood. Considering cost-effectiveness and easiness of implementation, open and filled trenches have been used in construction and infrastructure projects for many years as vibration isolation methods (wave barriers). Due to numerous maintenance issues such as localized collapse, open trenches are not appropriate in some of the applications of the construction industry. Therefore, suitable filling material has been used to fill the trenches and it can support the wall of the trenches. Beyond the conventional rectangular designs, researchers have recently investigated a variety of trench shapes to improve their performance. Trapezoidal trenches, V-shaped trenches, one-sided inclined trenches, and a combination of rectangular and trapezoidal trenches are a few of these alternate configurations. Thus, carrying out field experiments on trapezoidal trenches is essential for developing this area of research and may lead to additional advancements.

Due to the special features of EPS Geofoam, it is used as a wave barrier in the modern construction industry. Among the traditional materials, EPS geofoam has special features such as a high strength-to-weight ratio and lightweight. Also, EPS geofoam has been used in retaining wall structures, bridge approaches and embarkment constructions. Therefore, studying the effectiveness of a trapezoidal trench filled with EPS geofoam may be helpful to additional advancements for future work.

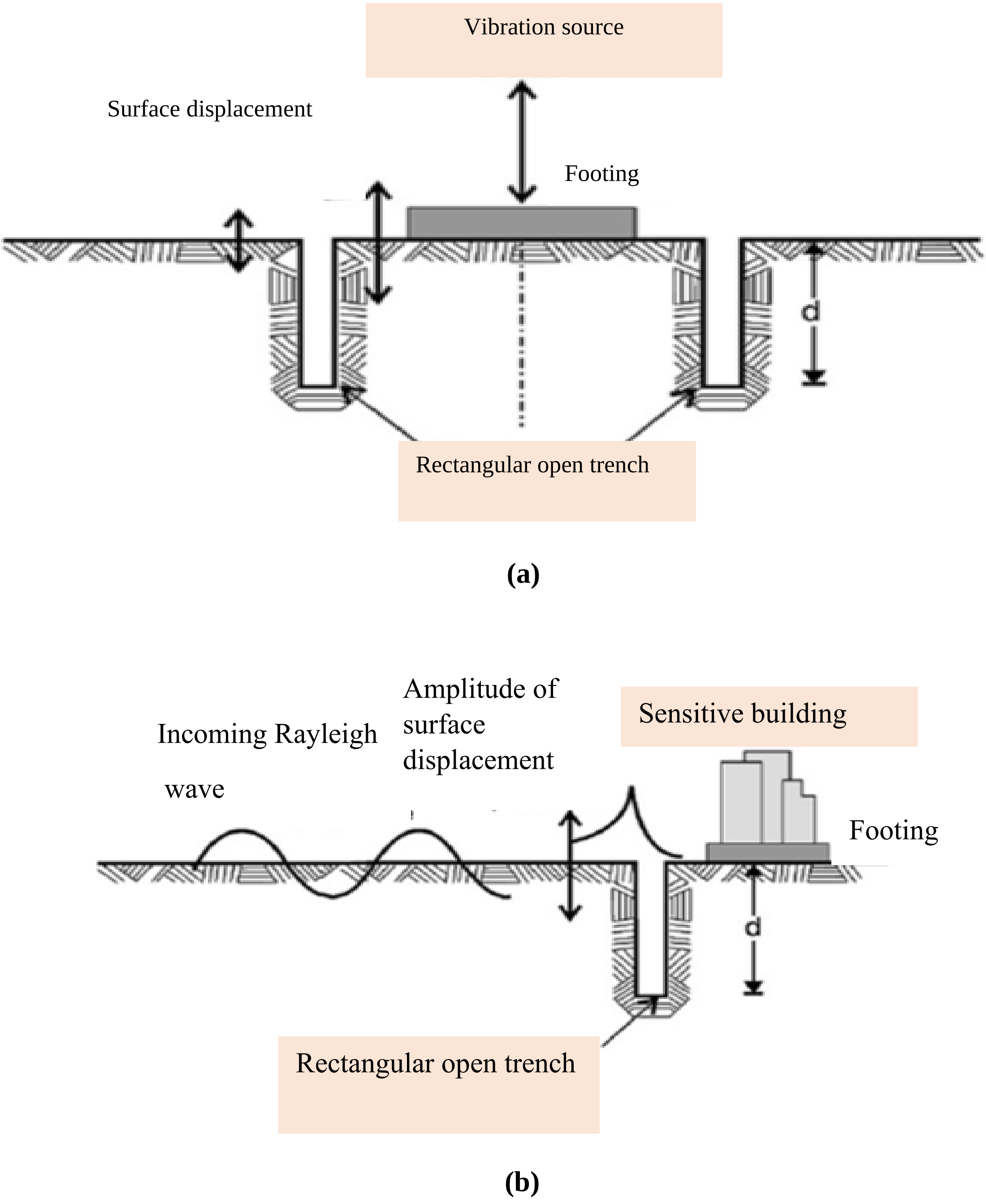


Figure 1.3: (a) Active and (b) Passive isolation system

1.2 Problem Statement

In the last few decades, a substantial amount of numerical, analytical, and experimental research has been conducted to investigate vibration isolation in filled trenches with EPS geofoam. It is observed that non-rectangular (trapezoidal, triangular) trenches appear to be well-isolating and financially feasible, but there is not much study on this topic, particularly because there aren't many field experiments to investigate these barriers. Therefore, it is revealed that an experimental test investigation to examine the trapezoidal infilled trench with EPS geofoam for various configurations is required.

1.3 Research Objectives

1. To study the characteristics of ground vibration for different frequencies and different distances from the vibration source.
2. To investigate the effectiveness of an open trapezoidal trench for different configurations of induced vibrations.
3. To investigate the effectiveness of a trapezoidal trench filled with EPS geofoam for different configurations of induced vibrations.
4. To compare the Amplitude Reduction Ratio (A_r) of the open and EPS-filled trapezoidal trench with previous studies.

1.4 Scope of the Research

This research aims to confirm earlier numerical studies on the topic and provide results that can be useful for validation and future improvements in numerical models.

1.5 Thesis Organization

The first chapter provides an introduction to ground born vibrations, vibration propagations, impacts of ground-born vibrations on surrounding environments and mitigation methods which are available in contemporary industries. The second chapter discusses the available literature on open and infilled trenches on mitigating induced ground vibration. In the third chapter, the research methodology, along with the materials and equipment used, is explained. The fourth chapter covers the study's outcome as results and discussions, while the fifth chapter presents conclusions and recommendations based on this research.

Chapter 2: Literature Review

2.1 Ground-Born Vibration Propagation

This chapter offers a broad overview of ground born vibration propagation and its isolation through wave barriers. It commences by explaining the process of wave propagation in an elastic semi-infinite soil medium, encompassing the various waves (body waves, surface waves) generated due to ground-borne vibrations. The source of vibrations can be categorized into two types: vibrations induced by natural causes such as earthquakes, or tsunamis and those generated by human activities such as construction activities.

In recent years, ground-borne vibrations have posed a significant challenge for large cities, impacting nearby buildings and structures. These effects span from disturbances to residents to observable structural damage[7]. Many things can cause vibrations in the ground, including vehicle traffic, pile driving, railroads, and blasting. Each of these is characterized by various mechanisms of excitations and effects.

When examining the challenge and impact of vibrations and vibration isolation through wave barriers, it is crucial to comprehend how elastic wave vibration propagates in a semi-infinite soil media. The wave propagation mechanism transfers the energy that causes ground motion from the source into the surrounding medium. These elastic waves might come from anywhere on the surface or somewhere inside the half-space.[8]. Since most building footings in metropolitan areas are located on or near the ground, seismic waves produced by surface sources are extremely important for vibration isolation investigations. Moreover, in the analysis of this type of wave propagation, it is assumed that the soil medium or vibration propagation medium can be considered as a homogeneous, isotropic, elastic half-space[5]. Body waves and surface waves are the two main types of elastic waves that are explained by the theory of elastic half-space.

During the propagation of vibrations, waves experience a damping mechanism inherent to the characteristics of the transfer medium[9]. Geometric damping diminishes vibration amplitudes as the distance from the source increases, as the same vibration or wave energy is dispersed over a progressively larger surface or volume[3]. The wave attenuation brought about by geometric damping is explained by several equations and phenomena found in the theory of energy conservation. The energy per unit area of a surface wave decreases inversely with distance from the source as the wave propagates as expanding rings. Surface waves provide less geometric dampening to seismic vibration propagation than body waves do. [10].

Conversely, material damping entails the dissipation of internal energy inside the material when soil particles react to the propagating seismic wave, resulting in the loss of wave energy. Seismic wave energy transforms into frictional heat, contributing to a decrease in wave amplitude as the energy is converted and attenuated. Unlike geometric damping, material damping involves the attenuation of elastic energy through viscous, hysteretic, or other mechanisms [11]. Damping mechanisms are the most impacting factor when the design of vibration isolation solutions.

2.2 Seismic Waves

Love waves and Rayleigh waves are two types of surface waves that propagate near the soil surface layer of solids and exhibit both longitudinal and transverse motions; the amplitude of Rayleigh waves decreases exponentially with distance from the surface, and particles move just beneath the surface of the earth. While surface waves go over the medium's surface, body waves move through the medium's interior.[12]

P-waves (Primary waves) are compressional waves that travel faster than other seismic waves and can propagate through any type of material[13]. As waves propagate, particles experience compression and dilation. Conversely, S-waves, also known as secondary waves, are one of the two main forms of elastic body waves. They move particles perpendicular to the direction of the wave as they propagate as shear or transverse waves.[14]. When a short-period impulse is delivered to the surface of an elastic half-space, Rayleigh waves radiate outward along a cylindrical waveform, whereas body waves propagate into the medium with a hemispherical wavefront. Figure 2.1 [5]shows the variation of Rayleigh wavelength with depth and impact of poison ratio

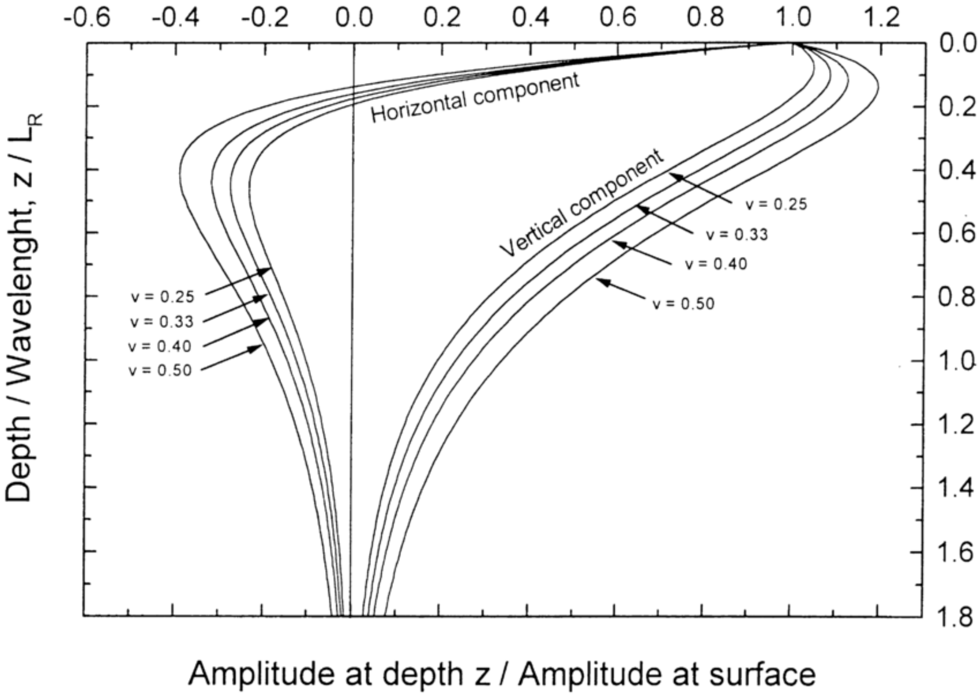


Figure 2.1: Variation of horizontal and vertical components of Rayleigh waves with depth [5]

The fastest seismic waves, or P-waves, usually come first and are followed by S-waves. The final waves to come are Rayleigh waves. When compared to P- and S-waves, Rayleigh waves produce a much greater ground displacement.[15].

