



Performance of In-filled Materials used as Wave Barrier For Vibration Isolation

**A Thesis Submitted
In partial Fulfilment of the Requirements
for the Degree of**

DOCTOR OF PHILOSOPHY

by

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(Roll No-2K19/PHDCE/07)**

Under the Supervision of

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Department of Civil Engineering

**DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daultpur, Main Bawana Road, Delhi-110042, India**

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Lastly, I give appreciation to my mother, father and wife for their support, particularly extend and express my sincere gratitude to my children for their continuous encouragement. Thanks, are also due to those who was directly or indirectly associated with the research work and achieving the goal.

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(Candidate's Signature)



ANNEXURE-II

CANDIDATE'S DECLARATION

It is declared that the research project titled "Performance of In-filled Materials used as Wave Barrier for Vibration Isolation" is a record of work done by me under the guidance of Prof. Anil Kumar Sahu (Supervisor) and Dr. Rajeev Goel (Joint Supervisor), for the partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy in Civil Engineering from Delhi Technical University, Bawana Road, Delhi-110042.

The matter embodied in this report is original, referred from work done by me and has not been submitted for the any other purpose.

Date: 18th June 2026

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To the best of our knowledge, the report has reached the requisite standard and the above statement made by Mr. Kumar Shashi Bhushan bearing Roll No-2K19/PHDCE/07, is correct.

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ANNEXURE-III



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CERTIFICATE BY THE SUPERVISOR(s)

Certified that Kumar Shashi Bhushan, (Enrolment No. 2K19/PHD/CE/07) has carried out his research work presented in this thesis titled “Performance of In-filled Materials used as Wave Barrier for Vibration Isolation” for the award of the Degree of Doctor of Philosophy from Delhi Technological University, Bawana Road, Delhi-110042, under our supervision. The thesis embodies results of original work, and studies are carried out by the research scholar himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT:

Surface waves generated by factors other than seismic sources such as construction activities, vibratory machines, movement of high-speed traffic, etc. may produce vibration effects causing distress to nearby structures and discomfort to dwellers. Reduction in this effect is possible significantly by placing suitable wave barriers in the ground near the source or structure. The wave barrier reduces the ground vibration by interception, scattering and diffraction of the surface waves. Properly designed open or in-filled trenches can be used for an effective vibration isolation (or screening) system. Rectangular wave barriers are frequently used in engineering practice to reduce the ground vibrations caused by propagating surface (Rayleigh) waves of relatively small wave lengths. This study will aim to evaluate performance of rectangular trench wave barriers with in-filled materials as Crumbed tyre rubber, Rice husk and Saw dust. Thorough comparisons with rigorous numerical solutions and available experimental data have also done. Also, an extensive parametric investigation has conducted and only vertical ground vibrations are considered in this study.

Full scale experimental study and numerical investigation have been carried out under this research study. Isolation of vertical ground vibration by rectangular open and in-filled (Stiffer than soil) trenches in a homogeneous isotropic visco-elastic half space has been studied. A 3D numerical study by using the FEM software PLAXIS-3D has been carried out in the study. Moreover, this study will identify the important dimensionless parameters that control the effectiveness of a vibration screening system. The results of experimental study has been validated by utilizing outcomes of numerical investigation. The comparison of results of experimental and numerical investigation has also been carried out. The performance of the in-filled material in rectangular trench wave barrier is presented in terms of efficiency percentage. Certainly, the isolation method will be helpful in overcoming unwanted effects of vibration in nearby structures due to factors other than seismic.



Conferences, Publications & Patent detail:

A. International Conference Papers: (Presented & Published):

1. **1st International Conference Paper:** The 1st Conference paper was presented on 11th April 2023 and published in IJIEMR as detailed below.

Paper detail: Bhushan K. S., Sahu A. K., Goel R., titled “Geotechnical Characterization of in-filled materials used in Trench Wave Barriers for Vibration Screening” published in International Journal for Innovative Engineering and Management Research, Volume 12, Issue 04, April 2023, pp 343-353

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- C. **Patent:** Application submission is due for Electro-Mechanical Oscillator



DEDICATION

<i>My Father:</i>	<i>To whom I am indebted</i>
<i>My Mother:</i>	<i>To whom I am indebted too</i>
<i>My Wife</i>	<i>Priyanka Bhushan</i>
<i>My Beloved Sons:</i>	<i>Yash & Harsh</i>
<i>My Beloved Daughter:</i>	<i>Mahima</i>

Who endured my engagement during this research project.

&

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LIST OF SYMBOLS:

A	Area of Trench
A_r	Amplitude Reduction Factor
C_c	Coefficient of gradation
C_u	Uniformity coefficient
d	Depth of trench
D	Normalized Depth
E_f	Efficiency
G	Specific gravity
I_d	Relative Density
L_R	Rayleigh wavelength
L	Screening distance
V_S	Velocity of Shear waves
V_R	Velocity of Rayleigh waves
V_s	Shear wave velocity
w	Width of trench
W	Normalized Width
f	Frequency of elastic wave
ρ_b	In-filled material Density
ρ_s	Mass density of elastic half space
γ_d	Bulk density (dry)
ν	Poisson's ratio
ξ	Damping coefficient
ρ_s	Soil Density

KEYWORDS:

Active isolation, Amplitude Reduction Ratio, Damping ratio, Efficiency of Screening, Geotechnical characterization, Normalized Ground Motion, Normalized dimensions, Normalized depth, Normalized width, Passive isolation, Rayleigh wave, Shear wave velocity, Shear modulus, Trench wave Barrier, Vibration Isolation, Wave propagation.



STRUCTURE OF REPORT:

Substantial parts of this report have been either published or has been submitted for possible publication in peer-reviewed technical journals and national and international conferences. It comprises 6 chapters, which present full scale experimental investigations and comprehensive numerical study on an innovative approach to reduce effect of vibration by in-filled trenches with Crumbed rubber, Rice Husk and Saw Dust. Wave barriers leading to provide solution to the vibration problem in structures due to sources other than seismic like moving traffic, construction activities, etc.

The report is organized into six chapters as follows:

- **Chapter 1** provides general background information about the concept of vibration isolation and mitigating it by wave barriers in terms of a brief summary about the principles of wave propagation in an elastic half-space medium and listing the different types of machine foundations excitations. The concept of vibration isolation is defined, the need for the present study is described. The objectives, the scope of the present work and the original contributions are listed and the contents of this thesis are briefly summarized.
- **Chapter 2** provides the literature survey of the past research works done on vibration isolation by wave barriers.
- **Chapter 3** deals with the geo-technical characterization of the in-filled materials used in the trench wave barriers. The characterization provides the concept of suitability of the material for the said purpose. It gives the broad view of the properties of the material to be used in trench wave barriers.
- **Chapter 4** is about the experimental investigation carried out in determining the performance of the in-filled materials used in the trench wave barriers. It includes selection of site, finalizing layout, formation of trench, installation of sensors, placing and shifting of source of vibrator



required for taking response of the system on different frequencies of the vibration and different locations of source of vibration (SOV). This chapter explains the site investigations, testing procedures, and the innovative approach to construct the trench wall. In addition, the protective effectiveness of both open and in-filled trench barriers and the influence of barrier geometry and location from the source of disturbance as well as the influence of changing the ratio between the barrier depth and its location are discussed.

- **Chapter 5** deals with the Numerical investigation to validate the experimental study already carried out. The finite element method has been used as a numerical tool to simulate the problem of wave propagation in soil medium. The developed three-dimensional (3D) time-domain finite element models for the adopted configurations of in-filled trench barriers placed at different locations and subjected to vertical harmonic excitations utilizing the finite element package PLAXIS 3D are presented in this chapter. The process of numerical model verification using well-documented reference studies are also included in chapter five. It also includes parametric study carried out by varying parameters which has effect on performance of wave trench barrier.
- Lastly, in **Chapter 6**, general conclusions on the effectiveness of using in-filled trench walls as wave barriers and prospects for future research are outlined. It also highlighted the benefits in terms of social impact.



CHAPTER-1

Elastic Surface Wave Propagation in Ground and Effectiveness of Trench Wave Barriers for Diminution of Vibrations: An Introduction

1.1 INTRODUCTION

When there is sudden slip at the faults in the interior of earth, there is release of enormous energy and energy releases in the form of waves. Seismic wave arrives after some time, then after comes stronger waves of low amplitude and then the surface waves of high amplitudes. The surface waves cause the most devastating effects on earth and are responsible for most of the damages on surface of earth as shown in Figure 1. Standards for design and analysis of foundations subjected to dynamic loads are now prominent and these standards represent an important stage in the state of art. But these standards are not capable for providing solution of each type of problem related to vibration. In a situation, a foundation may design as per the norms of standards which may reduce the damages to the machinery it supports but this machine may cause vibration problem to the in an around facilities.

Taking another situation in which some zone is required to be free from even ambient vibration as in case of sensitive instruments in hospitals or research locality. Presently, these vibration problems are still under research and clear-cut solutions are not available for them. Further attempts to find out the solutions are still in progress and concerned theoretical and experimental works are going on.

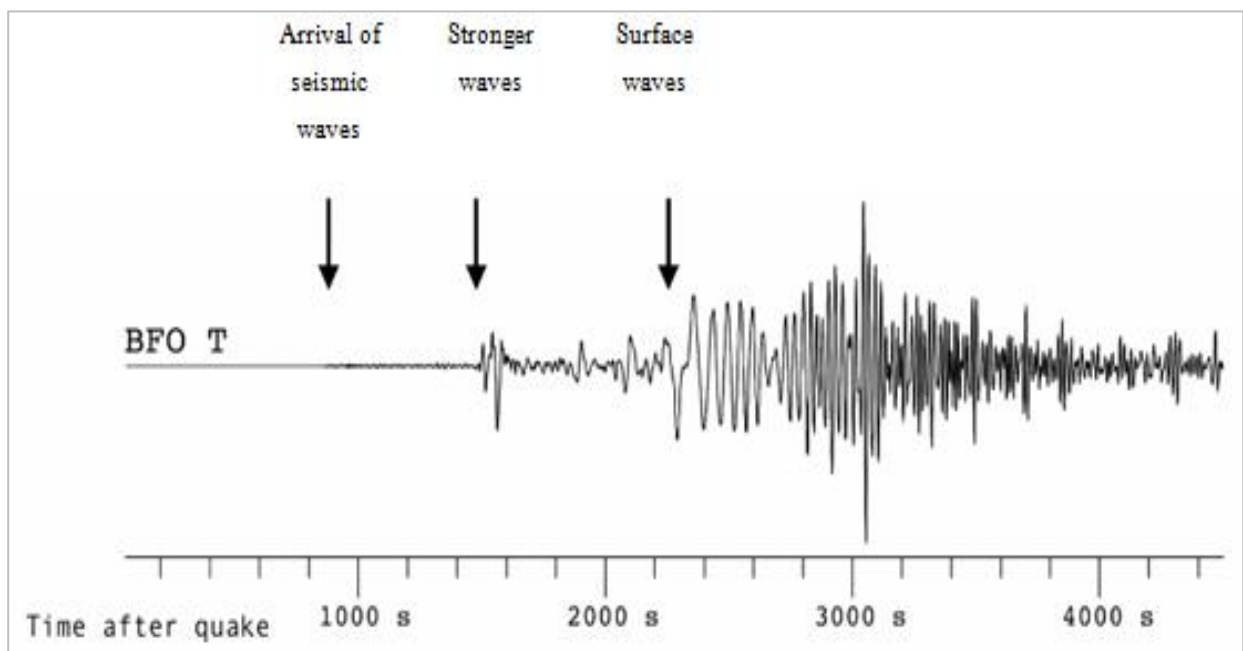


Figure 1: Seismogram recorded by Seismometer for a typical earthquake (Source: Soil dynamics and-machine foundations by Swami Saran Fig 1.2 Page 3)

For efficient design of foundation isolation system, a logical approach on the basis of cognizance of surface waves in the area of obstruction must be known to the researchers and practitioners. The prime focus of the past reviews is to get a thorough understanding of mitigating effects of surface ground waves by trench barriers on the basis of rational approach.

1.2 DIFFERENT TYPES OF ELASTIC WAVES

Body waves emanating from seismic effect, travels within interior of earth crust are found in two different forms i) p-waves and ii) s-waves. P-waves also called primary waves or compressional waves or longitudinal waves. It involves sequential squeezing of medium i.e. compression and expansion of medium i.e. rarefaction from which wave passes. These are similar as sound waves in the manner in which the vibration of particles of the medium as p-wave passes in solids and liquids. S-waves also termed as secondary wave or shear waves or transverse waves. It gives rise to deformation in shearing when the waves pass through the medium. In secondary waves, the movement of the individual particle is perpendicular with the direction of s-wave travels.

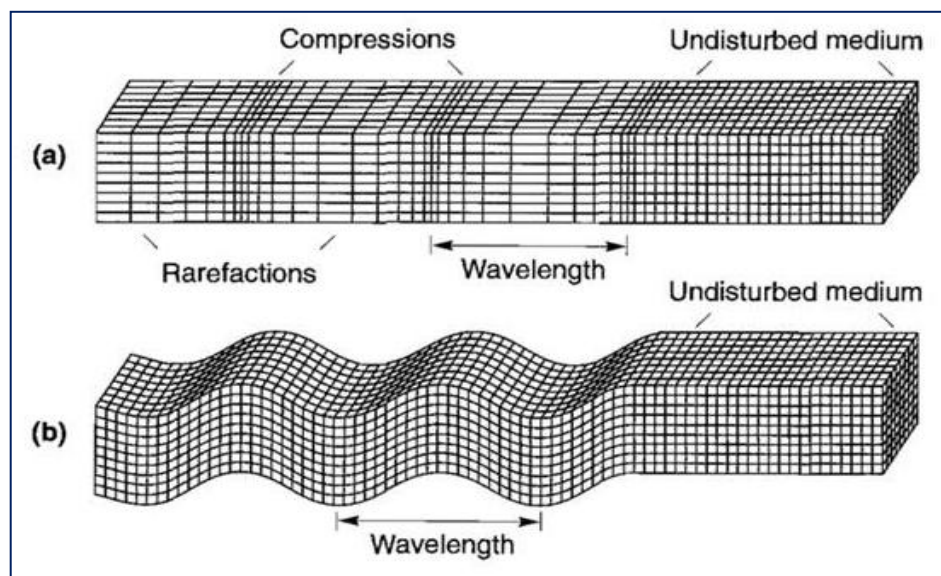


Figure 2: Deformation caused due to body waves (a) p-waves (b) SV-waves (Source: Geotechnical Earthquake Engineering by Steven L Kramer Fig 2.1 page 19)

The direction of movement of particle is used to classify s-wave into two constituents, vertical and horizontal plane movement designated as SV & SH respectively. The velocity of the body waves travel,



changes with stiffness of medium materials through which they pass. As we know, the geologic materials have the highest stiffness in compression; p-waves have the highest speed as compared to other seismic waves. Therefore, these waves are the first one to reach at a particular site. Fluids on the other hand not having shearing stiffness cannot sustain s-waves.

It is evident that surface waves are produced as a result of interaction of body waves and surface layers of earth crust. Surface waves travel through the surface of earth with decreasing amplitudes exponentially with respect to depth as shown in Figure 2. It is the nature of interaction required to produce the surface waves, these waves are notable at farther points from the origin of seismic effect. At distances more than twice the depth of the crust of earth, it is surface waves as compared to body waves which cause peak ground motions. Since, the earth does not resemble an infinite body and it has very large outer surface and existence of stresses not possible on it. The earth is generally assumed as semi-infinite body with a planar free surface. In case of planar surface, the effect of curvature of earth is not taken in account. The linked boundary conditions with the free surface require some more solutions to the equations of motion. These solutions explain nature of waves whose motion is focused near the free surface in a small region (referred as surface waves). Surface waves attenuate slowly with distance as compared to body waves; it means surface wave causes more destruction on earth surface.

Two different types of surface waves are significant to study. One of the types is Rayleigh wave shown to lie in a homogeneous and elastic half space as shown in Figure 3. Another surface wave is Love wave which needs a surficial layer having lower s-wave velocity as compared to the underlying half space. Some more types of surface waves also present but are not significant. Two forms of waves i.e. Rayleigh waves and Love waves are significant surface waves in geotechnical engineering domain. Rayleigh waves are formed by interaction of p-waves and SV-waves with the surface of earth. It involves both type of particle motion i.e. vertical and horizontal both. The phenomenon can be best understood by considering the similar case when a stone is thrown into water and the waves are produced. Love waves are produced by the interaction

of SH-waves with a surface layer of soft nature. It has not vertical component of particle motion.

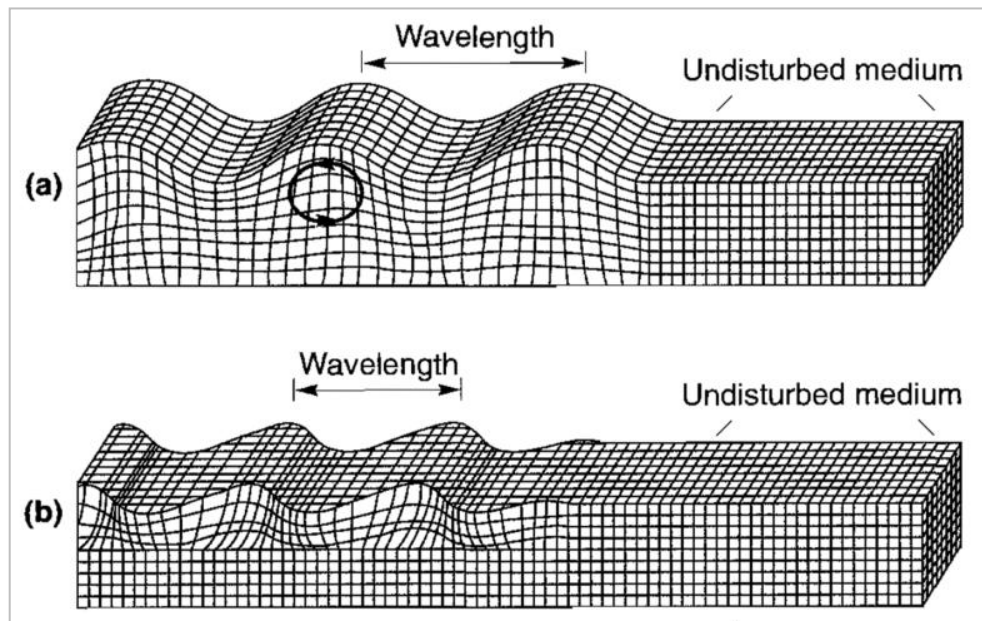


Figure 3: Deformation produced by surface waves (a) Rayleigh-waves (b) Love-waves (Source: Geotechnical Earthquake Engineering by Steven L Kramer Fig 2.2 page 20)

Study of elastic wave propagation in half space is very much required before taking up the issue of vibration isolation by trenches. Energy in the form of Ground wave propagation is propagated within the soil in form of elastic displacement waves. In studying the wave motion, the earth is approximated by homogeneous, isotropic and elastic half space. The elastic half theory is applicable as long as the amplitude of displacement is small and materials are not subjected to strain beyond proportional limit. Study regarding elastic wave propagation in homogeneous, isotropic and elastic half space is carried out by so many researchers. Theory of elastic half space states two forms of body waves (i) P wave or Primary wave or Compressional wave or longitudinal wave and (ii) S waves or Secondary waves or transverse waves.

Production of surface elastic waves propagation may take place caused from number of factors like construction activities, operations of vibration machines, blasting, etc. The sources which are producing elastic waves may lie in the region of half space or may lie on the surface. As these vibrations are produced near the surface of earth and the building and other structures are also near the surface of earth and consequently, they experience vibration effect. And due to this reason, the isolation of vibration from the foundations of the structures is of concern. The energy produced by a surface source is distributed away

which is a coupled form of waves consisting of all three types of waves i.e. Primary, Secondary and Rayleigh waves. While producing the vibration by vertical oscillation, Miller and Pursey [17] had found out the share of energy between these waves in elastic half space shown in Figure 4.

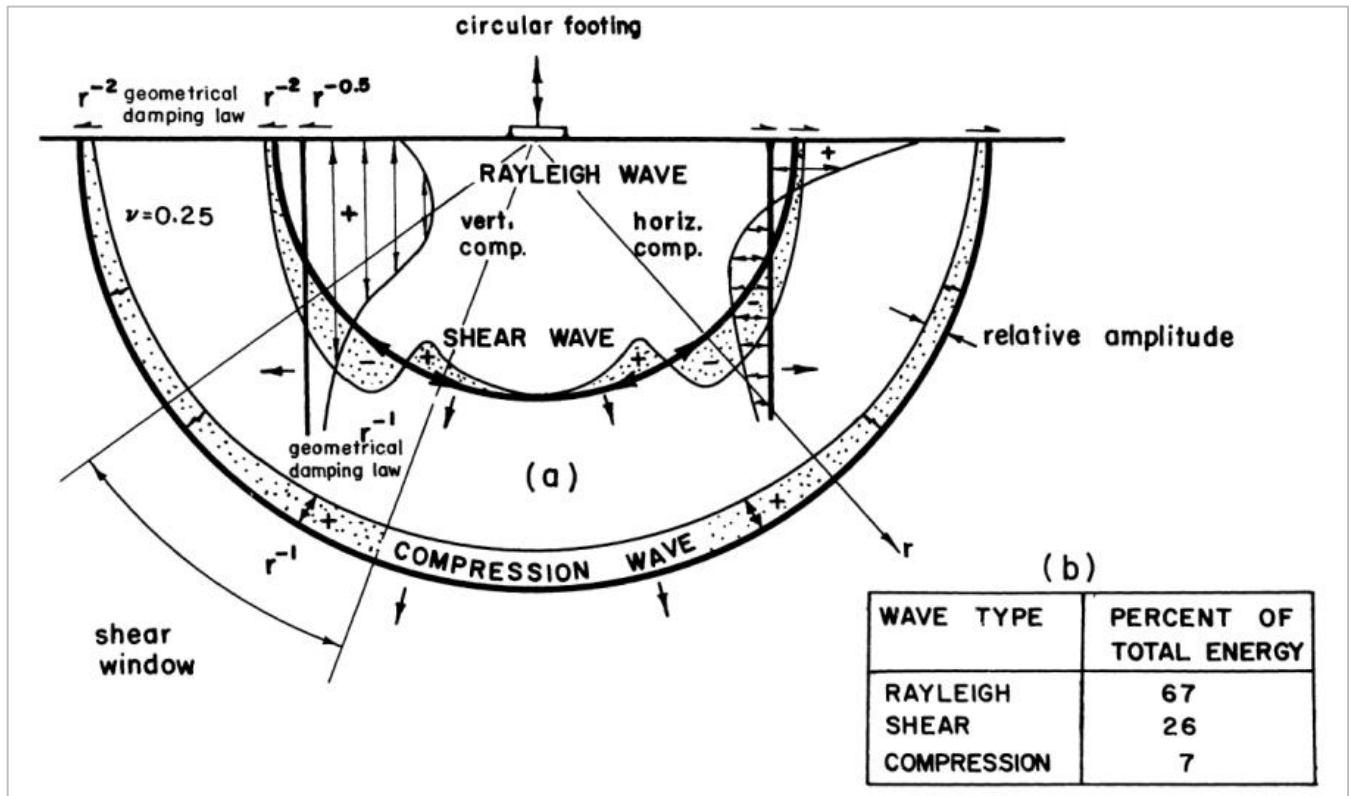


Figure 4: Propagation of Elastic waves in homogeneous, isotropic, elastic half space (Miller and Pursey 1955) (Source: Arab J Geosci (2017) 10:513, <http://doi.org/10.1007/s12517-017-327-3>)

1.2.1 Rayleigh Waves

Wave which exists near the surface of a homogeneous elastic half space in predominant form is Rayleigh waves. To understand Rayleigh Waves, consider a wave plane which propagates in x-direction and the motion of particle in y-direction is zero. Potential functions such as ϕ is the displacement in x direction and ψ in y direction. If there is harmonic wave with frequency ω and wave number k_R propagating with Rayleigh wave velocity $v_R = \omega / k_R$, the potential functions can be described as; $\phi = F(z)e^{i(\omega t - k_R x)}$ and $\psi = G(z)e^{i(\omega t - k_R x)}$ where F and G are two functions that depicts the manner in which there is a variation of amplitude of the dilatational and rotation constituents of Rayleigh wave with depth. Rayleigh waves are generated by electro-mechanical oscillator and their velocity is measured at site is used to investigate stiffness of soil at



surface of earth. The particles of soil during motion are in case of Rayleigh wave near the surface of half space is like retrograde ellipse.

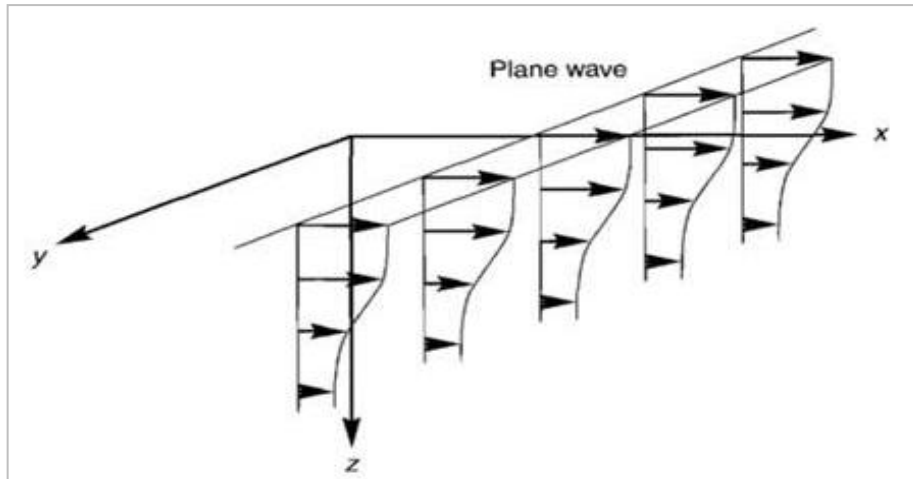


Figure 5: Motion by a typical plane wave propagating in x-direction (Source: Geotechnical Earthquake Engineering by Steven L Kramer Fig 5.8 page 157)

Measurement of seismic waves is done on the basis of movement in three directions i.e. Transverse, Radial and Vertical as shown in Figure 5. In Vertical direction, the P waves arrive later and it is due to the nature of two different types of seismic waves i.e. Rayleigh Wave and Love Wave named after Lord Rayleigh and August Love. Rayleigh waves are amalgamation of longitudinal vertically polarized transverse waves, oscillate in a retrograde and elliptical fashion as shown in Figure 6. They oscillate in a manner similar to water waves. In Rayleigh and Love waves both, the amplitude diminishes with depth. Love waves oscillate in a transverse fashion and are trapped in a layer. Rayleigh waves are dispersive.

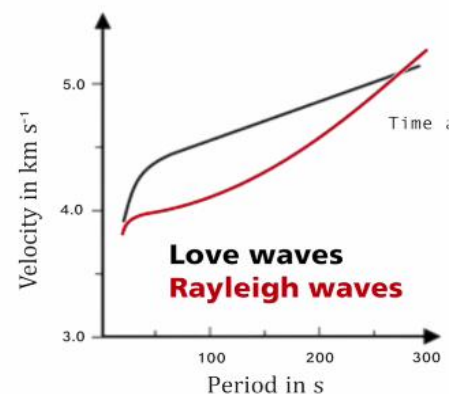
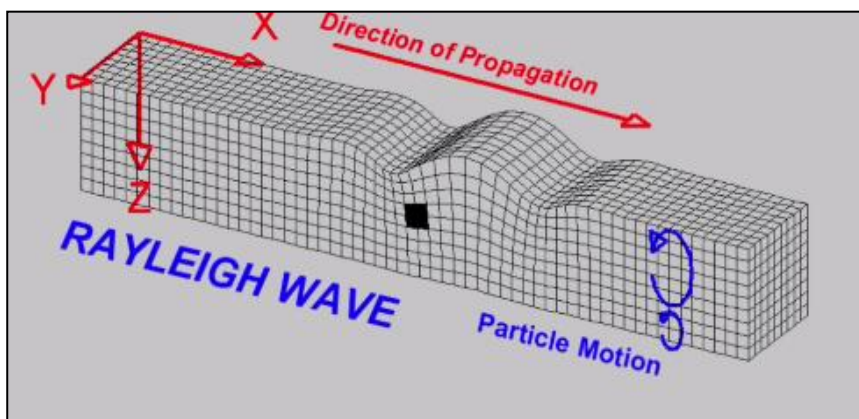


Figure 6: Movement of particles and direction of propagation in Rayleigh waves as compared to Love waves (Source: Content from Lecture module on NPTEL)



1.3 FUNDAMENTAL WAVE & SCREENING CHARACTERISTICS

It is important to identify ground motion parameters reflecting the features which may be adequate to explain the attribute of ground motion which is of significant in engineering terms. Three types of attributes of ground motion are paramount are amplitude, frequency content and period of ground motion. Various parameters of ground motion are proposed each of them provides information about these characteristics. It is typically important to use one or more parameters in order to characterize any particular ground motion adequately.

1.3.1 Ground Motion Parameters

To describe the important characteristics of ground motion in compact and quantitative form, parameters are necessary. So many parameters have been proposed to specify the features of amplitude, frequency content and period of ground motion. Amplitude is often used as commonest way to describe a ground motion with a time history. Besides, displacement, velocity or acceleration is the other parameters considered separately or collectively. Only one of these quantities is measured directly and the other computed from it by integration and/or differentiation. The frequency content explains that amplitude of a ground motion is distributed with frequencies of different magnitude. The duration of ground motion may have influence on effect of motion. Many physical phenomena, such as the reduction of stiffness and strength, etc. are prone to the load or stress cycles occur during a sustained ground motion.

1.3.2 Geometrical Parameters of Influence

The geometrical characteristics are the dimensions of trenches i.e. depth of trench ' W_d ', trench width ' W_w ' and the distance between source and barrier ' L ' which influence the efficiency of screening in vibration isolation. These geometrical characteristics were normalized by the Researchers in their past studies. This normalization has been done in association with Rayleigh wavelength in order to give dimensionless study.

1.3.3 Normalized Trench Depth (W_d)

Depth of trench is one of the most important factors considering the efficiency of screening in vibration isolation. Past studies and as shown in Figure 7, states that while considering vertical vibrations, adding



more depth improves the trench performance. In contrast, superficial trenches with more width produce lesser efficiency of trenches [1], [2], [13] & [14].

1.3.4 Loading

Studies show that, width of the trench has little impact in the performance of the trench. Yang and Hung [23] stated that in case of trenches with shallow depth and with more width has poor performance. The explanation for the observation that a trench nearer to the source of vibration, body waves are predominant and trench with shallow depth does not restrict the body waves to move underneath the trench.

1.3.5 Source to Trench Barrier Distance (L)

Past studies reveals that source to barrier distance have insignificant effect on trench performance except in shallow trenches.

1.3.6 Frequency and Amplitude as Loading Parameters

In wave barrier trenches, the parameters are normally represented as ration of Rayleigh wavelength; It means that the frequency has an indirect effect on the trench performance. In a nutshell as frequency increases, there is a decrease in wavelength and there will also an increase in normalized dimension of trenches and this will enhance the performance of barrier. The range of frequency (ISO 1990) for most of the vibration generating activities is less than 100 Hz. The parameter Amplitude Reduction Factor (A_r) determines the efficiency of the trench barrier. It is calculated as the ration of Amplitude of particle velocity with trench to the amplitude of particle velocity without trench at the same observation point. Bo et al. observed that there is no significant role of dynamic loading amplitude.