2.3 Vibration Mitigation by Trenches

The isolation of structures from ground-borne vibrations has undergone extensive investigation and examinations and has yielded varying degrees of success in different kinds of aspects. Over the past few decades, numerous analytical, numerical[16]–[19], experimental studies[12],

[20]–[22] and numerical with experimental studies[8], [23], [24] have explored the use of wave barriers for vibration isolation, also referred to as vibration screening. These efforts have aimed to enhance our understanding of vibration scattering. The subsequent conclusions briefly outline the impact of filled trenches on screening vibrations, considering various perspectives.

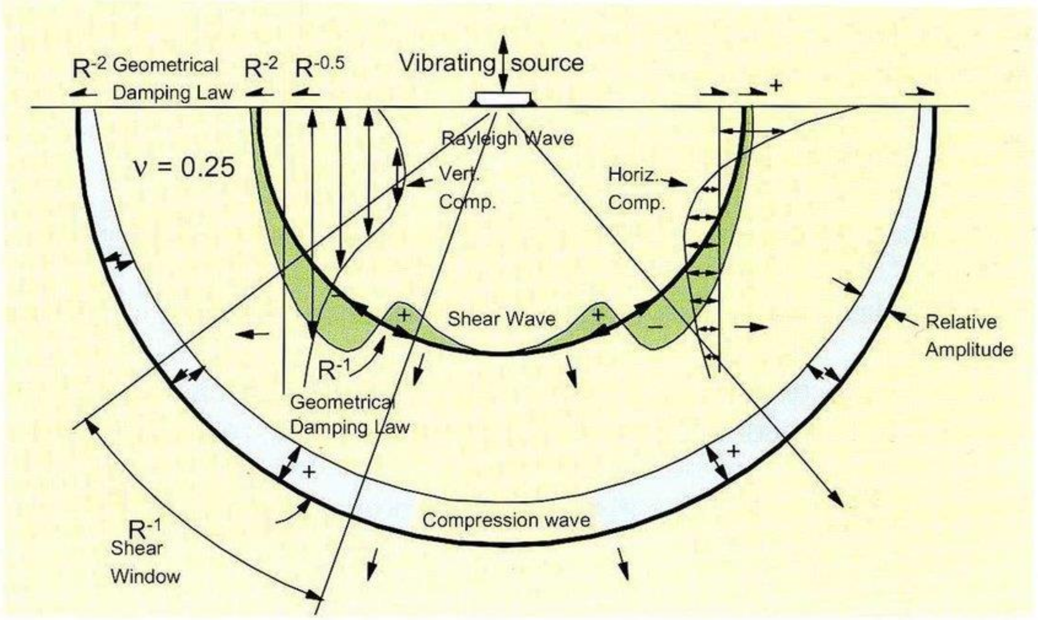


Figure 2.2: Distribution of displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space (after Woods, 1968 [25]**)**

Ahmed et al. found that an average amplitude reduction ratio value of 0.3 or less can be obtained from a concrete rectangular trench wall, whether it is used in active isolation or passive isolation, with dimensions like D as low as 1.2, W equal to 0.35 (and with variations in B from 0.5 to 1.0, and active lengths L ranging from 0.21 to 0.38 or passive lengths L from 2.7 to 6.3). This suggests that amplitude reductions of at least 70% on average can be accomplished. Significantly, the application of a soil-bentonite barrier for passive isolation is also covered by this finding.[26]

In vibration isolation research, Andersen, L. and Nielsen, S. R. used a model that integrated boundary elements with finite elements. According to their findings, ground wave propagation may be mitigated more effectively by soft barriers than by hard wave barriers. Their findings indicate that the wave intensity decreases by around 50% after passing the wave barrier.[27].

Infield studies were carried out by Celebi et al. to compare open and infilled trenches. Although open trenches are more successful than infilled trenches, their practical applicability is restricted to relatively modest depths, as their conclusion shows. On the other hand, using softer backfill material allows for deeper trench depths and improves the efficiency of infilled trenches without requiring support measures for the trench's vertical walls. Furthermore, at both measurement points, the study discovered that barriers work better in passive isolation than in active isolation.[28]

Finite-element studies in the three-dimensional time domain were carried out by Ju, S.H. and Li, H.C. et al. They came to the conclusion that open trenches attenuate ground vibrations more effectively than water-filled trenches when it comes to shear and Rayleigh waves. They clarified that there are distinct phases to the incident wave that travels through the water trench and the diffraction wave that emerges from the trench bottom. Water did not, however, appreciably lessen the wave's amplitude since the expansion wave was compressive as it passed through the water trench. As a result, the incident wave was significantly greater than the trench bottom diffraction wave, which decreased the wave barrier's effectiveness.[29].

Alzawi and El-Naggar evaluated the efficacy of infilled wave barriers with EPS geofoam and open wave barriers using a full-scale field experiment. To create ground vibrations, a mechanical oscillator was operated in the experiment. The decrease in soil particle velocities and the wave barriers' placement were used to gauge how effective the barriers were. The study discovered that the relationship between the depth and the distance to the source determines how effective the open trench barrier is. The wave barrier's efficacy falls as this ratio rises.

However, under comparable circumstances, no appreciable alterations were found for the geofoam barrier[30].

In a review paper, Ehsan Mahdavi's fat et al proposed that non-rectangular trenches appear to be economically viable and effective for vibration isolation[9]. However, research in this area is limited, especially considering the scarcity of field tests for such barriers. Herbut, A., et al. discovered that the efficiency of an inclined, curved, open trench is over 5 times better than that of a classic rectangular open trench[19]. Numerical results from Chen, Q et al. indicate that open trenches with sidewall inclination are the most efficient sections, improving isolation efficiency by nearly 10.2% compared to rectangular open trenches[18].

While open trenches are reported to better control induced vibrations compared to filled trenches, they are associated with disadvantages:

- Instability of Trench Walls: Deep trenches may face instability issues with open trench walls.
- Groundwater Level Fluctuations: Open trenches may convert to water-filled trenches due to fluctuating groundwater levels, reducing vibration isolation efficiency and potentially causing environmental issues.
- Construction Risks: Constructing open trenches in public places poses risks and may lead to potential life loss.

To address these limitations, it is suggested to fill trenches without compromising vibration isolation efficiency. The chosen filling materials should be economical, durable, environmentally friendly, and readily available[17].

Various filling materials have been investigated, including water, bentonite, soil-bentonite mixture, concrete, rice husk ash, tire-derived aggregates (TDA), rubber-sand mixtures (RSM), and EPS geofoam. Among these, EPS geofoam has shown considerable performance in mitigating ground vibrations. Alzawi et al. observed from field tests that a geofoam barrier can be a practical alternative for wave scattering, with a protective effectiveness of up to 68% or higher[8]. However, Mahdavisefat et al noted that geofoam, while effective, has low shear strength parameters[31].

2.4 EPS Geofoam as Vibration Mitigation Material

Since its invention in the USA in 1960, when EPS geofoam was awarded a patent for use as a pavement insulating material, the material has been used in geotechnical engineering applications for many years such as embarkment construction and slope stability [30]. The EPS geofoam cell walls yield and collapse under compression, releasing trapped air, and they may even shatter under excessive loads. Using unpublished data for short-term strain-controlled unconfined compression experiments from BASF (BASF SE, Germany), Horvath examined the material behaviours of EPS geofoam with a density of 21 kg/m3[31]. Between 1 and 2% strain, the material displays linear-elastic behaviours, with an increasing elastic limit with density [32]. Instead of happening all at once, yielding happens over a range, and strain-hardening is shown in the post-yield behaviours. The behaviour of the material becomes non-linear with higher stresses.

Itoh et al. looked at how EPS geofoam barriers affected the ground vibrations caused by trains spreading less widely. They observed a strong correlation between the frequency of the dynamic loading and vibration surrounding the EPS geofoam barrier. The use of geofoam barriers for vibration isolation was covered in research by Murillo et al. To assess the impact of geofoam wave barriers, they carried out a centrifuge parametric analysis, calculating efficiency using the initial amplitude reduction ratio[32].

Chapter 3: Methodology

This chapter provides a comprehensive overview of the field experimental work conducted to examine the protective performance of both open trapezoidal trenches and in-filled trapezoidal trenches employing geofoam material. The investigation also delves into the effects of excitation frequency and the proximity of the trench to the vibratory source on the isolation efficiency.

3.1 Selection of Experiment Site

As a part of my study, it is required to select suitable locations within the National University of Sciences and Technology (NUST) for conducting field experiments. To achieve this, geotechnical investigation reports of three already investigated locations were collected from the geotechnical departments of NICE. Below are the specific details for each of these locations.

Table 3.1: Description of the investigated sites

Site No.	Description	Location
01	Centre for international peace and stability – II (CIPS – II)	Next to IGIS and the Cafeteria building Adjacent to Sholars Avenue
02	Male BOQ Building	Adjacent to under construction of BOQ Male
03	Interdisciplinary cluster for higher education (NICHE)	Behind the already constructed NSTP

3.2 Soil Properties

Initially, the most important parameters suggested for consideration are derived from the geotechnical investigation reports in the literature. The soil properties and ground conditions extracted for all three sites up to a depth of 4 meters are provided below.

Table 3.2: Parameters of investigated sites

Site No	**Water table**	**Density(kg/m^3)**	**Soil description**	**Soil class (USCS)**
01	Not encountered	1910	Light brown silty clay	CL (Low plasticity soil)
02	Not encountered	2590	Dark brown / Greyish brown moderately weathered large boulders of sandstone/siltstone and shale	CL (Lean clay)
03	Not encountered	2670	Dark brown Hard silty Clay	CL-ML (Silty clay with sand)

Based on the data extracted and the literature review of these experimental works, Site No. 01 fulfilled the following requirements.

- In the context of wave propagation from a seismic source, it is essential to minimize energy dissipation and damping in the wave transmission medium to achieve the most effective results in the experiment. According to the literature, lower-density soil is known to exhibit lower energy dissipation compared to higher-density soil. Hence, using lower-density soil is recommended to optimize the experiment's outcomes.
- CL (Low plasticity soil) is less susceptible to significant volume changes. It is crucial to avoid plastic deformation throughout the experiment.
- Homogeneous soil ensures that the material properties, such as density, stiffness, and damping, remain uniform throughout the test area. This consistency leads to more

reliable results, allowing researchers to draw accurate conclusions and make meaningful comparisons between different tests or sites.