1.3.7 General Properties of the Responses

To assess the effects of the barrier geometry on the screening effectiveness, all vibration tests were conducted with the same initial conditions and with the specified vibrating frequencies. A trench with more width has the advantage that it provides much free surface and helps in conversion of surface waves from body waves. As the distance between the source and trench barrier increases, surface waves prevalence over body waves.

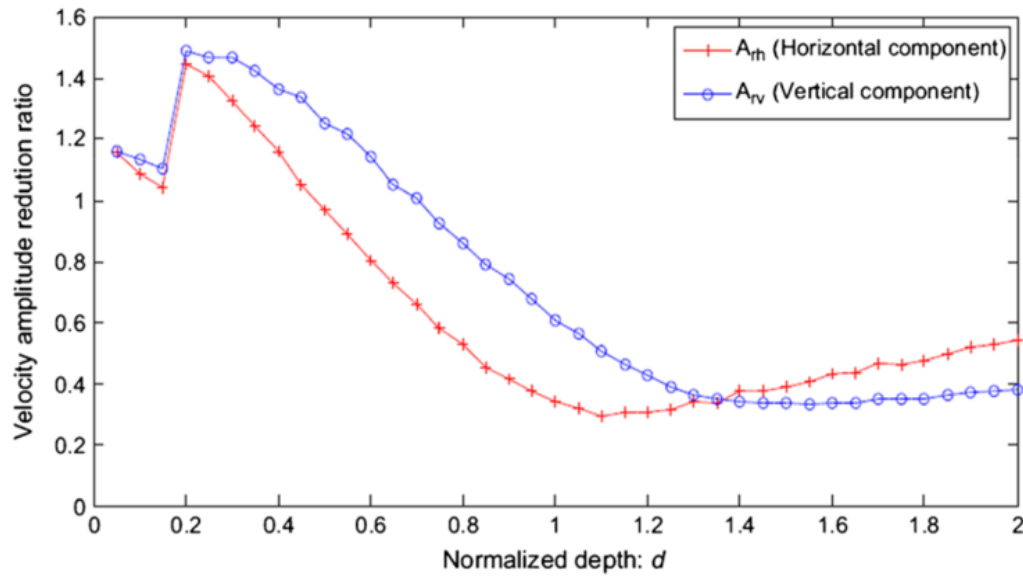


Figure 7: Influence of trench depth on degradation of Vibration (Source: Arab J Geosci (2017) 10:513, <http://doi.org/10.1007/s12517-017-327-3>)

1.3.8 Vibration Induced by Sources Other Than Seismic

Civil Engineering Structures experiences vibrations not only due to seismic factors but also the factors attributed are forces by wind, blasting in nearby area, operations related to construction activities, high speed road and rail traffic, heavy vehicles such as multi-axle trucks and Buses, machinery subjected to dynamic loads, etc. The vibrations due to traffic occur due to interaction of wheel with the irregularity on the road pavement, accelerate and de-acceleration of vehicles, etc. as shown in Figure 8. Vibration due to internal factors includes Machinery, HVAC system, Elevators and activities of the occupants can also be considered as important factors in producing vibrations. Vibrations generated by these factors are a common and significant concern in cities. Due to induction of these vibrations, occupants often complaint about inconvenience and the structural damages occurs. Building with archaeological importance may experience adverse long-term effect. Several précised instruments in Hospitals, Scientific Research Laboratories and High-tech industries also got affected.

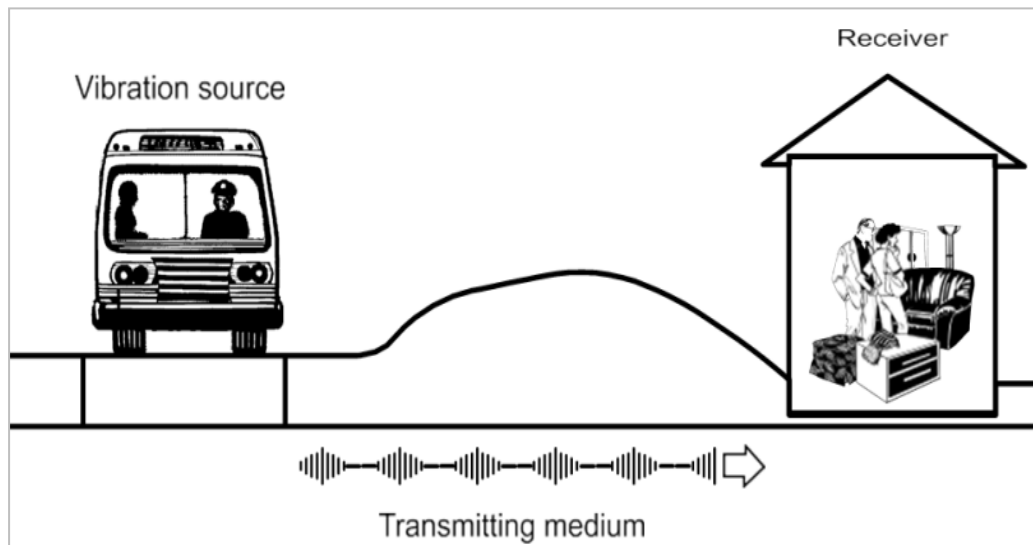


Figure 8: Traffic vibrations can be characterized by a source- path-receiver scenario

1.3.9 Strategies for Preventing Vibrations

Vibrations caused by factors like high-speed traffic, construction activities, etc., are not a healthy and safe aspect. There are no norms or standards to evaluate the vibration caused due to these factors. IRC researchers have though developed some surrogate methods for evaluating vibrations. Several preventive measures are adopted and recommended to restrict the vibration level to bearable extent by occupants and the structures itself.

The various preventive measures may include (a) Regular maintenance of pavement in order to avoid axle shocks caused by irregularities on pavement (b) Controlling the speed of traffic or high speed trains in those areas which are prone to these sorts of vibrations (c) Improvement of road structure and soil (d) Providing sufficient gap space between the roads/rail route and the building or other structures (e) Utilizing vibration isolation techniques by in-ground barriers as shown in Figure 9.

1.4 ELASTIC WAVE PROPAGATION

Surface waves do not propagate in the interior of earth but along the surface of earth just like water waves on surface of earth. These waves generate larger ground movements than body waves. Their oscillation is greater than the body waves. Different forms of attenuation have been observed for different types of waves along their paths.

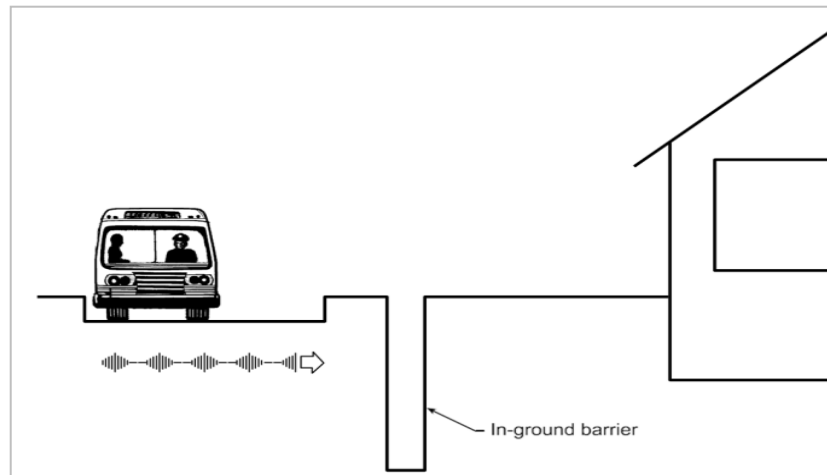


Figure 9: Schematic Illustration of an in-ground vibration barrier

Surface waves are radiated two dimensionally with a penetration 'd', hence their energy is distributed over cylinder with a surface area of $A=2\pi dr$. It means the attenuation is varying linearly with distance. Body waves on the other hand spread out in three dimensions, hence, their energy is distributed of the surface of sphere of size $A=2\pi r^2$.

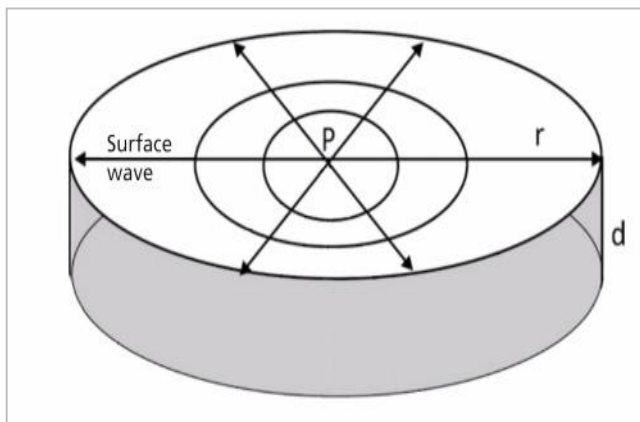


Figure 10 Radial Geometric energy distribution energy in Surface waves

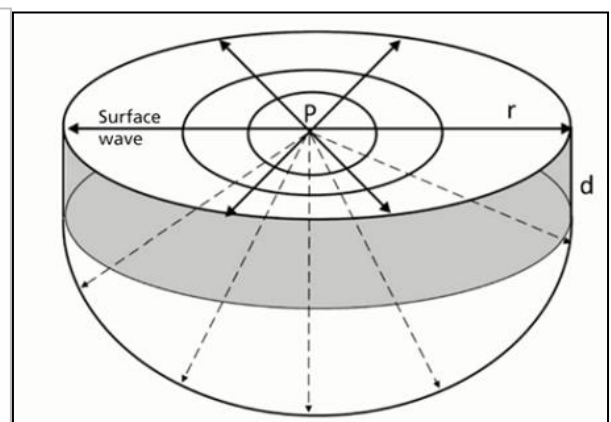


Figure 11: Three-dimensional Geometric distribution in Body waves

(Source: Geotechnical Earthquake Engineering by Steven L Kramer)

It means the amplitude in case of body waves decreases proportionally to the square of the distance making at lower the greater distances than it is case of surface waves. These waves are dispersive and have low velocity than the body waves. In general, surface have lower velocity than body waves, they have high amplitude and causes more destruction. Hence, it is necessary to know about the propagation and oscillation characteristics.



Both the waves i.e. Body waves and Rayleigh waves have their propagation emergence radially outward from the vibration source but the wave front used by body waves are hemi-spherical whereas Rayleigh wave uses the cylindrical wave front as shown in Figure 10. As we know that the energy density of both waves decreases with respect to increasing distances from the source because all the waves face increasing volumes of soil as they travel away from the source. This property in which the energy dissipation increases or there is a decrease in displacement amplitude when waves move away from the source radially is termed as geometrical damping. As per the geometrical damping law, in case of body waves, the damping can be represented as $1/r$ whereas in case of Rayleigh waves, the damping is represented as $1/r^{1/2}$. In case of waves along the surface, the damping can be represented by $1/r^2$, where r is the distance between point of observation and source. Angle of dip may be defined as the angle which is measured downward at the level of surface at the source center.

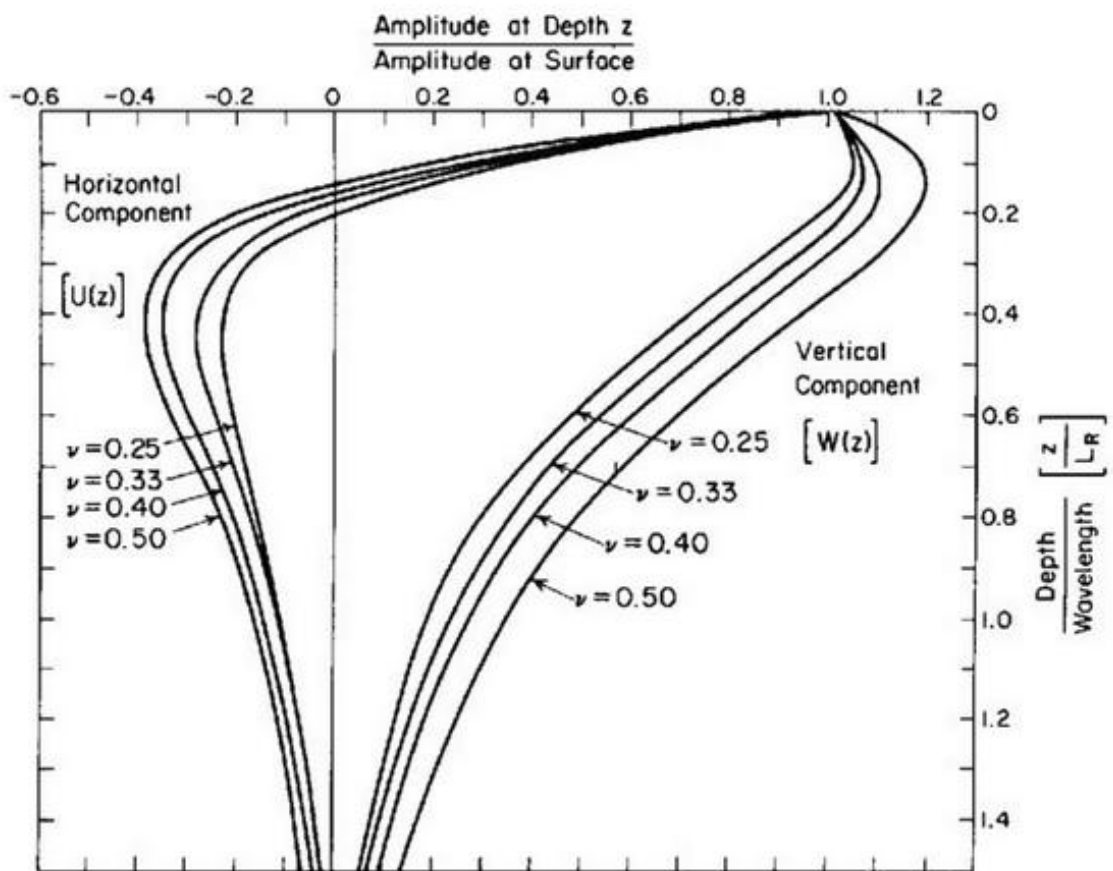


Figure 12: Amplitude ratio vs trench depth for Rayleigh wave (Source: Soil dynamics and-machine foundations by Swami Saran Fig 3.18 Page 92)



The shaded zones in Figure-10 on different wave fronts in case of body waves represent the relative amplitude of displacement of particles as a function of the angle of dip. According to the Geophysicists, zone of elastic half space for which there is maximum amplitude of shear wave is called as ‘shear window’. Vertical and horizontal components are required to describe the Rayleigh wave, there is a quick decay in amplitudes with depth as observed from Figure 12 each of the components dissipate with respect to depth but follow separate distribution. While working with vertically oscillator in form of circular energy source, Miller and Pursey [12] calculated distribution of energy from the incoming waves. It was found that out of three elastic waves, energy distribution among waves i.e. Rayleigh waves, shear waves and compression waves are 67%, 26% and 7% respectively. The fact emerged that in energy distribution among three elastic waves is 67% which is 2/3 of total input energy radiating from the source by Rayleigh waves. And the dissipation of Rayleigh waves slowly as compared to body waves. It reflects the fact that Rayleigh waves are of prime importance while dealing the isolation problem for foundation or problem of such types. In the Figure-11, it is assumed that value of Poisson’s ratio of material is 0.25 and the distance between the source of energy and the wave fronts is in proportion to the velocity of each wave. In elastic half space, the velocity of propagation of primary waves is represented by $V_p = \sqrt{(\lambda + 2\mu)/\rho}$ where λ and μ are Lamé’s constant and ρ is the material’s mass density. The V_s i.e. velocity of shear waves is state by $V_s = \sqrt{\mu/\rho}$ and the velocity of Rayleigh waves is given by $V_p = kV_s$ where k is constant whose value depends on material’s poisson’s ratio. It is surprising to see that V_s and V_r are almost equal for all practical consideration for all values of Poisson’s ratio.