- To carry out the two planned experimental setups at the site, two different tests are scheduled: Multichannel Surface Analysis followed by Infilled trench with wave propagation. These experiments required a minimum open space of 25 meters in length and 10 meters in width. This area is required to accommodate the equipment, and setup, and ensure sufficient space for the wave propagation tests and data collection during the experiments.
- In this experimental work, the setup involves creating a single trapezoidal trench, 1.65 meters in width and 1.22 meters in depth, with a length of 2.45 meters. One important observation is that when the soil density is lower, the process of implementing the trenches becomes easier compared to other sites. This is likely because lower-density soil is generally less compacted and easier to excavate, making the trenching process more manageable and requiring less effort and equipment.
- Employing machinery for trenching will result in higher costs compared to manual trenching. However, for smaller-scale projects or situations where the soil is easily workable, manual trenching can be a more budget-friendly alternative.
- In vibration propagation tests, it is important to have relatively less interruption from other vibration sources. This ensures that the test results are not influenced by external vibrations, and the measurements accurately represent the behavior of the waves being studied. Minimizing interference from other sources allows for a more controlled and reliable experiment, leading to meaningful and accurate conclusions about the wave propagation characteristics of the tested material or structure.

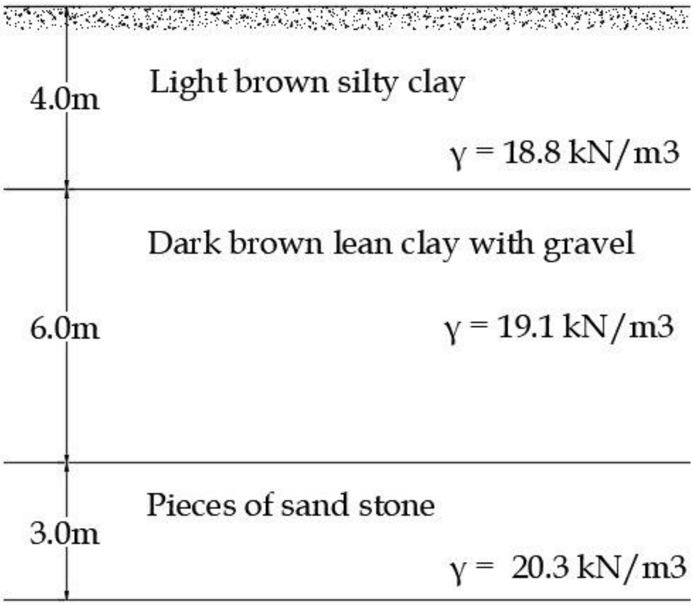


Figure 3.1: Soil profile of Site No. 01

3.3 Fill Material Properties

Expanded polystyrene (EPS) was selected as the fill material due to its remarkable ability to minimize induced vibrations. The geofoam group includes EPS foam, which is widely used in a variety of structural and geotechnical applications. Among the essential characteristics of EPS are:

- High absorption or dissipation of Energy: Because of its well-known ability to efficiently absorb or dissipate energy, EPS is a good fit for situations where reducing vibration is a major concern.
- Elevated compressive strength: Because of its high compressive strength, EPS can be used in situations where load-bearing capability is crucial. It also offers stability and support.
- Minimal density: The low density of EPS is one of its distinguishing qualities. This feature adds to its lightweight design, which facilitates handling and transportation.

- Low permeability: EPS indicates that it is not easily permeable by water or other substances. This attribute has potential benefits in a range of geotechnical and construction settings.
- Simpleness of Use: The user-friendliness of EPS in geotechnical and construction applications is well established. Because of its adaptability and versatility, it is a recommended option for a variety of applications.
- The density is 18.4 kg/m ^{3}: Because of its lightweight nature and stated density of 18.4 kg/m ^{3}, EPS is a good fit for situations where minimizing total weight is a priority.

All things considered, EPS is an excellent material for reducing induced vibrations and a flexible choice in a variety of engineering applications due to its high energy absorption, compressive strength, low density, low permeability, and ease of use.

Figure 3.2: EPS Geofoam blocks

3.4 Multi-Channel Surface Wave Analysis (MASW)

Dynamic properties of soil are important for this research study because of particle displacements ground ground-born vibration energy. Rayleigh wave velocity is one of the key parameters to identify the impact of the vibration source, barrier distance from the source and depth of the different types of trenches. To identify the Rayleigh wavelength shear wave velocity profile is required. Therefore, to provide a soil profile of shear wave velocities and investigate layer stratification, the Multichannel Analysis of Surface Waves (MASW) approach is utilized. Seismic surface waves produced by a seismic source (Sledgehammer) are identified during the MASW process using geophones.

(a) **(b)**

Figure 3.3: (a) Seismograph (b) Employed geophones

Shear wave velocity can be inferred from these readings by analyzing the surface wave propagation velocities. Dispersion curves are made by plotting the frequency of the generated surface waves against their phase velocity as part of the data processing. The variations in shear wave velocity with depth are obtained by inverting these dispersion curves. To analyze the recorded data Seis Imager ID geophysical software was used. Field test parameters are given as follows,

Table 3.3: MASW test parameters

Parameters	**Value**
Channel	12
Maximum depth to investigated	10 m
Source (Sledgehammer) weight	10 kg
Receiver Frequency	4 Hz
Receiver spacing	1.5 m
Array length	16.5 m
Source offset	2 m and 6 m on both ends
Sampling time	0.5 milliseconds
Sample rate	2000/s
Record length	0.5 seconds
Vertical stacking	5 shots

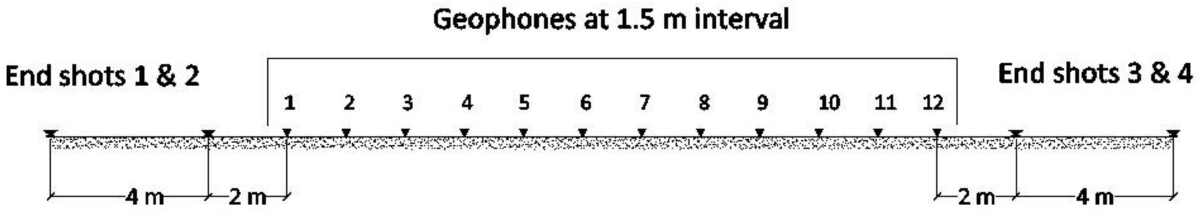


Figure 3.4: Experimental layout (Sideview)

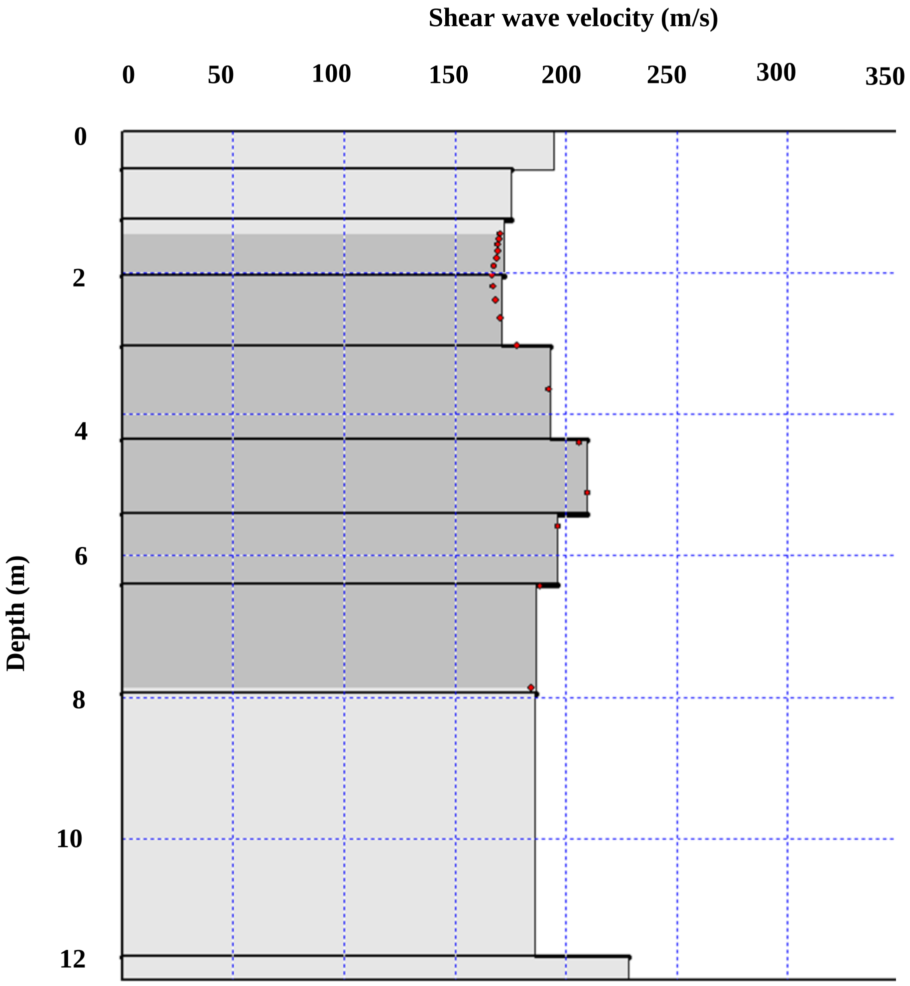


Figure 3.5: Shear wave velocity profile with the depth

3.5 Field Experiments

Different types of designed extensive, large-scale field tests were conducted to evaluate how the system's effectiveness was influenced by frequency and distance from the vibration source. Using a range of test configurations, highly sensitive accelerometers were used to measure the acceleration amplitudes of ground vibrations.

3.5.1 Vibration Source

Sources of vibration can cause either transient motion, like those produced during blasting operations, or continuous motions, like those produced during the operation of vibratory pile drivers or compactors. An oscillatory vibrator was used in earlier research by Woods[25], Çelebi et al.[22], and Alzawi and El Naggar[30] to produce continuous motions. In this present field experiment, a test plate vibratory compactor was chosen due to its economic feasibility and easy availability. It was used as the excitation frequency source to create ground-born vibrations caused by real-case scenarios such as construction and traffic, where the typical ranges of frequencies and centrifugal forces are 12–210 k N and 15–105 Hz, respectively.

The aim is to use a plate vibratory compactor to generate harmonic loading. However, obtaining undisturbed harmonic motion is challenging due to the nature of the operation and contact material. According to previous studies, the main objectives of this research do not impact the type of vibration source, as the acceleration amplitude at each location is measured.