1.4.1 Scattering and Diffraction of Elastic Waves

Discussions held up to this point dealt only those cases of half space which it is without any obstruction, where waves do not involve any kind of barriers. The fundamentals of foundation isolation by means of trenches, sheet piles, etc. lies on the fact how the barriers intercept or scatter and diffract the surface waves. It was in the year 1959 when Tyutekin, Knopoff, Baron and Matthews’s theoretical solutions provided an



insight into diffraction and scattering of body waves through elastic medium while encountering obstacles in form of simple shapes of spheres and cylinders. In the line, Mal and Knopoff [16], Viktorov and deBremaecker presented 2D theoretical and experimental theories regarding transmission and reflection of surface waves by encountering such obstructions as step varies in elevation, notches or corners. However, in the present preview, studies explaining the diffraction and scattering of surface waves by obstruction of finite length or depth is not known. Also, no abundance empirical data is available based on which a rational approach to the problem can be adopted. This reflects the scope where future study is needed to enhance the understanding of foundation isolation or vibration screening by trench wave barriers, particularly, efficiency of screening of 2D and 3D obstructions at the surface of half space.

1.4.2 Theory of Vibration Measuring Instruments

The prime objective of using a vibration measuring instruments is to produce signal as output which represent the phenomenon of vibration as closely as possible. Vibration system produces the phenomenon such as displacement, velocity or acceleration which becomes the basis for calling the instrument as vibrometers if it picks displacement, velometers if it picks velocity or accelerometers if it picks acceleration. These instruments reproduce signals which are proportional to the signals produces by vibration system. Vibration measurement can be carried out by two systems (i) Direct connected system: In which one reference surface is available and measurement of motion can be done with this surface (ii) Seismic system: No reference surface is required in this type of system and often used for vibration measurement. Vibration measuring instruments consists of a mass m supported by a frame with the help of spring K and damper C . During vibration, the frame vibration accordingly.

1.5 VIBRATION ISOLATION

There may be two types of problem arise in transmission of vibration which is ultimately affecting structure: (i) A machine installed on a foundation block may producing vibration of its own or receiving vibrations transmitting from nearby other machines and (ii) A structure subjected to objectionable vibration from surrounding. In the first case the objectionable vibrations producing can be restricted for minimized by

providing a layer of damping material between machine and the foundation. Such type of isolation of machine foundation from machine is called vibration isolation. Vibration isolation can be Force isolation or Motion isolation. The second condition in which the transmitted vibrations from the surroundings can be restricted or minimized by controlling the vibration energy approaching to the specific locations is known as vibration screening. Vibration can be effectively screened using interception, scattering and diffraction of surface waves by utilizing trench, sheet pile walls and pile barriers. According to the placement of trenches proximity with the source of vibration may be the basis for different types of screening i.e. Active screening and Passive screening.

1.5.1 Active Isolation

If the source of vibration is surrounded by the screening devices or provision of trench is given near to the source, then it is called active screening or isolation. In this isolation, the sources of the vibration are closed from periphery by circular trench as shown in Figure 13(a). The distance from the center of source of disturbance to center of trench is radius ' R ' and the trench depth is ' H '. The trench barrier is designed based on observations from field work and researches carried out. According to Barkan [16], vibration amplitude reduction will be effective if the dimension of the trench is comparatively large as compared to the wave length producing by the source of vibration. Also, Dolling (1966) worked on the efficiency of trench with respect to the shape and size of trench.

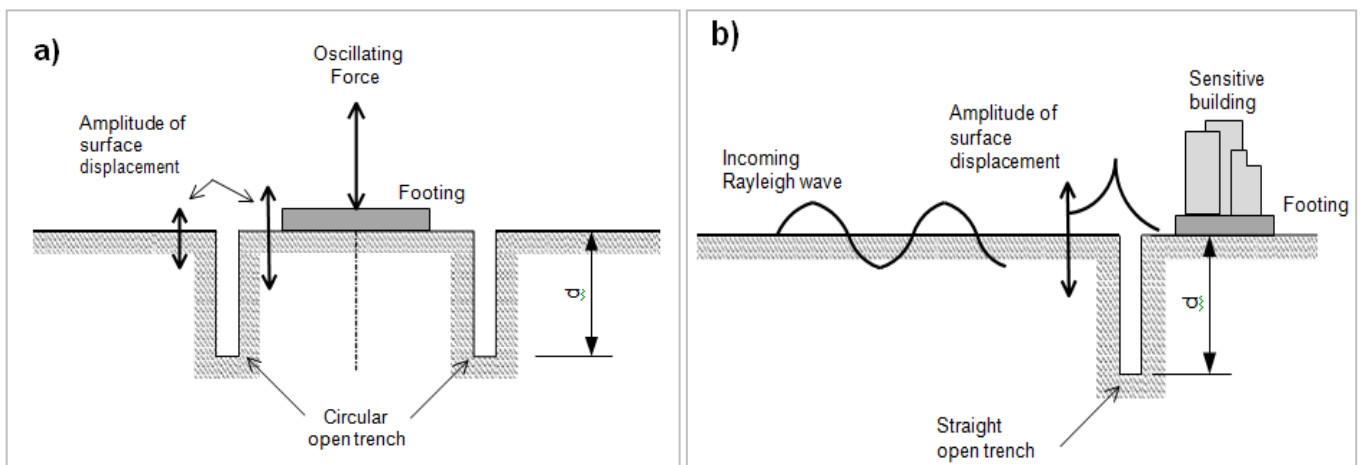


Figure 13: Vibration Isolation systems a) Empty trench around source of vibration (Active) and b) Empty trench near structures required protection (Passive)



1.5.2 Passive Isolation

In this type of isolation, screening devices are placed remote to the vibration source or nearby the structure to be protected as shown in Figure 13(b). The amplitude of the vibrations has to be reduced to a bearable level. According to Woods, measurement for amplitude reduction factor on straight trenches with various depths and lengths has been observed. The efficiency of passive isolation is lesser than that of active isolation as observed by Beskos [7]. The results were placed in form of amplitude reduction factor (A_r) contour diagram which showed that amplitude reduction is highest just behind the trench. The diversion of the surface waves at the trench end develops a zone of increased amplitude.

1.6 DISCUSSION

Available research works carried out in past on vibration isolation through various types of trenches in the half space, provided lot of significant understanding on the propagation of elastic waves where the nature of soil medium is inhomogeneous. Practically, the order of prevailing Rayleigh Wave length be in range of 8-8.5m (considering the $V_R = 200$ m/s; $f = 25$ Hz). Based on this data, the minimum depth in case of passive isolation varies from 5-6 m in case of active isolation and 10-11 m in case of passive isolation. Trenches with such a depth requires special and extortionate treatment. Suspension with liquids is also not significant practically. Vibration isolation by concrete walls is also not technically feasible. Gas cushion panels as a barrier in vibration isolation is systematic as worked out by Massarsch. However, the stability of the gas cushion trench barriers is a crucial problem.

Though, the extensive literature survey presented here reveals the wider extent of subject related works carried out by researchers & academicians and concluded their objectives in a significant manner, yet it is felt that some of the research gaps in the studies still exist. A Significant Numerical Study has been carried out, but only a few experimental investigations have been carried out to study vibration isolation through trench barriers. Studies are based on the frequency range-which was assumed long back. Studies have not shown inclusion of investigation of use of softer in-filled materials. Potentialities of in-filled materials were



not explored much. The techniques were tried with varying degree of success. Variation in geometries and the location of the barriers were not given importance. The method used for wave barrier was not economical. Characterization of in-filled materials was not considered in analyzing the performance of in-filled trench. Efficient screening has not obtained except in few cases with specific dimension, limited to certain configurations

1.7 CONCLUSION

The at hand report describes the elastic wave propagation in ground has represented on the one hand about the basic understandings of vibration isolation. This understanding is essentially required for the dynamic problems related to effectiveness of barriers in overcoming the causes due to vibration. A comprehensive idea for vibration isolation measures is given in form of experimental and theoretical studies. To reduce the complexities of inhomogeneity in the interior of half space is required to be solved by use of present day advanced featured Finite Element Methods and Boundary Element Methods. Experimental studies (presently only few experimental test results available) are more crucial to carry out for full understanding of the vibration isolation problem. Development of measures practically applicable, stable and inextortionate, all should be forwarded. Vibration Isolation is a technique to ensure the stability of structures and safety to occupants under dynamic conditions. Under the intense shaking conditions, vibrations are confined directly underneath the structures and there are chances of resonance with any of the multiple frequency values. To avert this condition, energy can be dissipated well in advance with suitable choice of the in-filled materials and technique of vibration isolation arrangements. Hence, the problem reduces to finding out ways to reduce the energy of the incoming waves before they strike some important structures.



CHAPTER-2

Literature Review

2.1. APPROACH TO THE PROBLEM:

Two fundamental approaches i.e. Numerical Investigation and Experimental study have been utilized to investigate the problem of screening efficiency from elastic waves. Several Numerical and Experimental study has been carried out in past to study the vibration screening. The relevant trench barrier dimensions i.e. trench barrier depth (W_d) and trench barrier width (W_w) can be found out in terms of wave length of Rayleigh elastic wave to normalize the dimensions.

2.1.1. Experimental Observations:

Woods after carrying out measurements by holographic interferometry of bore holes in rows established the phenomenon of effect of variation of geometrical parameters on efficiency of screening. In the test, the normalized depth was eliminated as variable. The zone around the source is of high amplitudes and behind the trench; the level of amplitude is low. ‘Effectiveness’ was used as a term for quality of screening rather than Amplitude reduction factor A_r . It was found that A_r decreases as there is an increase in diameter of hole (up to a limit of $L_R / 6$) or decrease in the clear spacing between the holes as shown in Figure 14.

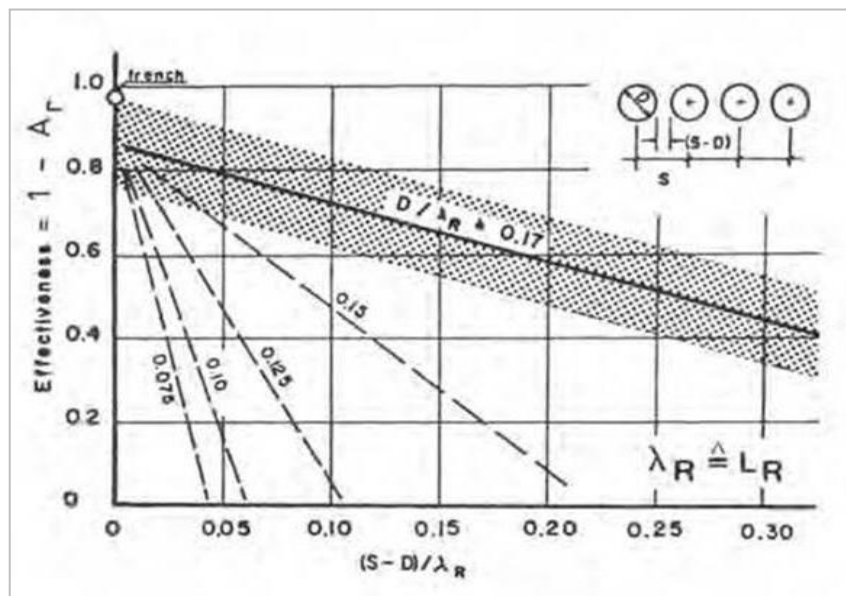


Figure 14: Efficiency of open holes dependent on geometrical parameters (Wood et al. 1974) (Source: 3rd International conference on recent advances in GE and Soil Dynamics, No SOA11))

Haput [14] performed model tests on bore holes rows and relation between A_r and normalized shielding area $(T * D) / (D + E)$, where T is the depth, D is the diameter and E is the clear spacing of holes. The



observed value of A_r was too high in the range of 0.60-0.90. The reason behind this remark was due to the reduced scale of model, small depth of holes and hole casings. Haput performed several experiments after removing casings and the reduce A_r has been observed in the range of 0.76 to 0.50. It was then taken as precaution in experiments that bore hole casings significantly impair the screening efficiency of the rows. Xiang-Jian (1991) performed experiments on piles and holes. In 1st experiment, by changing the configurations of rows and diameter of holes in loess and clay soil, it was found reduction in amplitude up to 20% within the area confined. In the 2nd experiment, rows of piles of 0.80m diameter were constructed around the boundary of building for vibration isolation. The A_r found was average in the range of 0.25-0.52. The author also worked on double rows of piles to find amplitude reduction factor. Liao-Sangre worked on propagating P waves in water. It was not rational findings to be used for reference. Woods et al. observed that if the diameter of the piles increases, the efficiency does not change significantly. But if the spacing of piles increases, the efficiency increases remarkably.

Ashref Alzawi, M. Hesahm EI Naggar [3] carried out Full scale field investigations on scattering using open and in-filled (Geofoam) trench wave barriers to mitigate vibrations produced from machine foundation. The impetus was to give some recommendations and guidelines for trench design. The experimental study was carried out on a selected number and type of trenches to evaluate the performance of Geofoam material. Results confirmed that in-filled geofoam trench barriers are effective to reduce the vibration. Barkan et. al. [5] reported a study to isolate a structure from traffic induced vibration using open trench and sheet-wall barriers. This installation was unsuccessful. Also, referring some more cases where no efficient performance was observed by providing screens such as a trench in which cinders was used as in-filled material and use of sheet-piling. Importantly, he recognized firstly that physical dimension such as depth and width of trench has not much effect on the effectiveness in screening. The effectiveness rather depends upon normalized depth and width with respect to the wavelength. The concluded observations for vibration screening practices keeping in view the safety and comfort of inhabitants in important civil engineering structures (CES). Going through the application related to control theory to large structures,

the paper highlighted the group of vibration suppression algorithms which can prohibit the crucial problems faced in the implementation of modern control methods implied to structures. Computerized simulation studies, analog investigations and experimental studies with various mechanical models of different modes (size and configuration) were given to show the feasibility, reliability and soundness of the proposed pulse-control methods. Baker [6] investigated out a series of field model tests to study the performance of trench wave barriers in which bentonite and concrete was used as in-filled materials were installed at different distances from the source to barrier, which are called accordingly active and passive screening.

Arnab Sur et al. [40] studied the vibration problem of underground moving train. The study includes the calculation for generated dynamic loads from moving train, propagation of the wave through the tunnel lining and soil medium. From this study, it is noticed that the free field ground vibration depends on parameters such as distance from tunnel, train speed, soil stiffness and depth of tunnel below ground. Ground vibration is inversely proportional to distance from tunnel, soil stiffness and tunnel depth, while is directly proportional to train speed. The tunnels in soil having SPT value > 40 generally do not exhibit significant vibration. Vibration can be reduced by increasing tunnel depth or by reducing train speed in affected section. Ashwani Jain, D. K. Soni [41] presented a summary of different methods of vibration isolation techniques that has been carried out in case of machine foundation. In these, most methods for active isolation have been discussed like inner balancing in machine, isolation by remote location, stabilization of soils, screening of disturbances, etc. Massarsch [18] discussed the factors influence the propagation of ground vibrations. The neglected part i.e. effects of wave bending, which can occur in soil deposits where the wave velocity increases with depth and it reduces the efficiency of vibration isolation trenches. It is proposed that the design for isolation screens is based on predominant frequency of vibration and corresponding wave length. Theoretical study shows that isolation effectiveness of gas cushions is practically identical to an open trench and isolation effect is greater than 50%.

Deniz Ulgen [9] examined the performance of open trench with special emphasis on active and passive vibration isolation control systems. Field results show that open trench wave barriers are an alternative

vibration control system in order to achieve reasonable efficiency. The vibration amplitudes generated by impact loading achieve an average reduction of 50% for a trench depth of 4.5m. Active isolation has better efficiency than passive isolation. Sivakumar Babu [10] carried out tests for vibration at site for the vibration testing room. Numerical analysis in 2D using finite difference tool FLAC 5.0 was used to state effective vibration screening systems. In the study, the numerical model was calibrated firstly with respect to material properties, damping value and boundary conditions in order to obtain the output comparable to the finding at site. The calibrated model was then forwarded to perform parametric studies. The study showed the use of vibration test results in the calibration of the stated numerical model and discusses the evaluation of effective vibration isolation systems using numerical simulations of various proposals. Ankurjyoti Saikia [2] studied the response of rectangular in-filled trenches in elastic, isotropic and homogeneous space. Softer barriers are considered in this study. The effect of shear wave velocity ratio on degree of isolation has been shown. Screening effectiveness depends on the barrier depth and width and also on component of vibration. Seyhan Firat [19] presented a thorough study on the mitigation of vibration at foundation caused by harmonic load which was generated by electro-dynamic shaker using a trench wave barrier. Effectiveness of open or in-filled trench wave barrier as a reduction measure has been shown. Open trench is effective than an in-filled trench but its practical application limits to very shallow depth considering its suitability for stability.

2.1.2. Theoretical Observations:

Gazetas [11] investigated numerically the vibrational behaviour of heterogeneous deposits with increasing wave velocities. Analytical-numerical methods have been demonstrated to find out the dynamic behaviour of such deposits due to vertical-shear or Rayleigh waves. Studies show that as the heterogeneity increases, the attenuation with depth increases sharply. The Rayleigh-wave induced vibration decay with depth has found to be dependent on shear wave velocity, rate of heterogeneity and also on frequency. Javier, Francisco [15] studied the wave barrier cases for underground explosions. It includes theoretically study about the vibration isolation using piles as wave barriers. It was proposed two models, one with infinite length piles

and second pile with finite length with different waves. In this study, effect of pile diameter, separation and length were considered and conclusion has been made relevant to guidelines for design. S. Ahmad et. al. [20] developed simple design expression for vibration isolation using rectangular open and in-filled trenches in homogeneous soils under plain strain conditions. The influence of parameters as frequency, aerial extent of reduction zone, trench dimensions, trench location, Poisson's ratio of soil and in-filled material properties such as wave velocity, density and damping have been investigated and conclusion has been made. Soil in two layers (single layer over half space) along with open trenches was also investigate and concluded.

Kattis [21] solved the numerical problem of vibration isolation by using a row of piles in 3-D context by an advanced frequency domain BEM. An advanced-frequency domain BEM code has been proposed for the dynamic analysis of complex 3-D elastic structural systems. The BEM analysis for row of piles as wave barriers in vibration isolation problems is analogous to that of trenches with the only difference being the size of the problem which is always much larger for piles than for trenches. The general screening behaviour of piles is similar to that of trenches with the latter being always more effective than piles. Configuration of piles influences its vibration isolation effectiveness in a manner analogous to trenches. Comina, Foti [8] carried out numerical stud for active and passive isolation, used in order to design a vibration reducing barrier showing that the relevance of these tests is manifold for the specific problem. Characterization of vibration has been carried out leading to obtaining Rayleigh wave length which is used for designing trench depth. Numerical simulations have been proposed to assess the effectiveness of different solutions. Alzawi, Naggar [4] developed numerical models to investigate the effectiveness of geofoam trenches as wave barriers. 2D & 3D numerical models were developed in time domain using FEM package ABAQUS. The parametric study is conducted by varying the barrier geometric dimension, location and soil properties. The barrier depth and location were varied independently as well as the soil dynamic properties. It was concluded that the soil density, Poisson's ratio and material damping are not so important. A trench with more depth is required to achieve effectiveness as proximity of disturbance increases. Effectiveness of



barrier improves in stiffer soil (with high V_s values).

Belinassi [12] developed a frequency domain direct BEM based numerical method to solve vibration isolation problems for a homogeneous, linear elastic and isotropic medium. This methodology was also helpful in performing studies with varying trench dimensions. The effect of changing the distance between source and trench barrier to obtain effective amplitude reduction is also possible. Bose [22] carried out PLAXIS based numerical finite element analysis to correlate the performance of empty and in-filled trench wave barriers. The performance of trench wave barriers with range of geometrical and material properties, different barrier type and loading conditions were studied. The formulated model was utilized to find out the crucial factors which have effect on the screening capacity of trench wave barriers. 2-D simulations were carried out to understand the effect of geometrical and material properties of trench wave barriers on performance of wave barriers in mitigating vibrations.



CHAPTER-3

Geotechnical Characterization of in-filled materials



3.1 INTRODUCTION

In-filled materials play a significant role in performance of trench wave barriers for vibration screening. Using waste materials in trench wave barriers as in-filled materials is an eco-friendly and sustainable step in services and application of geotechnical engineering techniques. But how these materials have suitable application in engineering domain, safety and stability, is an important concern. To know its application and comparison with other materials as in-filled materials in vibration isolation, it is required to ascertain its geotechnical properties. In the present paper, the geotechnical characterization of in-filled materials i.e. rice husk, saw dust and crumbed tyre rubber had been carried out. Several laboratory tests had been carried out such as particle size distribution, specific gravity, bulk density, relative density and permeability. Since trench wave barrier is exposed to dynamic loading, its dynamic properties in addition to these properties are also important. Several dynamic tests had also been conducted such as shear modulus, damping ratio, stiffness and shear strain to ascertain down the suitability of these materials as in-filled materials which was used in trench wave barriers for vibration screening. Based on the experimental study for performance of in-filled materials in trench barriers, the results indicate that the materials possessed good characteristics of in-filled materials in trench barrier for vibration isolation.

The in-filled materials to be used in trench barriers for vibration isolation play a significant role in efficiency of screening. Type of in-filled materials used will finally decide the performance or efficiency of the trench wave barriers with respect to screening. In civil engineering applications, the in-filled materials should have possessed much of desired engineering properties so that suitability of materials for filling in trench wave barriers can be defined.

The experimental study has been carried out for investigation of performance of in-filled materials in vibration screening, the materials used had shown characteristics as performance criteria could be ascertained by adhering in the range of values of these properties. The in-filled materials used in the experimental study in trench wave barriers for vibration screening are saw dust, rice husk and crumbed tyre rubber.

3.2 MATERIALS AND METHODS

Based on the factors such as suitability for purpose, availability of materials, sustainability, waste nature, economy and handling, following three types of material were selected under this research study. Considering the above factors, the materials selected as in-filled materials were (i) Saw Dust (ii) Rice Husk and (iii) Crumbed Tyre Rubber as shown in Figure 15:

(i) Saw dust

(ii) Rice husk

(iii) Crumbed tyre rubber



Figure 15: Three types of In-filled materials used in Trench wave barriers for Vibration screening

3.2.1 Saw Dust

Sawdust (or wood dust) is dark brown in colour and angular in shape [36], a waste obtained or by-product obtained after carrying out operations on wood i.e. routing, sawing, milling, sanding and planing. It consists of small sized chippings or even fine powder from wood. These operations generally performed by wood-working portable power tool machinery or hand tools. In some manufacturing industries, the saw dust can be a significant fire hazard and as a source of occupational dust exposure. The particulates are the chief component of particleboard. Dust and chips are the two waste products forms at the working area during wood working operations as stated above. Dust is created by shattering of wood cells, while degradation out of whole groups of wood cells generates chips. Finer dust particles will be formed as more cell-



shattering occurs [11]. For example, sawing and milling are mixed cell shattering and chip forming processes, whereas sanding is almost exclusively cell shattering. Sawdust is a waste produced from various sawmills in the country. It is mostly disposed off in the open environment and thus become factor pollution [12]. Hence using sawdust as filling materials in trench barriers for vibration isolation can enhance the utilization of saw dust waste in the longer run and help in sustaining the environment to a little extent.

3.2.2 Rice Husk

The rice husk is also known as rice hull, is flaky particles brown in colour, is the rice seed coating or grain coating. It is produced from hard materials, which includes silica and lignin which protects the seed in season of growing. In 1 Kg of milled white rice results in about 0.28 kg of rice husk obtained as a by-product in rice production during milling. Common by products produced from rice husk are: like solid fuel (in loose form or as briquettes and pellets), carbonized rice husk generated after burning, and the rice husk ash at the end after combustion. In its loosest form, Rice husk is mostly utilized for energy production. When the density of rice husk increased the product forms are rice husk briquettes and pellets which have higher combustion performance. These forms of densified rice husks are utilized in boilers which help in saving fossil fuels. Produced during rice milling, the rice husk is already dried and accumulated at the factory. Since long, rice husk was treated as a waste after milling process and their disposal was a cumbersome task. Because the rice husk is collected easily and is not costly, rice husk has been in application as an energy source.

3.2.3 Crumbed Tyre Rubber

Crumb tyre rubber is a form of recycled rubber of fibrous in shape and black in colour which is produced after scrapping the automotive Tyres. In the recycling process, its components such as steel wires and tyre cord (fluff) are separated, leaving tyre rubber part with a granular consistency.

Further, in a granulator, with the help of cryogenics or by mechanical means, the size of particles is further reduced. The particles are then separated as per size of grains and grouped on the basis criteria including colour. The crumbed tyre rubber used in this research study has been collected from recycle tyre factory

located at Mayapuri, New Delhi. The factory produces three different grades of crumb tyre rubber graded as 40, 20 and 16.



Figure 16: Layout of the process for formation of Crumbed Tyre Rubber from waste Tyres (Source: Journal of Engineering Science and Technology, No. 1(2021) 510-526), Volume-16

As shown in Figure 16, the various stages in producing crumb tyre rubber, from the waste tyre when cut into chipped tyre by means of cutting machine and then undergo shredding. It is then sieved using sieve machine and rubber crumb and steel wire are separated. In this research, crumbed tyre rubber has been characterized by carrying out testing on the selected material [37]. It is important to note that though the waste rubber tyre is separated from its metallic wire component, even remnant of metallic element may present in crumb tyre rubber undergoing processes. A fact that the Tyres are one of the industrial wastes, which makes interest to the researchers to explore its utilization. Pelisser et al. [37] mixed rubber in concrete mix to develop concrete products in form of Rubcrete with enhanced properties like thermal insulation,



sound-proofing and low density. The addition of rubber content in concrete has decreased the density of the concrete. Nadal Gisbert et al. also observed that adding rubber content in form of fibers or aggregate to concrete mix can produce concrete of lower density. Other than particular applications in civil engineering, concrete with rubber particles has the property of occluding a large volume of air, which enhances workability. Also, the enhanced characteristic of rubber to dissipate and absorb energy the utility may be found in production of sound barriers.

3.3 EFFECT OF VARIOUS PROPERTIES ON ATTENUATION OF WAVE MOTION

Screening performance of in-filled materials in trench barrier depends on the property of attenuation of waves. Wave attenuation is affected by number of factors such as particle size, specific gravity, saturation, stiffness and dynamic properties such as damping ratio, Shear modulus and Shear wave velocity. Though, there is less availability of resources revealing much about the dependence of the factors on wave attenuation, the influence of these factors on the attenuation of wave is dealt herewith:

3.3.1 Effect of particle size of soil on Wave attenuation

M. Sadeghi et al. [30] observed that when particle size of soil increases, soil reflectance, R , decreases. This occurrence has been derived by using model of analytical radiative transfer. Reflectivity (ρ), and Absorptivity (k) are the two parameters which the optical properties of soil depend and are used in the model. This assumed model has been deduced for surface and volume reflectance using two different models for beam tracing.

3.3.2 Effect of specific gravity on wave attenuation

Though, not many studies are available which show the effect of specific gravity on wave attenuation. The study showed that for the width of the tested zone, the low specific gravity is not much effective in attenuating wave energy.

3.3.3 Effect of Saturation on wave attenuation

The correlation between permeability and attenuation is not well defined. Study revealed that attenuation coefficient is high with permeability less than 50 md and attenuation coefficient is low with permeability more than 50 md preferably greater than 1dB/cm [25].

3.3.4 Effect of Stiffness of soil on attenuation of wave motion

Bornitz equation of attenuation [31] has been used to evaluate the frequency independent attenuation coefficient, a_0 , caused by damping of material. The equation adequately related the attenuation of Rayleigh wave varying with distance. It was based on the analytical value of attenuation coefficient caused by radiation and material damping. Attenuation of amplitude of Rayleigh wave over a distance increases exponentially with respect to frequency of waves propagating. The frequency and wavelength of the waves transmitting, affects the vibration by a source. Attenuation in stiffer material is lesser than the soft soils.

3.3.5 Effect of Wave attenuation on Shear wave velocity

In Bender element test, Gao et al. [26] concluded the factors affecting the attenuation of wave. The absorbing attenuation is related to damping characteristics of soil which in turn dependent on soil type, stress stage and water content as shown in Figure 17.

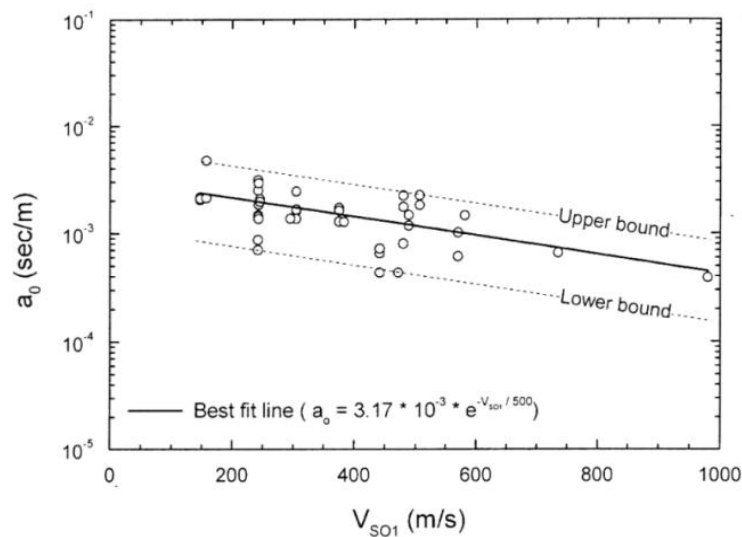


Figure 17: Frequency-independent attenuation coefficient, a_0 , as a function of low-amplitude Shear wave velocity of soil (Source: Soil Dynamic and Earthquake Engineering 19 (2000) 277-288))

It has been observed that attenuation decreases with increase in confining pressure in Bender element test. Higher length to thickness ration also reduces wave attenuation. The attenuation of waves may be minimized by adopting suitable excitation frequency or efficient testing system.

3.3.6 Effect of Density ratio on Wave attenuation

Zhifei Shi [27] observed that relation between density of soil and higher filling part should be in parallel to get a comparatively wider attenuation zone in the region of low-frequency. Dry density of the soil sample when increased, the frequency of the attenuation zone can get reduced. It was concluded that an appropriate porosity of soil is advantageous for attenuation of waves. Density ratio is defined by finding the ratio of barrier density to that of the soil sample. Hossein observed while study on effect of density ratio on performance of screening with various normalized cross section area that by keeping all parameters constant, if density ration increases, it will increase the efficiency of barrier for screening as shown in Figure 18 [28].