Figure 3.6: Plate vibratory compactor

Table 3.4: Plate vibratory compactor specifications

Parameter	**Details**
Frequency	5800 VPM (Vibrations per Minute)
Engine Type	Air-cooled, 4-stroke, single cylinder
Centrifugal Force	13 k N
Power of Engine	4 kW
Plate Size	560 x 430 mm
Travel Speed	20 m/min
Net Weight / Gross Weight	77 / 85 kg

3.5.2 Rayleigh Wavelength

The Rayleigh wavelength is calculated using the output of the Multichannel Analysis of Surface Waves (MASW) technique in conjunction with empirical formulas from pertinent literature with the assumptions of homogeneous, isotropic, and elastic half-space. This is a key parameter to define the active and passive isolation for the test configuration. Active isolation occurs when the barrier is placed near the disturbance source, approximately between 1.0 and 1.5 Rayleigh wavelengths away. On the other hand, passive isolation is used when the barrier is located further away, as Nitish Jauhari et al.[4] pointed out.Average har wave vlocit($\boldsymbol{V_S}$) extracted from the Multi-Channel Shear Wave Velocity (MASW) test. Then by following the equation[5].

$$\boldsymbol{V_R = \frac{0.862+1.14\,v}{1+v}\,V_s} \qquad \textbf{(1)}$$

Where Rayleigh wave velocity and $\boldsymbol{v}$ **is** Poisson’s ratio. The Rayleigh wavelength is calculated by the following equation.

$$\boldsymbol{\lambda_R = \frac{V_R}{f}} \qquad \textbf{(2)}$$

Where $\boldsymbol{f}$ is excitation frequency.

3.5.3 Schematic Diagram

To establish the field setup, the previous study's findings were concerned. When the distance between the vibration source and the in-filled EPS trench barrier was less than 0.5 times the Rayleigh wavelength, the barrier's inefficiency was visible[33]. Active isolation is defined as the isolation that occurs when the barrier is placed near the source of disturbance, roughly between 1.0 and 1.5 wavelengths; passive isolation is the absence of this[4]. As per Ehsan Mahdavisefat's [9] findings, most researchers have consistently reported that this parameter does not affect trench performance.

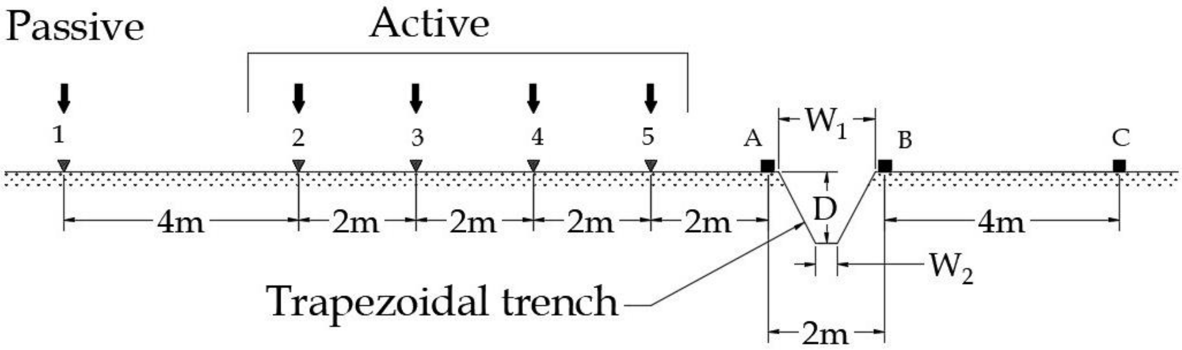


Figure 3.7: Schematic diagram of the field test (Side view)

To make configurations easier, the source-barrier distance for the passive isolation system was maintained at 12 m for all excitation frequencies. Since this distance satisfies the lower excitation frequencies, it will likewise satisfy the higher excitation frequencies. To achieve precise outcomes and monitor the trench's maximum efficiency, source-barrier distances were adjusted for every excitation frequency in the active isolation system.

In Figure 3.7, Point 1 indicates the vibration source placed for passive isolation, while Points 2, 3, 4, and 5 indicate the vibration sources placed for active isolation. Details regarding the excitation frequency and their distances are discussed in the latter section. D, W_1, W_2 indicate the depth of the trench, top width of the trench, and bottom width of the trench, respectively, in Figure 3.7.

3.5.4 Trench Dimensions

To define the trench dimensions initially thorough literature has been done. For the normalized trench width, most studies indicate a small amplitude reduction effect. It has been noted that wider trenches typically perform worse when it comes to shallow trenches (normalized depth of 0.5 and below). However, variations in the trench width have less of an effect as the depth of the trench rises. Most studies show that the depth of the trench is the key factor affecting trench performance. Ehsan Mahdavisefat[9] offers important guidelines for trench dimension optimization when designing trenches, suggesting that the upper limit be taken into consideration when designing the trenches, which is 1.5 λ_R. Finally, by market availability and the suggestions from the literature, the following dimensions were selected.

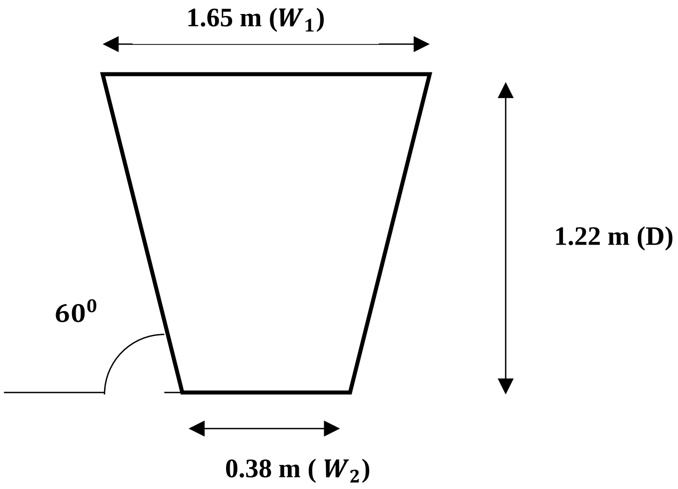


Figure 3.8: Cross-sectional view of the trapezoidal trench

3.5.5 Data Acquisition

An onboard triaxial accelerometer on the G-Link-200 was used to measure and identify the acceleration amplitude of the vibrations that were induced. This apparatus facilitates the acquisition of high-resolution data with remarkably low noise and drift. The G-Link-200 offers superior performance detection capabilities with its onboard triaxial accelerometer, featuring a measurement range of ±2 to ±40 g, adjustable low- and high-pass filters, and an integrated temperature sensor.

Figure 3.9: G Link 200 accelerometer with probe

To mount the accelerometer on the surface of the soil, 8 cm probe tips were attached to the base of the accelerometer as shown in Figure 3.9. This method is widely used to measure ground-borne vibration in studies. Probe tips can accurately and precisely measure soil displacement, thereby increasing the accuracy of the results in this work.

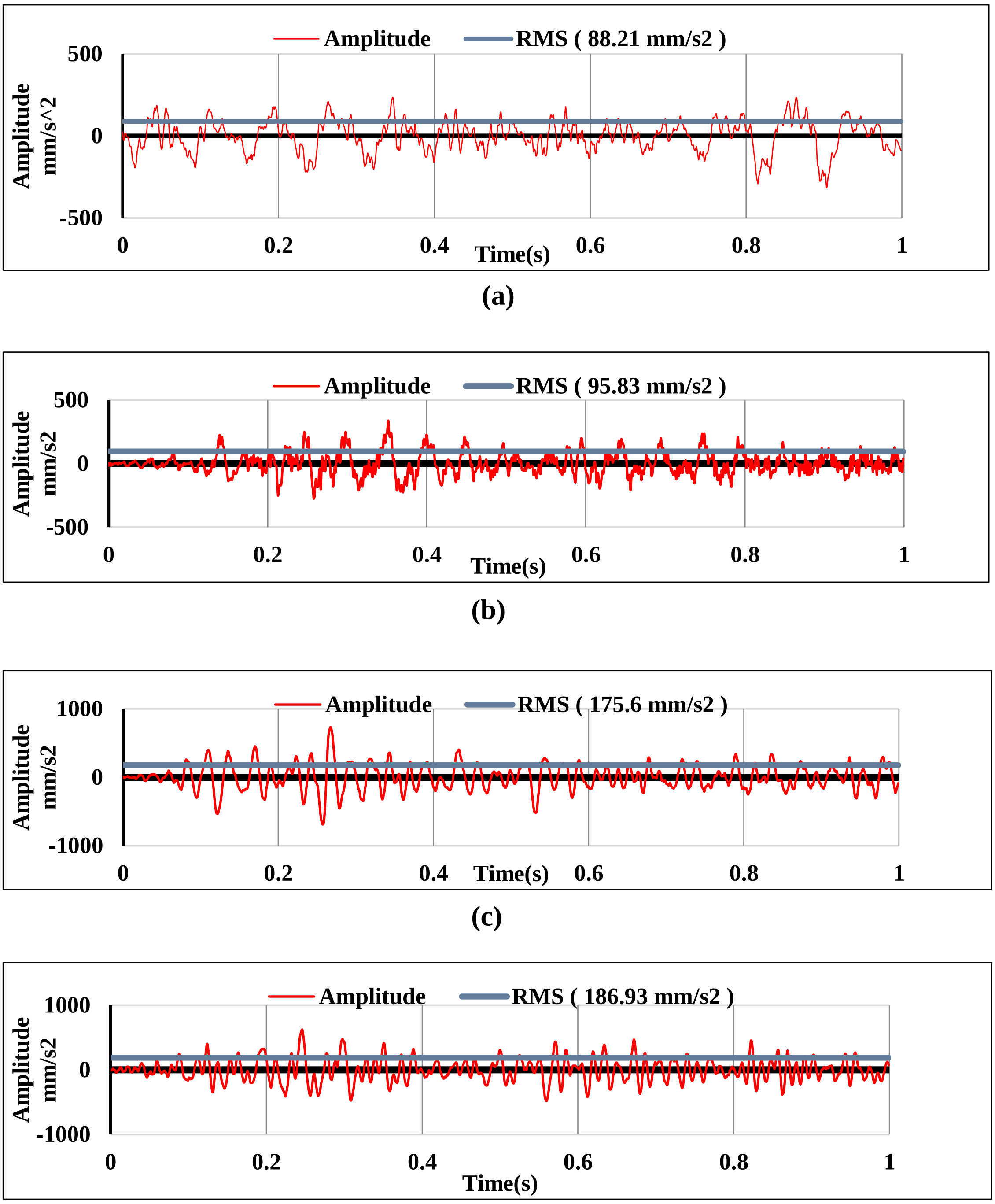
The wireless sensor base station acts as the data acquisition gateway and receives the measured data. Via a wireless sensor, the base station gathers data from the accelerometer. After that, a laptop or host computer is connected to it. The data is optimized by the web-based sensor cloud interface. This software application was used to gather data and analyze it for the intended results of this work.

3.5.6 Excitation Frequencies

To define the active isolation system and passive isolation system excitation frequencies were measured. The measurement was conducted by positioning the accelerometer at 0.4 m from the centre of the vibration source. The plate vibratory compactor operated at four different speeds, each corresponding to different frequencies. The frequencies at each speed were determined using both time domain analysis and frequency domain analysis. Time domain analysis was employed to calculate the Root Mean Square (RMS) amplitudes, providing a representation of the overall vibration amplitude. Fast Fourier analysis (FFT) was then utilized to convert the measured acceleration data from the time domain to the frequency domain, revealing the dominant frequencies. This analysis identified four types (Table 3.5) of excitation frequencies.

Table 3.5: RMS Amplitude and Predominant Frequencies

Frequencies	RMS Amplitude (mm/s^2)	Predominant frequencies (Hz)
F 1	88.21	12
F 2	95.83	20
F 3	175.66	37
F 4	186.93	59



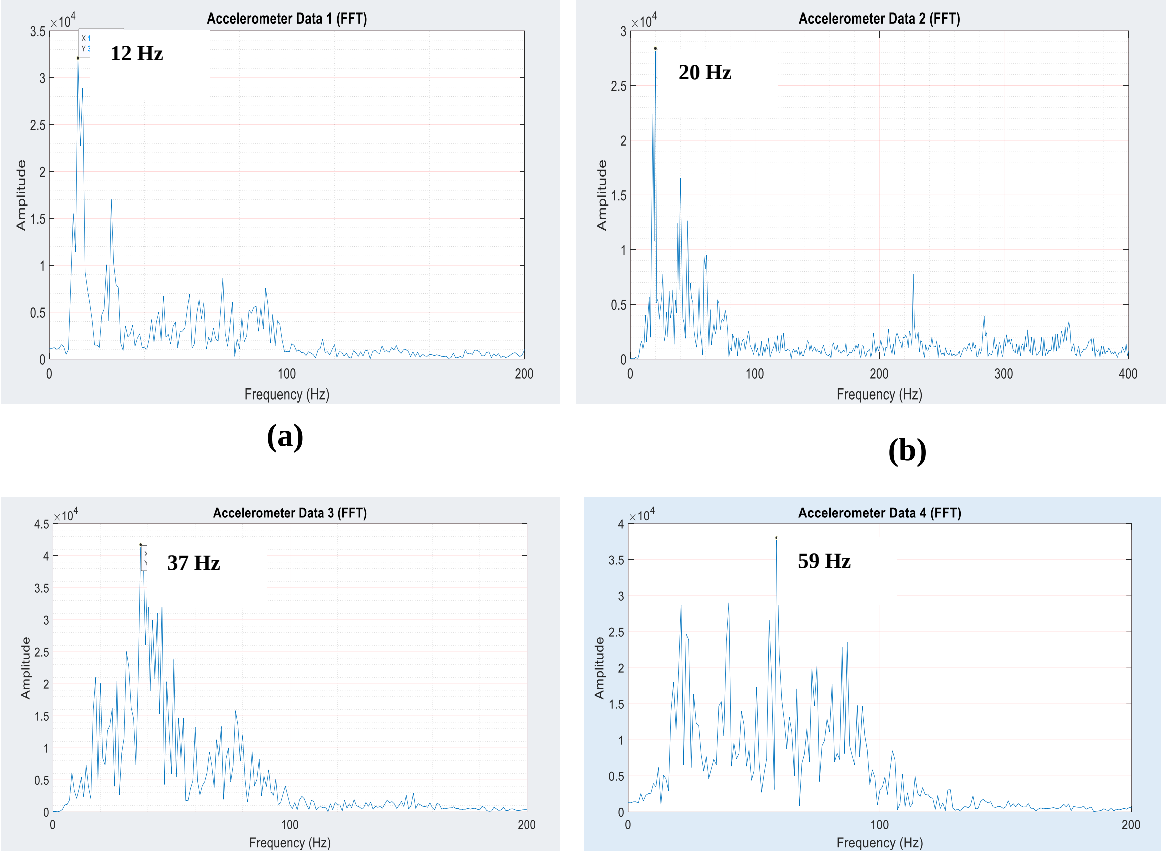
(a)

(b)

(c)

(d)

Figure 3.10: Time domain of excitation frequencies (a) 12 Hz (b) 20 Hz (c) 37 Hz (d) 59 Hz



(a)

(b)

(c)

(d)

Figure 3.11: Frequency domain of excitation frequencies (a) 12 Hz (b) 20 Hz (c) 37 Hz (d) 59 Hz

Chapter 4: Results and Discussions

4.1 Test Description

The field practical and experimental test series is aimed to investigate the effects of parameters on screening effectiveness notably operating or exciting frequency and source-barrier distance (Active isolation and Passive isolation) of the open trapezoidal trench and the trapezoidal trench filled with EPS geofoam per the test schematic diagram (Figure 3.7). To achieve this goal, three distinct test configurations were conducted such as control measurements or free field measurements (CT), measurements with an open trapezoidal trench (OT) and measurements with EPS-filled trapezoidal trench (ET). To avoid digging numerous trenches for active and passive isolation systems, the vibration source's location was changed rather than the barrier's location to examine the impact of the distance between the vibration source and the trench barrier. Three accelerometers were placed at specific locations A, B, and C (Figure 4.1).

For the control measurements initially, the plate vibratory compactor was positioned 12 meters from the trench at a passive point (Figure 4.1 (a)). The vibratory compactor created vibrations with excitation frequencies of 12 Hz, 20 Hz, 37 Hz, and 59 Hz. The accelerometers measured the vibration amplitudes vertically under free field conditions (without trench). Secondly, the vibration source was positioned at the frequencies of each excitation's active points (Figure 4.1 (b)) and created the same excitation frequency as the previous. Here, without any wave barriers, in the field, the attenuation or dissipation trend of the created vibrations at the given frequencies was found for both active and passive isolation systems.

Following that, for the measurements with an open trapezoidal trench, an open trapezoidal trench of 2.45 m length, 1.65 m top width, 0.38 m bottom width, and 1.22 m depth was excavated as mentioned earlier. The length and width of the open trench did not affect vibration isolation effectiveness[9], so they were not changed during the tests. The vibrations were generated again at the same excitation frequencies, and their amplitudes were measured at the same locations as in the control measurements for both active and passive isolation systems. Finally, for the measurements of an EPS-filled trapezoidal trench, the open trapezoidal trench was then filled with EPS geofoam blocks. The same procedure was then followed for both active and passive isolation systems.

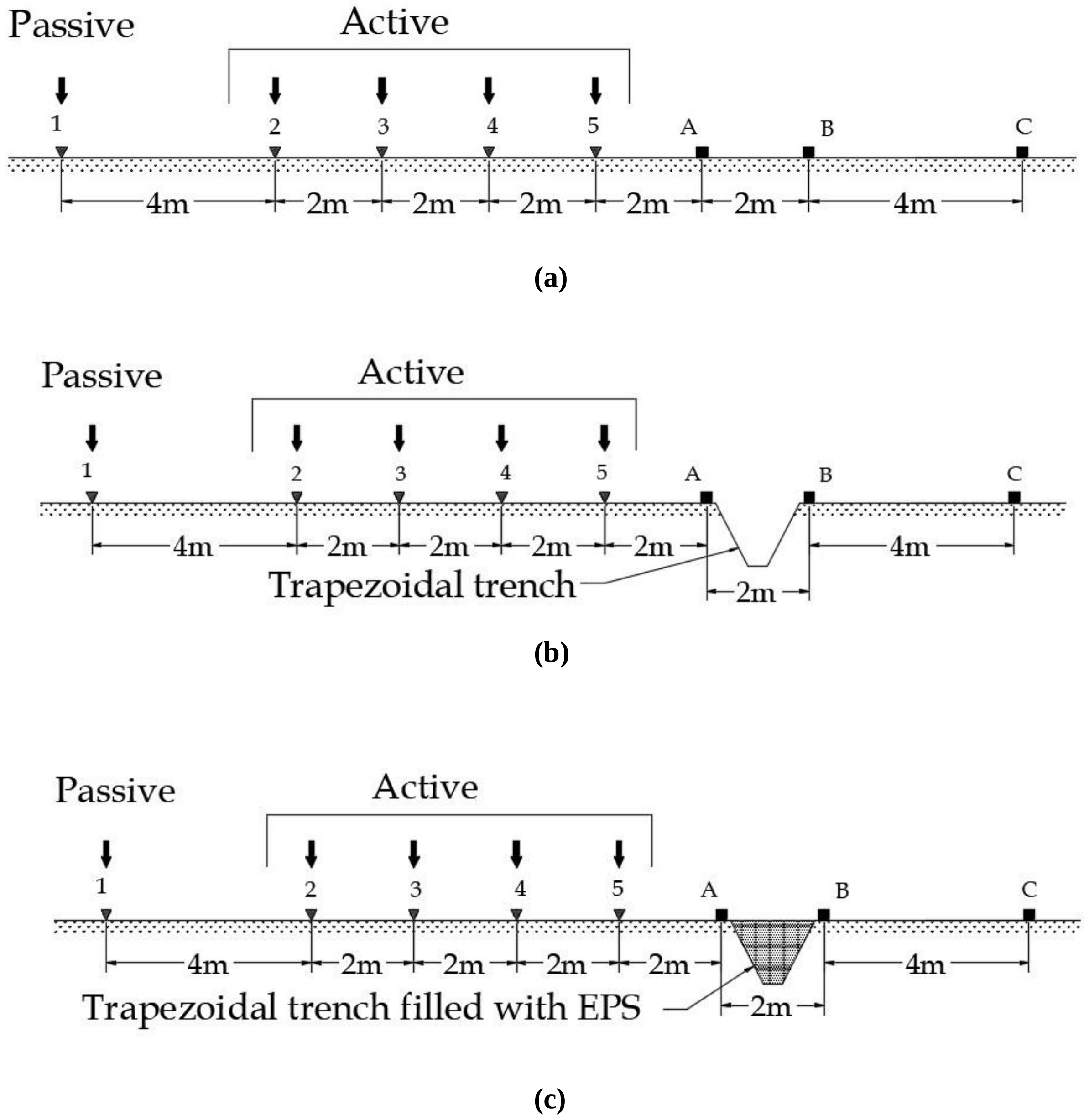


Figure 4.1: Schematic diagrams of test configurations (a) Without trench (b) Open trench (c) EPS-filled trench

Table 4.1: Field test configurations

Test No.			Points	Frequencies (Hz)	Type	Distance - D (m)
Control measurements	Open trench	EPS filled trench				
1 CT	1 OT	1 ET	1	12, 20, 37, 59	Passive	12.175
2 CT	2 OT	2 ET	2	12	Active	8.175
3 CT	3 OT	3 ET	3	20	Active	6.175
4 CT	4 OT	4 ET	4	37	Active	4.175
5 CT	5 OT	5 ET	5	59	Active	2.175


(a)
(b)

Figure 4.2: (a) Control measurements (b) Open trench measurements

Due to the highly difference variables involved in the study, to compare these results with previous results normalizing the key parameters with Rayleigh wavelength common practice. This allowed for the examination of the depth of the barrier as well as the impacts of the exciting frequency and field conditions (by using the soil's Rayleigh wave velocity). For every test, the geometric characteristics of the trapezoidal trench were standardized using the Rayleigh wavelength.