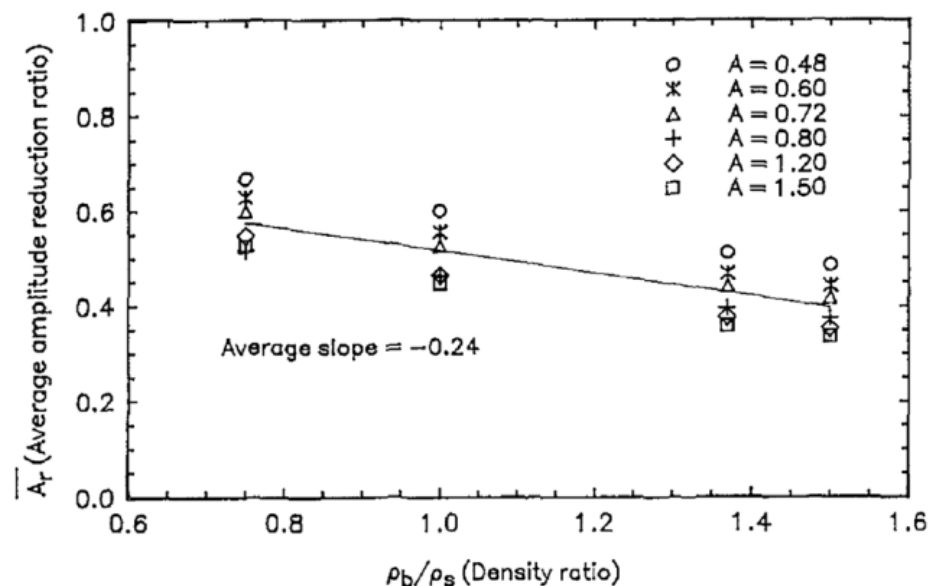


Figure 18: Effect of density ratio of material used for filling and soil (Source: Arab J Geosci (2017) 10:513, <http://doi.org/10.1007/s12517-017-3279-3>)



3.4 CHARACTERIZATION OF SAW DUST, RICE HUSK & CRUMBED TYRE RUBBER USED AS IN-FILLED MATERIALS

The detailed Characterization of three waste materials has been done to focus on its geotechnical properties while using for in-filled materials in trench barriers for vibration isolation. The various properties to be considered for characterization of these three in-filled materials are as follows:

1. Particle size analysis
2. Specific Gravity
3. Bulk Density
4. Relative Density
5. Permeability
6. Young's modulus

Dynamic Properties:

1. Shear Modulus
2. Damping Ratio
3. Stiffness
4. Shear wave velocity
5. Density ratio

3.4.1. PARTICLE SIZE DISTRIBUTION: (As per IS: 2720-Part 4-1985)

Particle size is the significant property used for finding suitability as in-filled materials in trench barriers for vibration isolation. This test is carried out to find distribution of particle sizes of soil in a given sample in order to classify the soil with respect to size of particles [32]. The grain size analysis is performed to find out the % age of size of each grain contained in the given soil sample as shown in Figure 19 and the test results obtained is used to draw particle size distribution curve. This is used to classify the soil and to predict its behavior. The sieve analysis was done as per IS:2720 Part-4 (1985) and the sieves used were in the order to 4.75 mm, 2.36 mm, 1.18 mm, 600 μ , 300 μ , 150 μ and 75 μ .



Figure 19: Pouring the soil sample on sieves and vibrating on sieve shaker

The % age of soil retained on each size of sieve has been obtained taking the basis of the total mass of in-filled material used and from the results of the % age sample passing each of the sieves has been obtained and tabulated in Table 1 below:

$$\% \text{age of sample passing through sieve} = \frac{\text{Weight of sample retained on IS sieve in g}}{\text{Total Wight in g}} \times 100$$

Based in these data, D_{10} , D_{30} and D_{60} has been derived then the value of C_u & C_c has calculated

For Saw Dust: $D_{10} = 0.17$, $D_{30} = 0.35$, $D_{60} = 0.55$, $C_u = 3.23$ & $C_c = 1.31$

For Rice Husk: $D_{10} = 0.15$, $D_{30} = 0.35$, $D_{60} = 0.55$, $C_u = 3.66$ & $C_c = 1.48$

For Crumbed Tyre Rubber: $D_{10} = 0.47$, $D_{30} = 0.95$, $D_{60} = 1.80$, $C_u = 3.82$ & $C_c = 1.06$



Table 1: Sieve Analysis Data sheet for (a) Saw Dust (b) Rice Husk and (c) Crumbed Tyre Rubber

Sieve Number	Sieve Size (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Cumulative % age retained	% Finer
#1	4.750	1022.50	1032.00	9.50	2.35	2.35	97.65
#2	2.360	875.15	883.15	8.00	1.98	4.32	93.33
#3	1.180	441.95	466.90	24.95	6.16	10.48	89.52
#4	0.600	824.30	918.95	94.65	23.37	33.85	66.15
#5	0.425	314.50	411.80	97.30	24.02	57.88	42.12
#6	0.300	756.95	830.75	73.80	18.22	76.10	23.90
#7	0.150	370.55	428.65	58.10	14.35	90.44	9.56
#8	0.075	303.90	325.85	21.95	5.42	95.86	4.14
Pan		958.95	963.25	4.30	-	-	-

Sieve Number	Sieve Size (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Cumulative % age retained	% Finer
#1	4.750	1022.50	1023.45	0.95	0.20	0.20	99.80
#2	2.360	875.15	877.35	2.20	0.47	0.68	99.32
#3	1.180	441.95	566.95	125.00	26.88	27.56	72.44
#4	0.600	824.30	1012.90	188.60	40.56	68.12	31.88
#5	0.425	314.50	377.40	62.90	13.53	81.65	18.35
#6	0.300	756.95	790.95	34.00	7.31	88.96	11.04
#7	0.150	370.55	402.30	31.75	6.83	95.78	4.22
#8	0.075	303.90	316.55	12.65	2.72	98.51	1.49
Pan		958.95	964.65	5.70	-	-	-
			TOTAL:	463.75	98.5		

(a)

Sieve Number	Sieve Size (mm)	Mass of Sieve (g)	Mass of Sieve & Soil (g)	Soil Retained (g)	Soil Retained (%)	Cumulative % age retained	% Finer
#1	4.750	1022.50	1097.25	74.75	15.25	15.25	84.75
#2	2.360	875.15	933.95	58.80	12.00	27.25	72.75
#3	1.180	441.95	612.09	170.14	34.72	61.96	38.04
#4	0.600	824.30	912.00	87.70	17.89	79.86	20.14
#5	0.425	314.50	378.55	64.05	13.07	92.93	7.07
#6	0.300	756.95	770.25	13.30	2.71	95.64	4.36
#7	0.150	370.55	374.85	4.30	0.88	96.52	3.48
#8	0.075	303.90	315.90	12.00	2.45	98.97	1.03
Pan		958.95	962.95	4.00	-	-	-
			TOTAL:	489.04	99.0		

(b)

(c)

Based on the values of particle sizes and coefficients, it has been found that all the sample of in-filled materials belonged to poorly graded soil. The data sheets of Sieve analysis for Saw Dust, Rice Husk and

Crumbed Tyre Rubber are illustrated in Table 1. Figure 20 shows the particle distribution curve based on the available data sheet of Sieve Analysis.

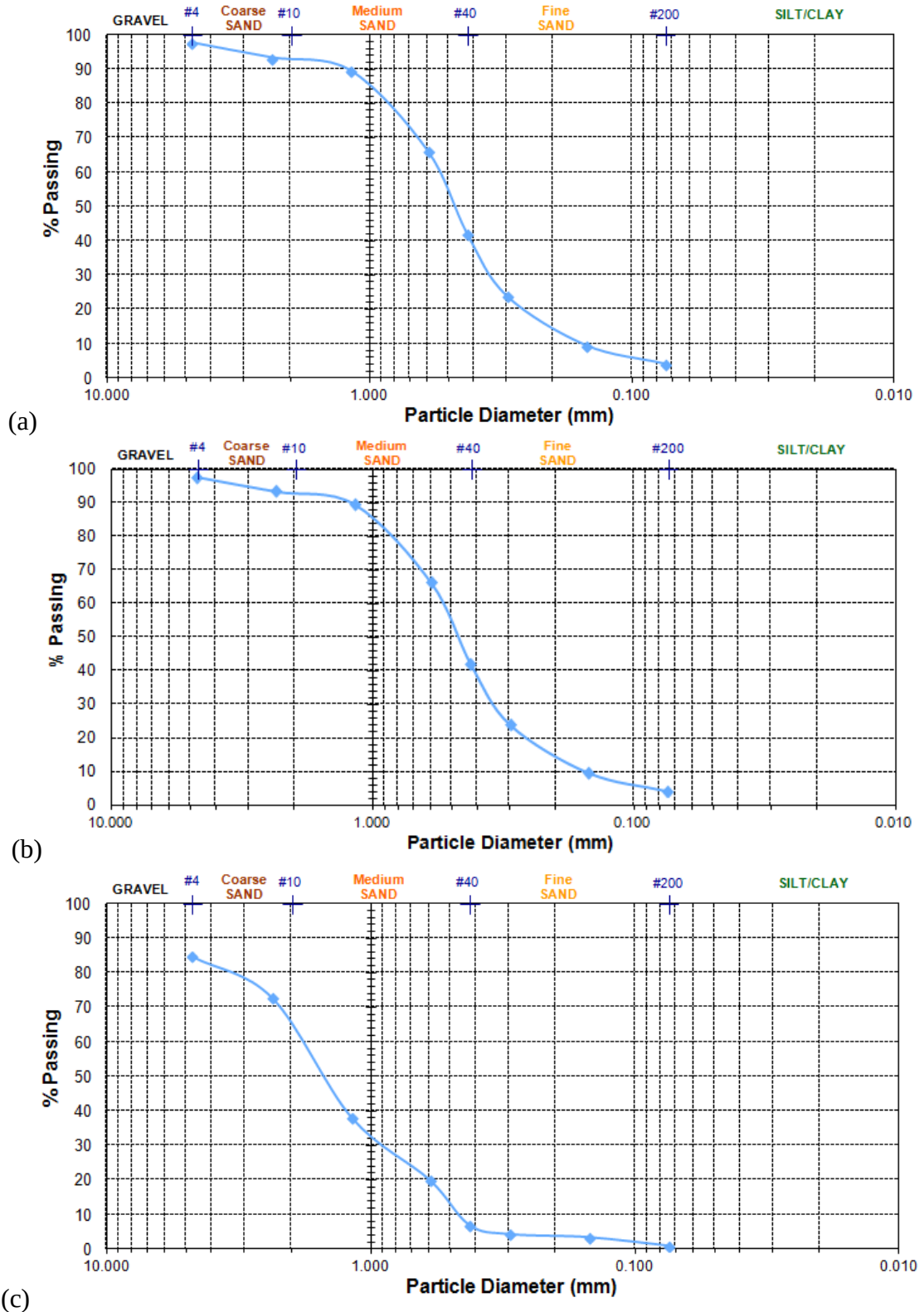


Figure 20: Particle size distribution curve for (a) Saw Dust (b) Rice Husk and (c) Crumbed Tyre Rubber

3.4.2. SPECIFIC GRAVITY: (As per IS: 2720-Part 3-1980)

The specific gravity (G_s) of any soil sample is defined as the ratio of mass of a unit volume of soil solids at a temperature (specific) to that of the mass of an equal volume of distilled water at the same temperature. The temperature specified for obtaining specific gravity of sample of soil is 20°C. The specific gravity obtained is helpful in calculation of the phase relationships of soil in terms of void ratio and degree of saturation. The specific gravity of soil has been found out as shown in Figure 21 and the density of the soil solids is calculated. The calculated values are tabulated in Table 2 below.

$$G = (m_2 - m_1) / ((m_4 - m_1) - (m_3 - m_2))$$

where,

m_1 = mass of density bottle in gram

m_2 = mass of bottle and dry sample in gram

m_3 = mass of bottle, soil and water in gram, and

m_4 = mass of bottle when full of water only in gram



Figure 21: Testing for Specific Gravity of the in-filled materials

Table 2: Value of Specific Gravity of in-filled materials

In-filled Material	Specific Gravity			
	S-1	S-2	S-3	Avg. Specific Gravity (G)
Saw Dust	0.65	0.65	0.66	0.65
Rice Husk	0.72	0.74	0.75	0.74
Crumbed Tyre Rubber	0.73	0.72	0.72	0.73



3.4.3. BULK DENSITY: (As per IS: 2720-Part 29-1975)

The bulk density may be defined as the ratio of weight of soil sample per unit volume in gram/cubic centimeter has been calculated from the formula and is tabulated in Table 3 as below [10]:

$$\gamma_b (\text{g/cm}^3) = (W_s - W_c) / V_c \quad \gamma_d (\text{g/cm}^3) = 100 \gamma_b / (100 + w)$$

W_s = Weight of sample and core cutter in gram

W_c = Weight of core cutter in gram

V_c = Volume of core cutter in cm^3 , and

w = Water content

γ_d = Bulk density (dry)

Table 3: Bulk density for the in-filled materials

In-filled Material	Bulk Density (g/cm^3)				Dry Density (γ_d) (g/cm^3)
	B-1	B-2	B-3	Avg. Bulk Density (γ)	
Saw Dust	0.26	0.24	0.24	0.24	0.23
Rice Husk	0.27	0.39	0.36	0.34	0.33
Crumbed Tyre Rubber	0.40	0.39	0.40	0.39	0.37

3.4.4. RELATIVE DENSITY: (As per IS: 2720-Part 14-1983)

Relative density or density index may be defined as the ratio of the difference between the void ratio of cohesionless soil in its loosest state and in natural state to the difference of void ratio in the loosest and densest states. Porosity of soil is affected by shape of grain, uniformity of grain size and condition of sedimentation. Porosity itself cannot indicate whether the soil is in a loose state or in denser state. This observation can only be obtained by comparing the porosity or void ratio of the given sample with that of the same sample in its loosest and densest possible state. Hence the term, relative density has been introduced. Relative density is an unpredictable feature of sandy deposits. Actually, relative density presents the ratio of actual decrease in volume of voids in a sandy soil to the maximum possible decrease in the volume of voids, which represents how further the sand under investigation are capable of densification



beyond its natural state. Relative density determination is helpful in compaction of cohesionless soils and in finding safe bearing capacity in the case of sandy soils. For very dense gravel sand, it is possible to obtain relative density more than one. The relative density of samples has been calculated by using the formula and tabulated in Table 4 as below:

$$I_d = (e_{\max} - e) / (e_{\max} - e_{\min})$$

$e_{\max}$ = void ratio of cohesionless soil in its loosest state

$e_{\min}$ = void ratio of cohesionless soil in its densest state

e = void ratio of cohesionless soil in its natural existing state in the field.

Table 4: Relative density for the in-filled materials

In-filled Material	Relative Density (%age)			
	R-1	R-2	R-3	Avg. Relative Density (I_d)
Saw Dust	40.99	40.13	40.20	40.44
Rice Husk	19.27	18.66	19.71	19.21
Crumbed Tyre Rubber	36.37	35.90	35.97	36.08

3.4.5. PERMEABILITY TEST: (As per IS: 2720-Part 17-1986)

Soil permeability also termed as hydraulic conductivity in soil. It is the rate at which water flows through voids in soil materials. It is an important characteristic of soil in the domain of engineering and earth-sciences. The coefficient of permeability (k) is a constant of proportionality expressing the ease with which fluid flows through a porous medium. In this test, falling head test method was adopted. Information related to the permeability of soil is necessary to calculate the amount of flow through earthen dams, from waste storage facilities (landfills, ponds, etc.) and the settlement in case of clayey soil deposits. Geotechnical engineers, hydro-geologists and soil & environmental scientists use this type of information related to projects such as structural foundations, embankments, earthen dams, flood management and more.