(a) **(b)**

Figure 4.3: (a) EPS block placement (b) Eps filled trench measurements

Table 4.2: Excitation frequencies and normalized parameters

Frequency (Hz)	λ_R**(m)**	**d = D/**λ_R	$w_1 = W_1/\lambda_R$	$w_2 = W_2/\lambda_R$
12	16.66	0.073	0.099	0.023
20	10.00	0.122	0.165	0.038
37	5.40	0.226	0.305	0.071
59	3.89	0.313	0.424	0.098

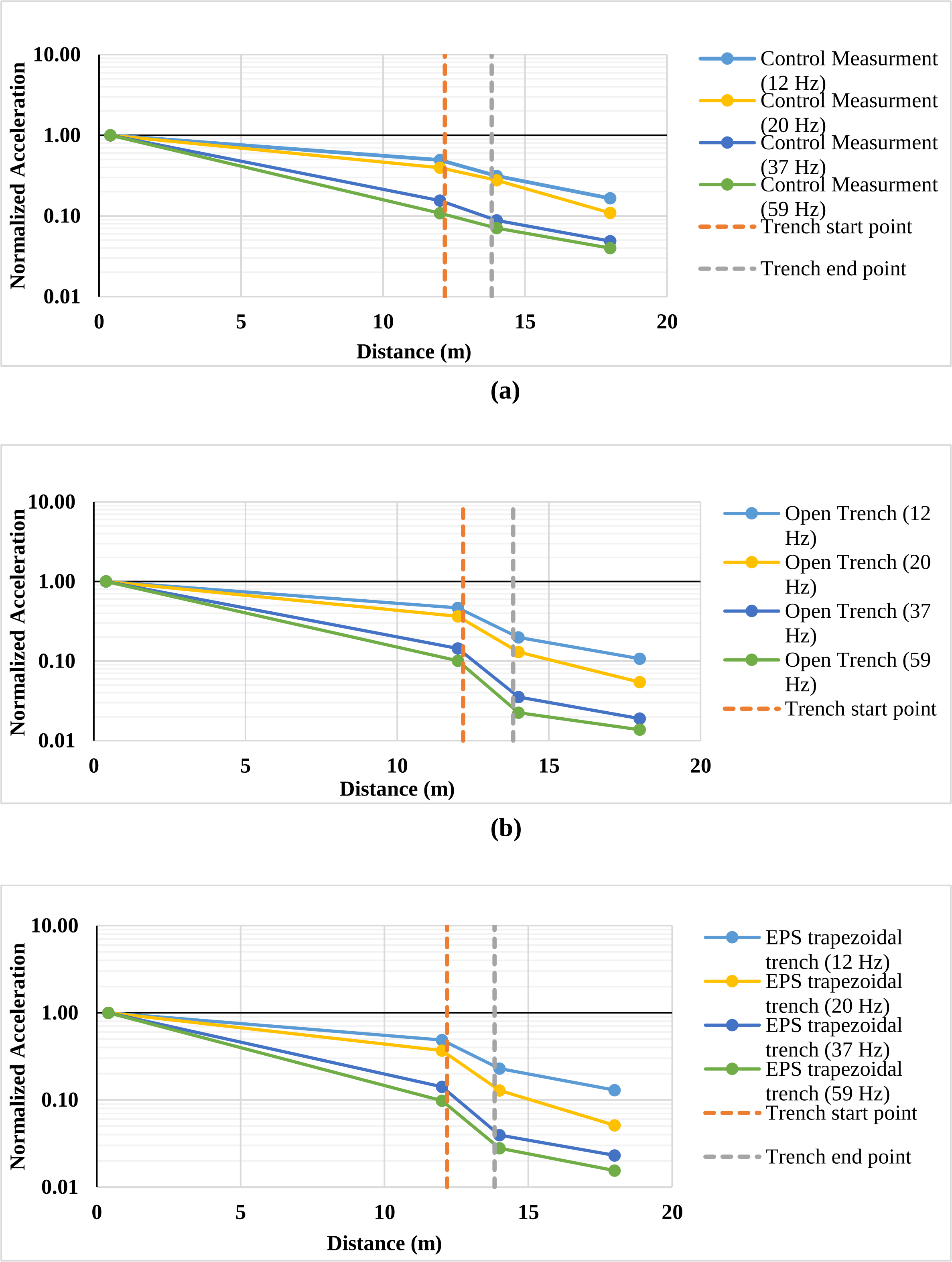
4.2 Attenuation of Ground-borne Vibrations

Highly sensitive accelerometers recorded the ground-borne vibrations with a sampling rate of 128 Hz. The peak particle acceleration recorded in all three measurement points (A, B, C) was normalized by the peak particle acceleration measured at the point of excitation frequency. Figure 4.4 shows the variation of the normalized accelerations concerning distance from the source of vibration for all three cases (Control measurements, open trapezoidal trench, and infilled trapezoidal trench) and all excitation frequencies. Figure 4.5 was constructed to examine the attenuation of ground-borne vibrations both in the absence (for control measurements) and the presence of wave barriers (open trapezoidal and EPS geofoam blocks filled).

$$\textbf{Normalized Acceleration} = \frac{RMS\ of\ Acceleleration\ amplitude\ at\ the\ recorded\ points}{RMS\ of\ Acceleleration\ amplitude\ at\ the\ vibration\ source} \quad \textbf{(3)}$$

The primary factors influencing the attenuation of vibrations are the geometric spreading of the wavefront and material damping (radiation damping). The normalized accelerations exhibit fast attenuation with increasing distance, as seen in Fig. 4.4. More than 90% of acceleration amplitude decreased at 12 m from the source of vibration compared to acceleration amplitude measured at the point at excitation frequencies. The influence of the Rayleigh wavelength on the vibration frequency can be observed in both Figures 4.4 and 4.5. When the Rayleigh wavelength decreases, or the vibration frequency increases, the attenuation increases. This observation can be explained by increased damping of the soil with increasing vibration frequency.

Sudden drops or reductions occur from the beginning to the end of the trench as shown in Figure 1.4 (b) and (c). It shows the presence of wave barriers as a trapezoidal trench makes a significant impact on vibration attenuation. The rate of these reductions also escalates with an increase in the excitation frequency for all cases. Geometrical irregularities of heterogeneous half-space soil medium, the special phenomenon may have occurred. Due to the reflection of waves at the layer interface in a layered soil medium, Al-Hussaini[26] emphasized that distinct peaks could be observed.



(a)

(b)

(c)

Figure 4.4: Vibration attenuation with distance (a) Control measurements (b) Open trench (c) EPS-filled trench

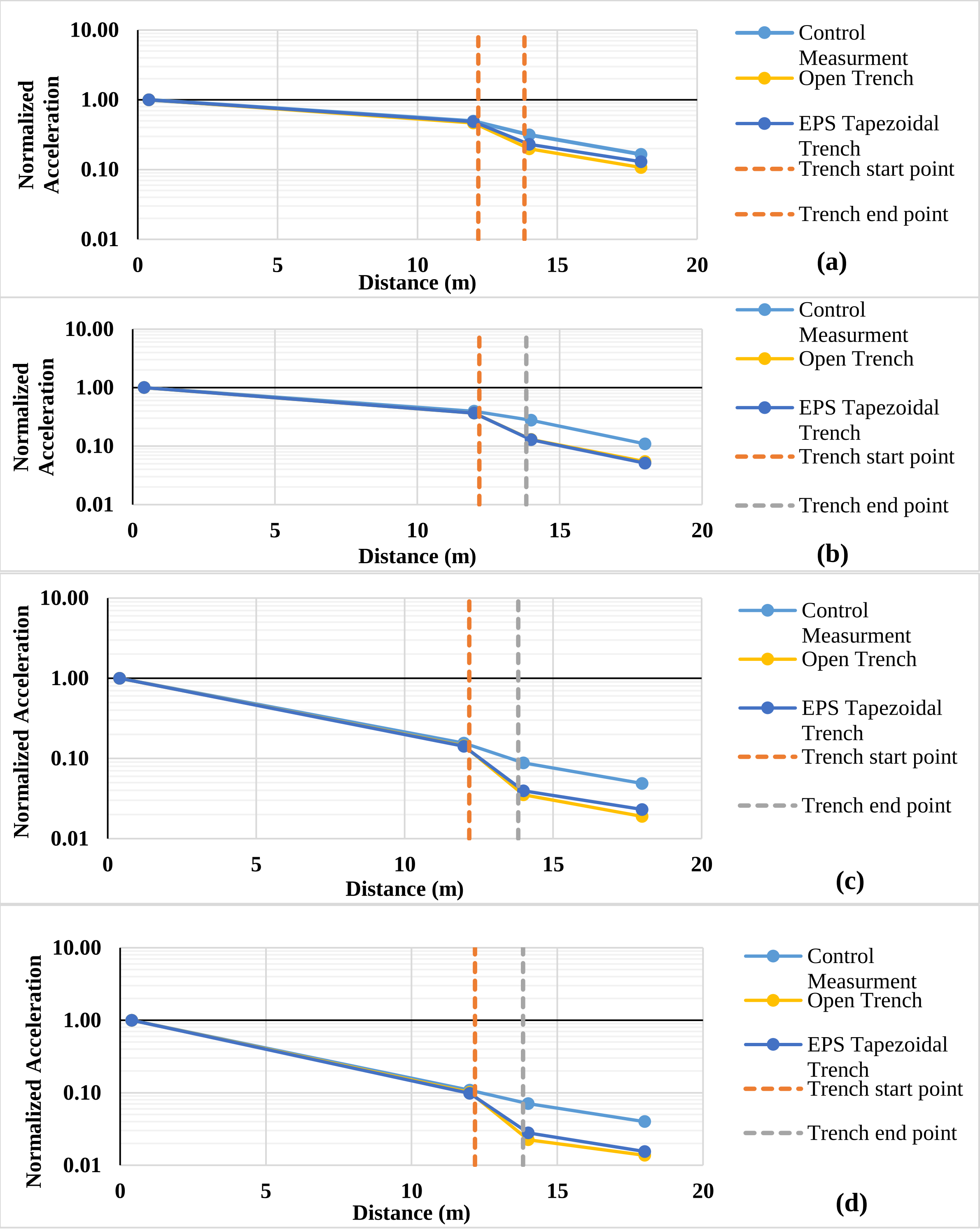


Figure 4.5: Vibration attenuation with distance for the passive isolation systems (a) 12 Hz (b) 20 Hz (c) 37 Hz (d) 59 Hz