Figure 22: Permeability Test for in-filled materials

Under falling head permeability test as shown in Figure 22, the permeability of the sample at temperature can be given by:

$$kT = ((2.30aL) / (At)\text{Log}_{10} (h_1/h_2))$$

Based on the calculations, the values of permeability for in-fill materials are tabulated in Table 5 as below:

Table 5: Permeability values for the in-filled materials

In-filled Material	Permeability (cm/sec)			
	P-1	P-2	P-3	Avg. permeability kT
Saw Dust	0.017	0.017	0.016	0.016
Rice Husk	0.010	0.010	0.012	0.010
Crumbed Tyre Rubber	0.031	0.032	0.032	0.031

3.4.5.1 Dynamic properties such as Damping ratio, Shear modulus, Resilient modulus and Stiffness: As per ASTM D5311-13 & ASTM D3999-11

Dynamic Tri-axial testing is carried out on soil when it is required to evaluate the strength and deformation characteristics under cyclic loading conditions. These dynamic loading conditions may include dynamic loading effects arising due to earthquakes, moving of high-speed vehicles and trains with high speed, movement of sea waves, high speed wind, operation of vibration machines etc. There are variations in

outcome of dynamic Tri-axial tests and thus selecting the test should be the one that is accurately simulating the nearest conditions at site. Cyclic loading is applied to the soil specimen by using the mechanical or hydraulic actuator component of the testing system. The amount of cyclic loading to be applied is decided by various factors, such as the establishment of effective stresses after the isotropic consolidation (the difference between the cell and Back Pressure), the type of soil, state of the soil (density, moisture etc.) and the characteristics of loading (frequency, waveform type). Based on the general rule, the cyclic loading is usually kept double the isotropic effective stress, multiplied by a factor (i.e. Stress Factor). The range of stress Factors usually is between 0 and 1. Its effect on number of cycles that a soil can withstand has a significant role. In cohesionless soils, the applied negative axial stress during the cyclic loading must not exceed the effective stress which has been applied during process of consolidation, otherwise it may detach the top platen from the top surface of the specimen.

3.4.6. Brief of the Cyclic Tri-axial Test System:

The Heico make Cyclic Tri-axial Test system as shown in Figure 3.9 and schematic as shown in Figure 24, has been used to determine the dynamic properties i.e. Damping Ratio, Shear Modulus. The test system is a highly advanced combination of hydraulic and pneumatic technology where σ_1 is applied by hydraulic system in dynamic tests and σ_2 & σ_3 are applied by pneumatic system. It is completely based on closed loop principle. The confining and back pressure is also controlled through computer and is operated on close loop control mechanism. Figure 23 & Figure 24 shows the detail and layout of testing equipment [38]. The applied loads were measured using a load cell. The axial deformation was measured using two Linearly Variable Differential Transducers (LVDTs). The confining pressure has been achieved through pressurized air which was measured by a pressure sensor attached to one of the outlets. The sample prepared was placed on a plate base attached with the load cell. The sample was then sealed with rubber circular rings and clamped to make application of confining pressure.

The various test configurations applied for testing is as follows:

The unsaturated samples were prepared by using a mould in form of cylinder of 50mm diameter and 100mm height in a membrane. Then compaction of the samples has been done in four to five layers, with 9 blows each layer in order to achieve uniform density. The sample was then placed on the base plate then attached with the vertical dynamic ram for application of axial load. Water is filled in the cell for developing confining pressure. Dynamic axial load was then applied to get the required responses as shown in Figure 25 in form of various characteristics due to deformation behaviour. The results are tabulated in Table 6 as below:



1. Cyclic Tri-axial frame 2. Load Cell 3. LVDT 4. Tri-axial cell 5. Sample of in-filled material 6. Volume changing device 7. Pore pressure control 8. Cell pressure control 9. Vacuum control 10. Power pack

Figure 23: Pictorial view of Tri-Axial Cyclic Load Test System for characterization

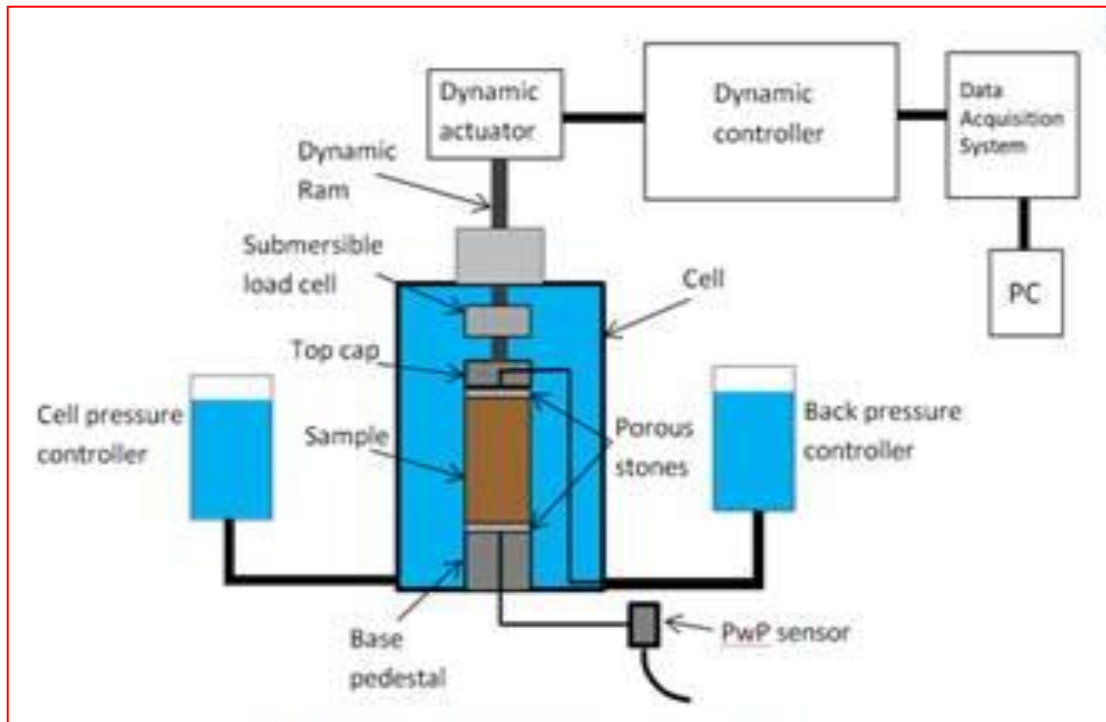


Figure 24: Schematic of Tri-Axial Cyclic Load Test System

3.4.6.1 Test Configuration:

Test configuration and Sample Description:

Length (cm)	= 10.00
Diameter (cm)	= 05.00
Area (sq.cm)	=19.63
Volume (cc)	=196.34
No of cycles	= 100
Frequency	= 1 (1 Active cycle & 9 Dead cycles)
Confining Pressure	= 0.50 KPa
Pore Pressure (kN/m ²)	=-1.96
Mass (g)	= 65g (Saw Dust), 95g Rice Husk) and 95 g (Crumbed Tyre Rubber)
Sp. Gravity	= 0.65 (Saw Dust), 0.74 (Rice Husk) and 0.72 (Crumbed Tyre Rubber)
Dry Density (g/cc)	= 0.24 (Saw Dust), 0.34 (Rice Husk) and 0.41 (Crumbed Tyre Rubber)
Void Ratio	= 0.96 (Saw Dust), 0.34 Rice Husk) and 0.51 (Crumbed Tyre Rubber)
Porosity (%)	= 49.07 (Saw Dust), 33.72 Rice Husk) and 33.23 (Crumbed Tyre Rubber)

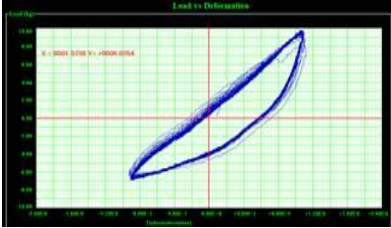
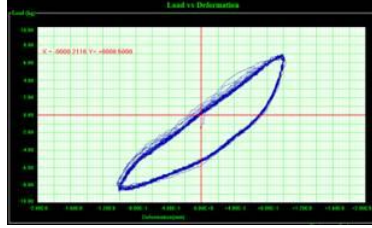
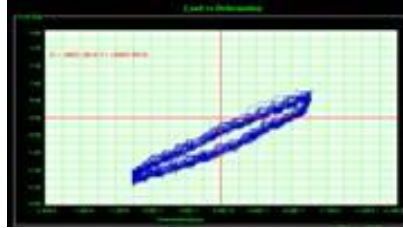
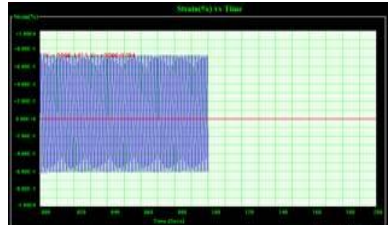
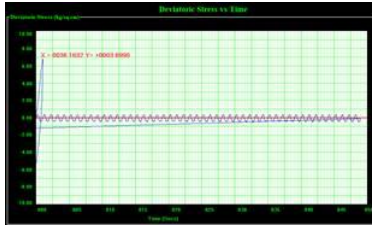
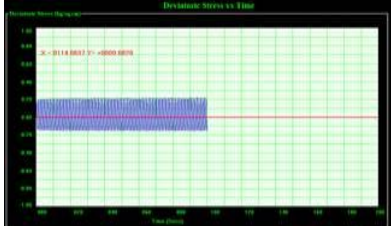
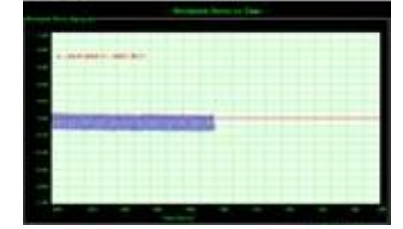
S. N.	Characteristics	Saw Dust	Rice Husk	Crumbed Tyre Rubber
1.	Load vs Deformation			
2.	Strain (%) vs Time			
3.	Deviator Stress vs Time			

Figure 25: Graphs of parameters in obtaining dynamic properties of the in-filled materials

Table 6: Results of dynamic characterization for the in-filled materials

Dynamic Properties	In-filled materials		
	Saw Dust	Rice Husk	Crumbed Tyre Rubber
Damping Ratio (%)	12.39	20.03	22.32
Shear Modulus (kN/m ²)	1237.00	1214.00	322.00
Young's Modulus (kN/m ²)	3712.00	3645.00	980.00

3.5 RESULTS AND DISCUSSION:

Based on the available data after laboratory tests for geotechnical characterization of in-filled materials, the results are discussed and analyzed, the following inferences have been arrived off:

- The in-filled materials i.e. sawdust, rice husk and crumbed rubber are of sand sized and they are non-plastic in nature.
- Dry density of saw dust is low as compared to the rice husk and crumbed rubber.
- Shear modulus of crumbed rubber is quite lower than that of rice husk and saw dust.
- In case of Saw Dust, the values of particle sizes and coefficients are as; $D_{10} = 0.17$, $D_{30} = 0.35$, $D_{60} = 0.55$, $C_u = 3.23$ & $C_c = 1.31$ whereas the values in case of Rice Husk are; $D_{10} = 0.15$, $D_{30} = 0.35$, $D_{60} = 0.55$, $C_u = 3.66$ & $C_c = 1.48$ and also for Crumbed Tyre Rubber, the values are; $D_{10} = 0.47$, $D_{30} = 0.95$, $D_{60} = 1.80$, $C_u = 3.82$ & $C_c = 1.06$. Based on above, the samples belong to poorly graded soil with more %age of finer particles. Three samples of in-filled materials are also non-plastic in nature.
- The value of C_u & C_c for rice husk, saw dust and crumbed tyre rubber is from 1 to 3 but the value of C_u for each material is not more than 6. Therefore, all the materials are classified as SP-poorly graded soil.
- The in-filled materials as Saw Dust, Rice Husk and Crumbed Tyre rubber are also non-plastic in nature



- The specific gravity in case of in-filled materials is found to be as low as to in-situ soils when compared. The difference may be due to variance in composition of minerals.
- The Bulk Density of three materials used in the trench is low.
- For relative density, all the three materials have different range of density. The density range of Saw Dust and Crumbed Tyre Rubber found to be in range of 35%-40% whereas for Rice Husk, it is found to be nearly 20%.
- The permeability coefficient of three in-filled materials was found good. Out of three, the Crumbed Tyre Rubber has the maximum permeability.
- All the three in-filled materials were having Young's modulus in the range of 3628-3922 kN/m².
- The values of Shear modulus for all the materials are in the range of 322-1235 kN/m².
- One of the significant dynamic properties of in-filled materials i.e. damping ratio, which has found to be in range of 12 to 23.50%.

Moreover, this study suggested that all the in-filled materials used in this experimental study are suitable for utilization as filling material for trench barriers for vibration screening.

3.6 CONCLUSION:

This section impetus on various investigations required for characterization of the in-filled materials which was used in filling of trench barriers for vibration isolation. The screening performance of the in-filled materials is inherently dependent on its geotechnical properties. It includes general properties to the dynamic properties of the samples. Damping ratio and the Stiffness are significant properties to be taken in consideration. The properties characterized and the performance in screening also helped in determining the suitability and deciding the range of values of properties. With respect of the existing properties of the materials, it also helps in deciding whether efficient or not for the purpose of vibration isolation. It has also supported in preparing the guidelines for selection of in-filled materials for the concerned purpose. The



samples collected for characterization are heterogeneous and feathery in nature. With relation to the experimental study carried out for determining the screening performance of in-filled materials and based on available data of characterization, the efficiency of the in-filled materials has found suitable for using as in-filled material.



CHAPTER-4

Experimental Study



4.1 INTRODUCTION

Vibrations caused by factors other than seismic sources such as high-speed rail, highway traffic, construction activities, vibrating machine footing, blasting, underground explosion, etc., are not healthy and safe aspect in human life. Vibrations generated from these sources may cause discomfort to occupants, settlement of foundation in a structure, heave, structural and non-structural damages in nearby structures, etc. Sources of vibration could be contained within the soil medium e.g. pile driving or machine foundation on ground surface. Vibration screeners are used to mitigate these vibration effects by means of providing empty or in-filled trench wave barriers. This paper deals with the experimental study on screening of steady-state surface vibrations and evaluation the performance of trench wave barriers in an elastic, isotropic, and homogeneous half-space by using in-filled materials in these trench barriers such as crumbed tyre rubber, rice husk and saw dust. The important properties of in-filled materials were also found out through characterization. The present experimental workout is first of its type with respect to material properties, damping value and boundary conditions to obtain the output as the actual field test results. Influence of geometric dimensions of trench wave barriers, shear wave velocity and source to barrier distances have been studied by parametric study for investigating the performance of in-filled materials on diminution of amplitude/displacements/velocity in surficial soil layers. This study considered a non-dimensional approach where the geometric parameters are normalized in terms of wavelength of Rayleigh waves of vibration in half-space. Trench wave barriers with shear wave velocity ratio less than unity are considered significantly effective. Effects of the parameters participating in vibration screening are elaborately discussed.