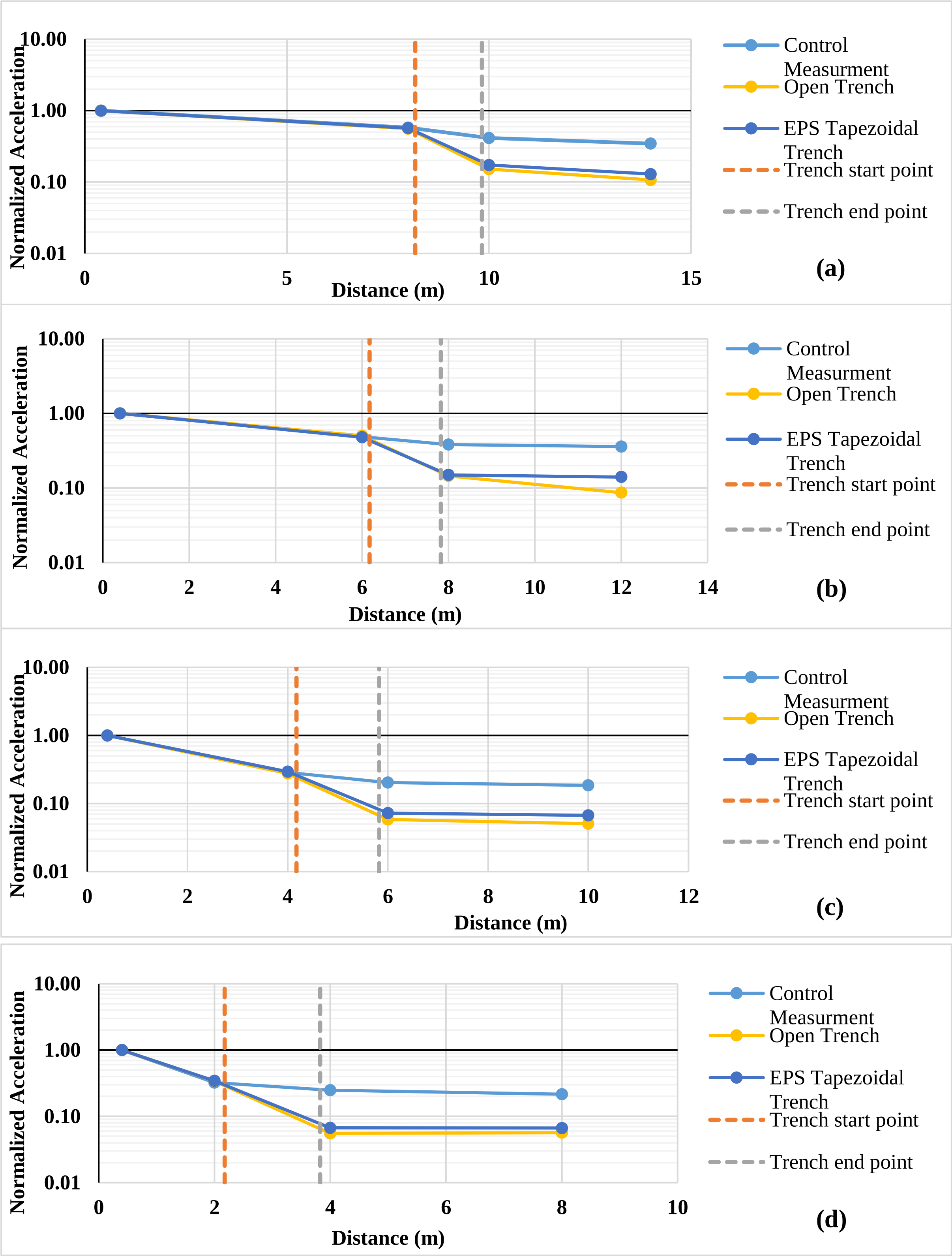


Figure 4.6: Vibration attenuation with distance for the active isolation systems (a) 12 Hz (b) 20 Hz (c) 37 Hz (d) 59 Hz

4.3 Isolation Efficiency of the Trenches

An amplitude reduction ratio, or AR, is the ratio between the root mean square of the acceleration amplitudes of vibrations measured before and after wave barrier installation. It is used to assess the isolation efficacy of wave barriers. Figure 4.7 shows the variation of calculated A_R values at points B, and C for the cases of the open trapezoidal trench and EPS geofoam-filled trapezoidal trench with an excitation frequency of 59 Hz. The variation of the values is given concerning the distance from the source of vibration. It is anticipated that the open trenches would outperform the wave barrier filled with geofoam to some extent. This might be because of an uneven and non-uniform soil media that results in the phenomenon.

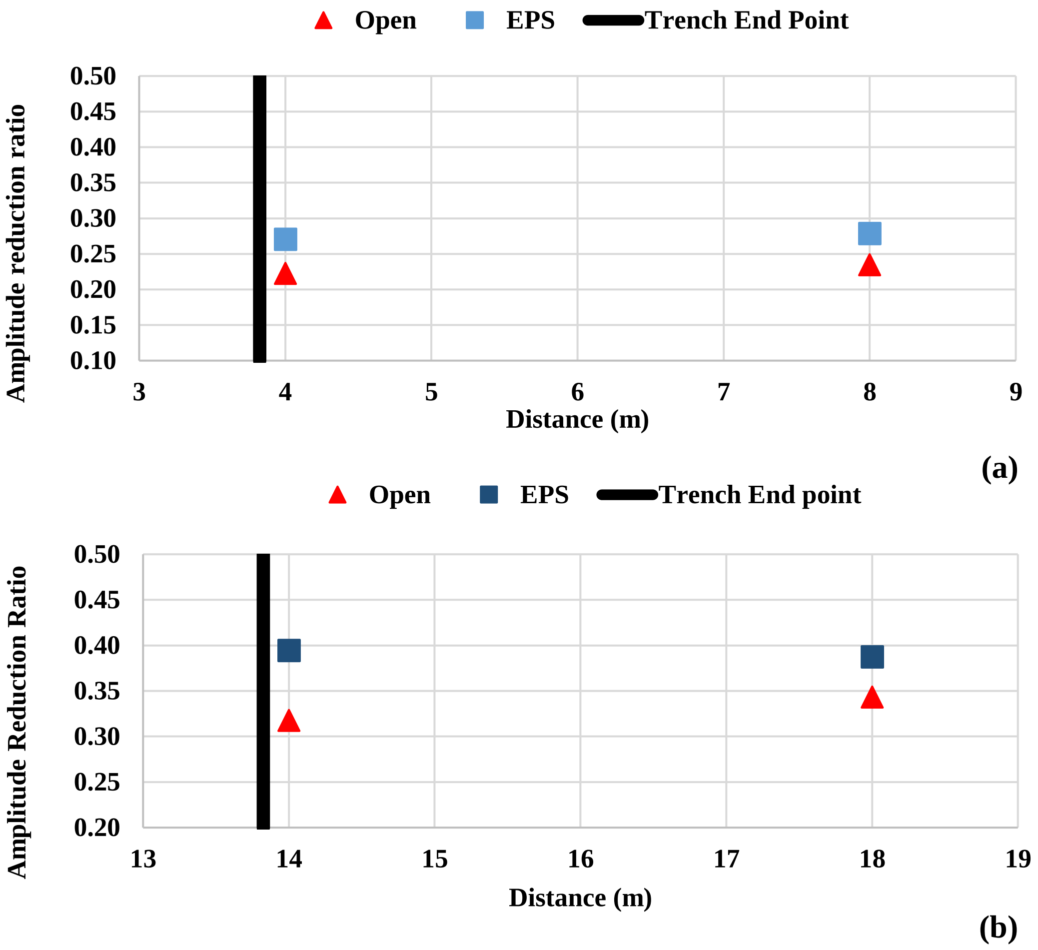


Figure 4.7: Amplitude reduction ratio for the excitation frequency of 59 Hz (a) Active (b) Passive

This may occur as a result of the reflected waves' amplification of vibrations distant from the trench. A trench filled with geofoam works exactly as well as an open trench because both barriers dampen vibrations coming from the ground directly behind the trench.

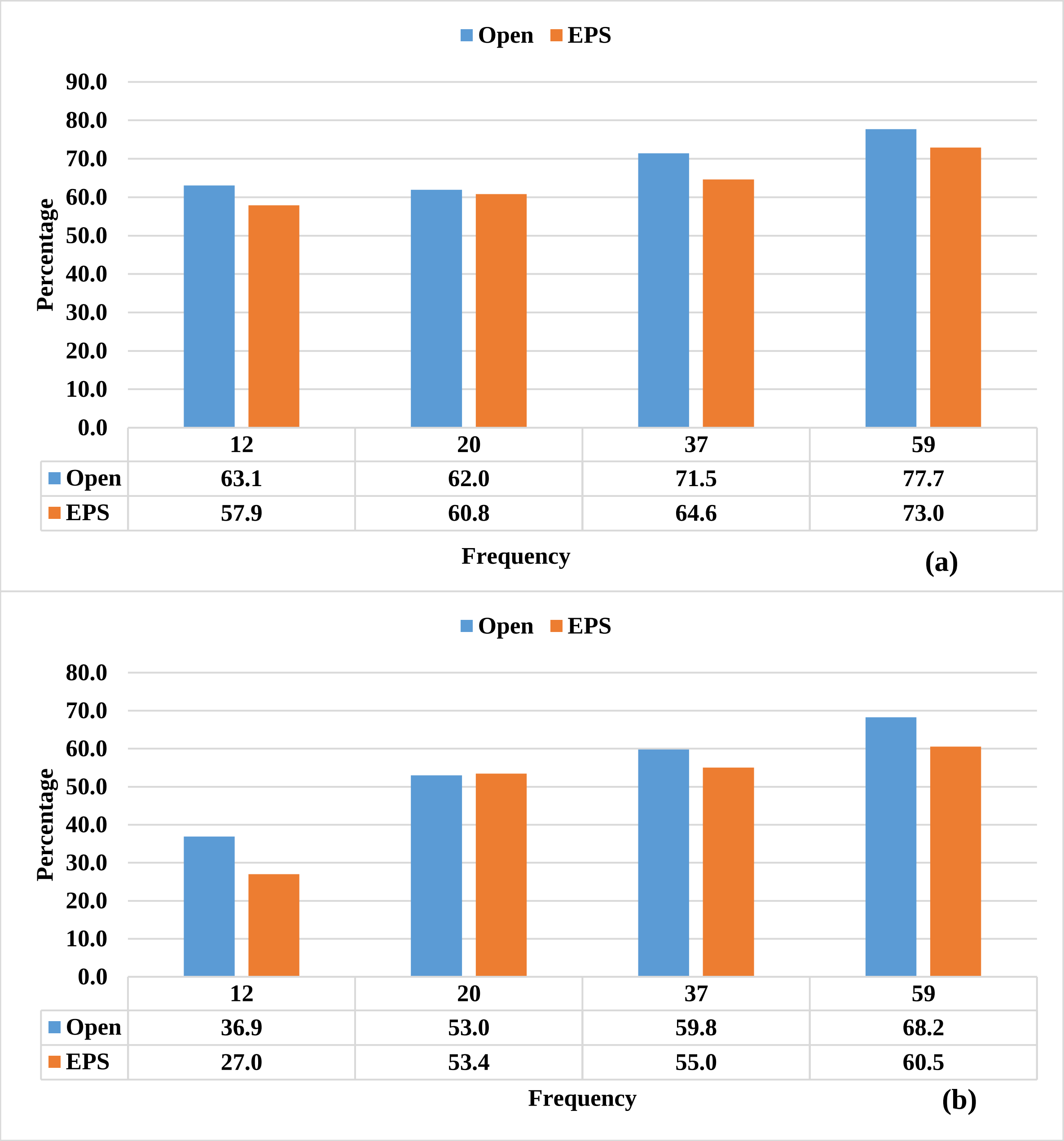


Figure 4.8: Amplitude reduction percentage with excitation frequencies (a) Active (b) Passive

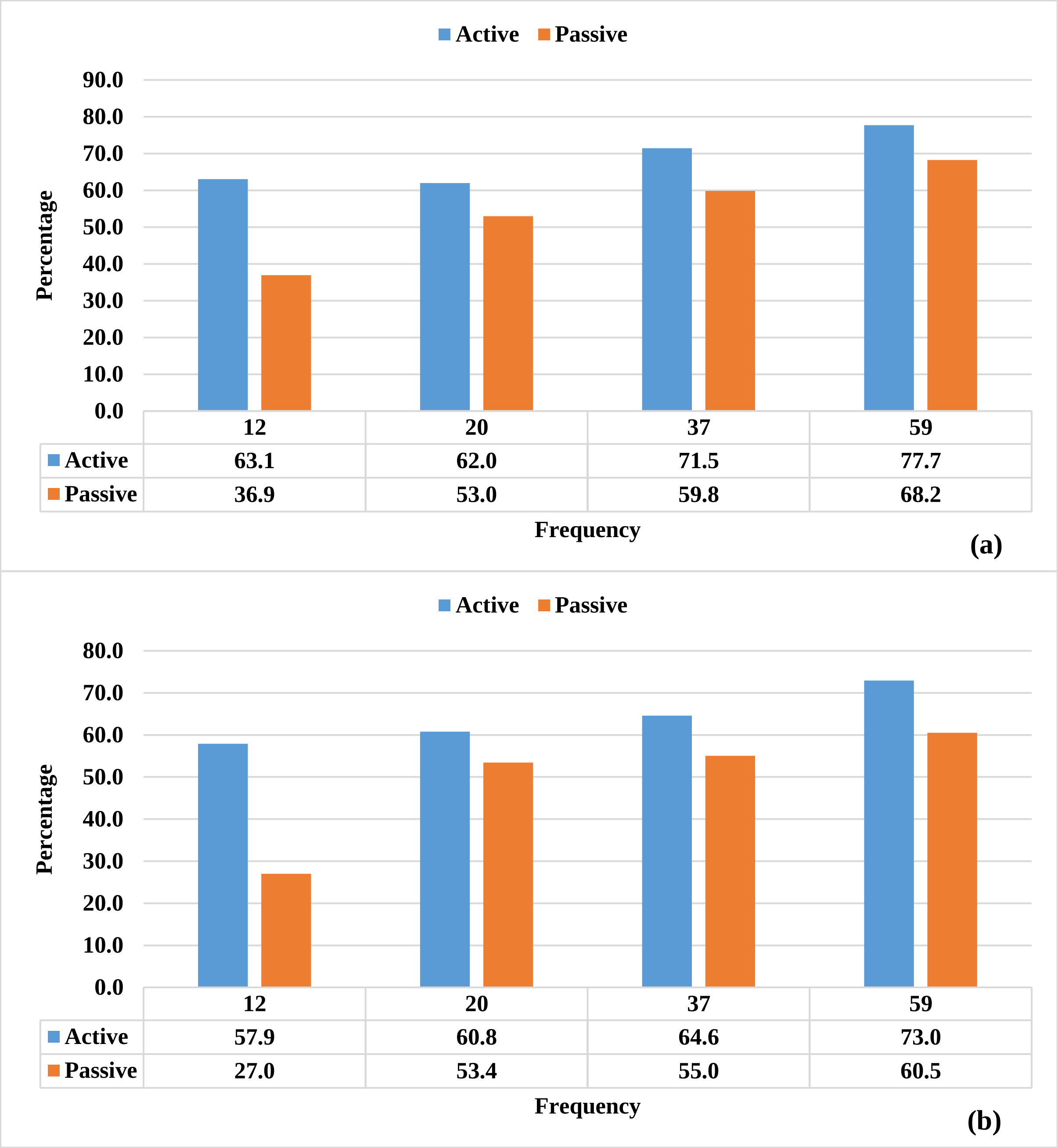


Figure 4.9: Amplitude reduction percentage with excitation frequencies (a) Open trapezoidal trench (b) EPS-filled trapezoidal trench

To get a further understanding of the trapezoidal trench performance, Amplitude reduction percentages were calculated by following the equation.

$$\text{Amplitude reduction percentage} = (1-\boldsymbol{A}_{r}) \times 100 \tag{4}$$

From this calculation, we can get clear information regarding the efficiency of the type of the trench and its performance. Figure 4.8 illustrates the amplitude reduction percentage for all excitation frequencies for both active and passive isolation systems. Both active and passive systems with the increase of excitation frequencies reduction percentage also increase. The trend of increase in performance is almost the same for both active and passive systems. Compared with the passive isolation systems with active isolation systems, active isolation systems perform better than passive isolation systems by 10% to 12%.

Figure 4.9 illustrates the amplitude reduction percentage for all excitation frequencies for both open trapezoidal trench and EPS geofoam-filled trapezoidal trench isolation systems. Both open and EPS trapezoidal trench systems with the increase of excitation frequencies reduction percentage also increase. The trend of increase in performance is almost the same for both scenarios. Compared with the EPS isolation systems with open trapezoidal isolation systems, open isolation systems perform better than EPS isolation systems by 5% to 7%. However, EPS trapezoidal trench performance is significantly higher than open rectangular trench and it can be used where open trenches are not practically suitable.

4.4 Comparison of Results with Prior Studies

To validate the results of this study comparison is crucial. Comparison with the same configuration is not available in past studies as trapezoidal trench filled with EPS geofoam. Therefore, this study was compared mainly by two categories with previous experimental studies.

- Open rectangular trench with the present open trapezoidal trench.
- EPS-filled rectangular trench with present EPS-filled trapezoidal trench.

The amplitude reduction ratio and the normalized depth were considered for comparison due to the defining impact of this study. Tables 4.3 and 4.4 show the extracted data from the present study for this comparison. Highly accurate and the most important parameters were chosen.

Table 4.3: Extracted data from the present study (Active–open trapezoidal trench)

Frequency (Hz)	Normalized depth	A_r
20	0.12	0.38
37	0.23	0.29
59	0.31	0.22

Table 4.4: Extracted data from the present study (Active – EPS filled trapezoidal trench)

Frequency (Hz)	Normalized depth	A_r
20	0.12	0.39
37	0.23	0.35
59	0.31	0.27

The graphic illustrates how the variance of A_r was shown as a function of the normalized depth. 4.10. The amplitude reduction ratios from the current investigation were compared to those from prior experimental studies on the screening efficacy of EPS-filled and open trenches, which were obtained at measurement site B (a vicinity to the trench). In comparison to earlier research findings, it is noteworthy that both the open and the EPS-filled trapezoidal trench exhibit a higher or at least an equivalent percentage reduction in the case of lower normalized trench depth.

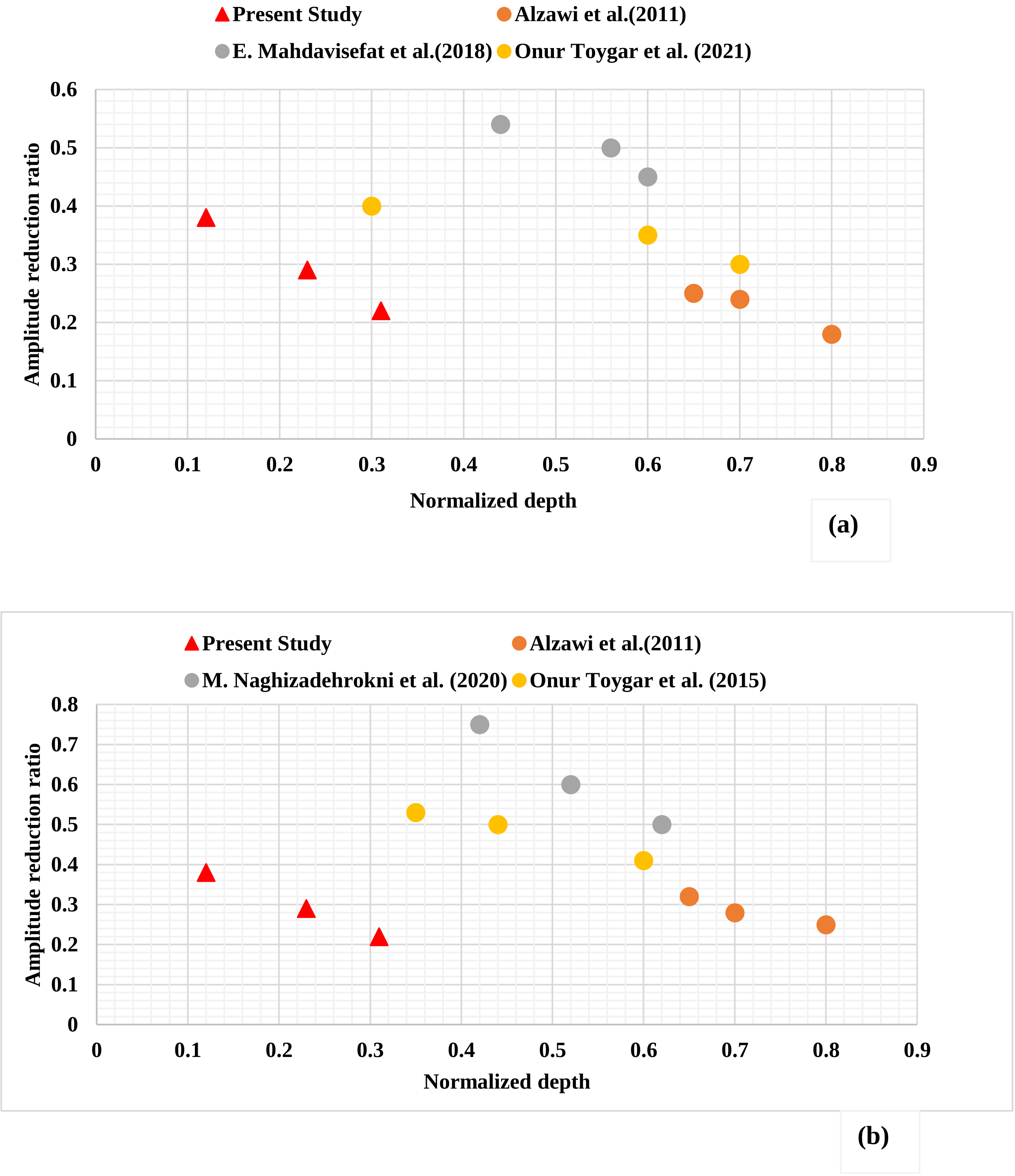


Figure 4.10: Comparison of Amplitude reduction ratio (a) Open trapezoidal trench (b) EPS-filled trapezoidal trench

Chapter 5: Conclusions and Recommendations

This study set out to investigate the effects of various configurations of induced vibration such as excitation frequency and the proximity of the vibration sources on the screening efficiency of open and in-filled trapezoidal trenches. To achieve this objective, a series of field tests were carried out using open, geofoam-filled trenches trapezoidal that were dynamically loaded using a vibrating plate compactor. The following is a summary of significant findings that came from the evaluation of the information gathered during the field tests:

- Higher excitation frequencies result in greater attenuation of acceleration amplitudes. Vibrations make more contact with material barriers, such as damping systems or physical barriers, at shorter wavelengths (associated with higher excitation frequencies). This increased interaction can lead to more efficient energy dissipation and vibration attenuation.

- If appropriate for the site, open trenches can be used as a wave barrier to reduce unwanted vibrations. Improved isolation was attained in an area near the open trench (Active). As one moved farther away from the trench, the amplitude reduction ratios rose, indicating less vibration mitigation. Based on the data, it can be concluded that active isolation systems perform better than passive isolation systems by 10% to 12%.

- When appropriate for the site, EPS trapezoidal trenches can be used as a wave barrier to reduce unwanted vibrations. The performance of an EPS-filled trench is marginally (between 5% and 8%) lower than that of an open trench. However, trapezoidal trenches filled with EPS are a better choice to get around the practical issues with open trenches.

- It is noteworthy that in the case of lower normalized trench depth, both the open and the EPS-filled trapezoidal trench exhibit a higher or at least an equivalent percentage reduction compared to previous research findings. It appears that the open and EPS-filled trapezoidal trenches provide more effective attenuation in situations where the trench depth is relatively low.

To attain more precise results, a comprehensive experimental study on a full scale involving multiple trapezoidal open and infilled trenches with varying trench dimensions is essential. This investigation will enable us to gather accurate data on the performance of these trench configurations.

To validate the experimental findings, numerical analysis through modelling can be conducted. This computational approach will provide additional insights and confirmation of the observed trends and behaviours in a controlled and simulated environment.

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