Amplitude reduction in wave propagation is the solution to reduce the effect of vibration caused by factors such as due to high-speed rail and highway traffic, construction activities, machine operations, blasting, underground explosion, etc. The methods employed for amplitude reduction in wave propagation may be accomplished either by:



- a) Adjusting the frequency contents of the source of excitation,
- b) Changing the location and direction of the vibratory source,
- c) Modifying the wave dissipation characteristics of the soil deposit, or
- d) Partially interrupting the spreading path of waves into the structure

It is also possible to modify the dynamic transmitting behavior of local sub-soil through a complex mechanism of wave reflection and mode alteration around the vibration source by constructing a suitable wave barrier in the path of the propagating waves between the dynamic load and the affected structures to be protected. When the wave barrier is located nearby the vibratory source, such application is known as active (near field) isolation. If the barrier is situated away from the source but around the structure to be protected from incoming waves, such far field isolation is known as passive isolation. Thus, the screening of vibration can suitably be done by either by Active or Passive isolation

4.1.1 Review of research

Full scale experimental investigation on vibration scattering for determining the efficiency of trench wave barriers was carried out by Ashref Alzawi, M. Hesahm EI Naggar [39] using open and in-filled (Geofoam) barriers in order to provide few recommendations and design guidelines for their implementation in design. The experimental study was carried out on a selected number and type of trenches. Field experimental study has been conducted to investigate the efficiency of Geofoam material. Experimental results confirmed that in-filled geofoam trench barriers can effectively reduce the transmitted vibration. Arnab Sur, Dr. Bappaditya Manna and Shiva Shankar Choudhary studied the vibration problem of underground moving train [40]. The study includes the calculation for generated dynamic loads from moving train, propagation of the wave through the tunnel lining and soil medium. From this study, it was noticed that the free field ground vibration depends on parameters such as distance from tunnel, train speed, soil stiffness and depth of tunnel below ground. Ground vibration is inversely proportional to distance from tunnel, soil stiffness and tunnel depth,



while is directly proportional to train speed. The tunnels in soil having SPT value > 40 generally do not exhibit significant vibration. Vibration can be reduced by increasing tunnel depth or by reducing train speed in affected section. Ashwani Jain, D. K. Soni [41] presented an overview of vibration isolation techniques that has been carried out in case of machine foundation. Most of the available methods for active isolation, i.e. isolation at the source and passive isolation i.e. isolation at the receiver have been discussed like inner balancing in machine, isolation by remote location, stabilization of soils, screening of disturbances, etc. Javier Aviles and Francisco J. Sanchez-Sesma [42] studied the wave barrier problems for underground explosions. It includes theoretically study about the foundation isolation from vibrations using solid piles as wave barriers. It was proposed two models, one with piles of infinite length and second pile with finite length with different waves. In this study, effect of pile diameter, separation and length were considered, and conclusion has been made relevant to guidelines for design. Deniz Ulgen and Onur Toygar [43] performance of open trench was examined with special emphasis on active and passive vibration isolation control systems. The field results show that open trench wave barriers can be used as an alternative vibration control system in order to achieve reasonable efficiency. The vibration amplitudes generated by impact loading achieve an average reduction of 50% for a trench depth of 4.5m. Active isolation has better efficiency than passive isolation. G. L. Sivakumar Babu et. al. [44] carried out field vibration tests at a proposed site for the vibration testing room. Ankurjyoti Saikia [45] studied the response of rectangular in-filled trenches in elastic, isotropic and homogeneous space. Softer barriers are considered in this study. Influence of shear wave velocity ratio on degree of isolation has been shown. The effect of barrier location on its screening effectiveness depends on the barrier depth and width and also on component of vibration. Barkan et. al. [46] reported on an attempt to isolate a building from traffic induced vibration using open and sheet-wall barriers and was unsuccessful. Moreover, he reported on several other cases where no positive results were achieved by the use of screening installations such as a trench filled with cinders and sheet-

piling. However, he was first to recognize that the effectiveness of the barrier does not depend so much on its physical dimensions, but rather on the normalized dimensions with respect to the wavelength of incident wave. Seyhan Firat, et. al. [47] presented a detailed investigation on the reduction of foundation vibration due to harmonic load which is produced by electrodynamic shaker using a trench barrier. Effectiveness of using open or in-filled trench as a reduction measure has been demonstrated. The use of an open trench is more effective than an in-filled trench but its practical application is limited to very shallow depth which is not suitable for stability of ground. The study aimed to provide few guidelines for the design of vibration isolation measures by means of trenches. K. R. Massarsch [48] discussed generation and propagation of man-made vibrations in the ground. Emphasis was placed on a simplified approach which is used to assess the most important factors, such as wave attenuation, refraction focusing and vibration amplification as a result of resonance. Practical guidelines are presented which can be used to predict vibrations and settlements in the ground. A semi-empirical relationship for the assessment of permissible vibration levels for buildings is proposed. Finally, a new ground vibration isolation method, the gas cushion screen is presented.

4.2. IN-FILLED MATERIALS FOR TRENCH WAVE BARRIERS

Based on the factors such as suitability for purpose, availability of materials, sustainability, waste nature, economy, handling, etc., following three types of material were selected under this research study. The materials selected as in-filled materials are shown in Figure 26:

- (iv) Crumbed Tyre Rubber (CR)
- (v) Rice Husk (RH)
- (vi) Saw Dust (SD)

4.2.1 Crumbed Tyre Rubber (CR)

Crumb tyre rubber is a form of recycled rubber of fibrous in shape and black in colour which is produced after scrapping the automotive tyre. In the recycling process, its components such as steel wires and tyre cord (fluff) are separated, leaving tyre rubber part with a granular consistency. Further, in a granulator, with the help of cryogenics or by mechanical means, the size of particles is further reduced. The particles are then separated as per size of grains and grouped on the basic criteria including colour. The crumbed tyre rubber used in this research study has been collected from recycle tyre factory located at Mayapuri, New Delhi. The factory produces three different grades of crumb tyre rubber graded as 40, 20 and 16 and in this study, the grade of crumbed rubber is 20. As shown in Figure 27, the various stages in producing crumb tyre rubber, from the waste tyre when cut into chipped tyre by means of cutting machine and then undergo shredding. It is then sieved using sieve machine and rubber crumb and steel wire are separated. In this research, crumbed tyre rubber has been characterized by carrying out testing on the selected material [49]. It is important to note that though the waste rubber tyre is separated from its metallic wire component, even remnant of metallic element may present in crumb tyre rubber undergoing processes.



Figure 26: Three types of in-filled materials used in Trench wave barriers for Vibration screening

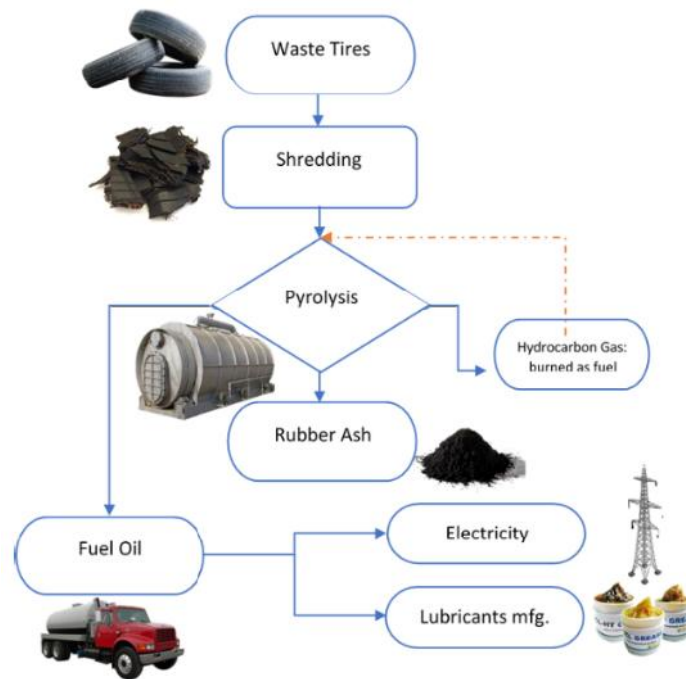


Figure 27: Layout of the process for formation of Crumbed Tyre Rubber from waste Tyre [49]

A fact that the tyre is one of the industrial wastes which makes researcher's interest to explore its utilization. The enhanced characteristic of rubber to dissipate and absorb energy the utility may be found in production of barriers.

4.2.2 Rice Husk (RH)

The rice husk is also known as rice hull, is flaky particles brown in colour, is the rice seed coating or grain coating. It is produced from hard materials, which includes silica and lignin which protects the seed in season of growing. In 1 Kg of milled white rice results in about 0.28 kg of rice husk obtained as a by-product in rice production during milling. Common by products produced from rice husk are: like solid fuel (in loose form or as briquettes and pellets), carbonized rice husk generated after burning, and the rice husk ash at the end after combustion. In its loosest form, Rice husk is mostly utilized for energy production. When the density of rice husk increased the product forms are rice husk briquettes and pellets which have higher combustion performance. These forms of densified rice husks are utilized in boilers which help in saving



fossil fuels. Produced during rice milling, the rice husk is already dried and accumulated at the factory. Since long, rice husk was treated as a waste after milling process and their disposal was a cumbersome task. Because the rice husk is collected easily and is not costly, rice husk has been in application as an energy source.

4.2.3 Saw Dust (SD)

Sawdust (or wood dust) is dark brown in colour and angular in shape [50], a waste obtained or by-product obtained after carrying out operations on wood i.e. routing, sawing, milling, sanding and planing. It consists of small sized chippings or even fine powder from wood. These operations generally performed by wood-working portable power tool machinery or hand tools. In some manufacturing industries, the saw dust can be a significant fire hazard and as a source of occupational dust exposure. The particulates are the chief component of particleboard. Dust and chips are the two waste products forms at the working area during wood working operations as stated above. Dust is created by shattering of wood cells, while degradation out of whole groups of wood cells generates chips. Finer dust particles will be formed as more cell-shattering occurs [51]. For example, sawing and milling are mixed cell shattering and chip forming processes, whereas sanding is almost exclusively cell shattering. Sawdust is a waste produced from various sawmills in the country. It is mostly disposed off in the open environment and thus become factor pollution [52]. Hence using sawdust as filling materials in trench barriers for vibration isolation can enhance the utilization of saw dust waste in the longer run and help in sustaining the environment to a little extent.

4.2.4 Geo-Technical Characterization of in-filled materials

In-filled materials play a significant role in performance of trench wave barriers for vibration screening. Using waste materials in trench wave barriers as in-filled materials is an eco-friendly and sustainable step in services and application of geotechnical engineering techniques. But how these materials have suitable application in engineering domain, safety and stability, is an important concern. To know its application and

comparison with other materials as in-filled materials in vibration isolation technique, it is required to ascertain its geotechnical properties. The geotechnical characterization of in-filled materials i.e. Crumbed tyre rubber, Rice husk and saw dust had been carried out in laboratory. In the series of laboratory tests, tests such as particle size distribution, specific gravity, bulk density, relative density and permeability has been carried out. Since trench wave barrier was exposed to dynamic loading, the dynamic properties of in-filled materials in addition to these properties are also important. With the help of Tri-Axial Cyclic load test apparatus, dynamic properties such as shear modulus, Young's Modulus, damping ratio, stiffness and shear strain had been conducted to ascertain down the suitability of these materials as in-filled materials which was used in trench wave barriers for vibration screening. The properties of the in-filled materials observed after characterization is summarized in Table 7 [53]:

Table 7: Properties of the in-filled materials used in trench barriers

S.N.	Property	Type of Materials			
		Rice Husk	Saw Dust	Crumbed tyre rubber	In-situ soil
1.	Specific gravity	0.740	0.650	0.730	2.650
2.	Field Density(kN/m ³)	3.857	2.976	4,215	15.230
3.	Bulk density (kN/m ³)	3.300	2.300	3.700	13.200
4.	Permeability (cm/sec)	0.010	0.016	0.031	0.006
5.	Relative Density (%age)	19.210	40.440	36.080	28.783
6.	Shear modulus (kN/m ²)	1214.00	1237.00	322.00	12140.00
7.	Damping Ratio (%)	20.030	12.390	22.320	7.259
8.	Poisson's ratio	0.210	0.257	0.430	0.300
9.	Young's Modulus (kN/m ²)	3645.00	3712.00	10500.00	33200.00



4.3. WORK METHODOLOGY

In wave barrier isolation study, realistic cases are often investigated. The work consists of several stages of work presented herewith. In this chapter, as an experimental study, electromechanical oscillator called as source of vibration (SOV) has been used to produce vertical harmonic vibrations in the frequency range of 10 to 50Hz and geophones are used to obtain responses at specified observation points. Two footings are constructed with clear distance where Rayleigh wave becomes dominant. The first footing is used to produce the harmonic load by means of oscillator and the other for geophones record and vice versa. A number of cases during experimental investigations are carried out in field in order to examine the performance of in-filled materials by obtaining screening efficiency of in-filled trench wave barriers, such as Crumbed tyre rubber, Rice husk and Saw dust (softer material than soil). The screening effectiveness of those barriers is determined from field measurements by comparing field data for cases with in-filled materials and responses received without trench barriers. Two different approaches are considered for vibration isolation, namely active and passive isolation. In active isolation, the source of vibration was kept nearer to the trench at a distance of 2.5 m, 5.0 m and 10 m from center of trench on one side of trench. In passive isolation, the source of vibration was kept at far distance of 23.75m from center of trench on the other side of the trench. Active isolation is preferred in cases where the space between source of vibration and structure is restricted such as in case of rail track and adjacent buildings. Passive isolation is preferred in those cases where space is not restricted but accessibility to that space is limited.

4.3.1 Test site selection and preparation

The test site is a flat area located in office premises of CSIR-Central Road Research Institute (CSIR-CRRI), New Delhi as shown in Figure 28. The soil was characterized as non-plastic silty soil by taking reference from previous works at the site and after conducting some of the tests at the site during the experimental study. Based on the data, the site soils are characterized as silty clays, clayey silt and sandy silt underlain by

stiff fine grained. This section includes the field experimental work that has been conducted to investigate the screening efficiency of empty trench as well as performance of in-filled materials by obtaining screening efficiency of in-filled trench wave barriers such as Crumbed tyre rubber, Rice husk and Saw dust. It also includes as well examining the influences of trench geometry and location of trench from the vibratory source on the isolation efficiency. Moreover, an experimental parametric study was conducted to investigate the influences of varying the ratio between the barrier depth and its location (i.e. to examine active and passive vibration isolation cases). The results of the field experimental investigations are analyzed and interpreted to provide recommendations for implementation in design. Furthermore, a finite element model was developed in order to simulate the field experimental work and comparison with field work. The developed finite element model has been calibrated using the field experimental results to demonstrate its utility in conducting an extensive parametric study to further our understanding of the behaviour of in-filled trench barriers in different filling conditions.



Figure 28: Drone view of Test site location at CSIR-CRRI, New Delhi



As per ASTM D8295, in order to investigate the shear wave velocity (V_R) of Rayleigh wave also called velocity of propagated wave or phase velocity, Bender Element Test has performed in in-situ soil. The small-strain shear modulus (G_{max}) of the soil has determined. G_{max} is an important soil property which helps us to understand the elastic behaviour of the soil and to evaluate its response to dynamic loading, such as earthquakes, passing vehicles and vibrations. Bender elements are used to examine the propagation of ground waves through a soil specimen and measure their velocity which depends on its elastic properties. The sine wave is causing the bender element to deform on the same way causing the soil particles to move as well. The movement of the particles is producing a shear wave (S) that propagates towards the other side of the specimen and arrives there after some time. When it arrives, the shear wave is causing the deformation of the receiving element (the one at the top cap) and this produces a corresponding electrical signal, many times smaller than the electrical signal than initiated the wave. Synchronizing by the oscilloscope and comparing the two electrical signals (initiated signal and correspondingly produced signal), the time of travel is obtained. Therefore, by knowing that the distance of travel is the tip-to-tip distance between the two elements, the speed of the shear wave, V_s , can be determined as $V_R = L/t$, where t is the time of travel and L is the distance that the wave travels. L can be taken as the distance between the tips of the two bender elements (transmitter and receiver). The average calculated value of shear wave velocity produced is $V_R = 198.65$ m/sec. The small-strain shear modulus, G_{max} , is then calculated by the equation $G_{max} = \rho V_s^2$ where ρ is the bulk density of the soil and the values comes at $G_{max} = 12.14$ MPa. The wave length of Rayleigh waves, L_R , can be calculated by the relation of propagating velocity V_R through the frequency of vibration, f , the equation $L_R = V_R / f$. The values of L_R will have different values at different running frequencies of lector-mechanical oscillator.

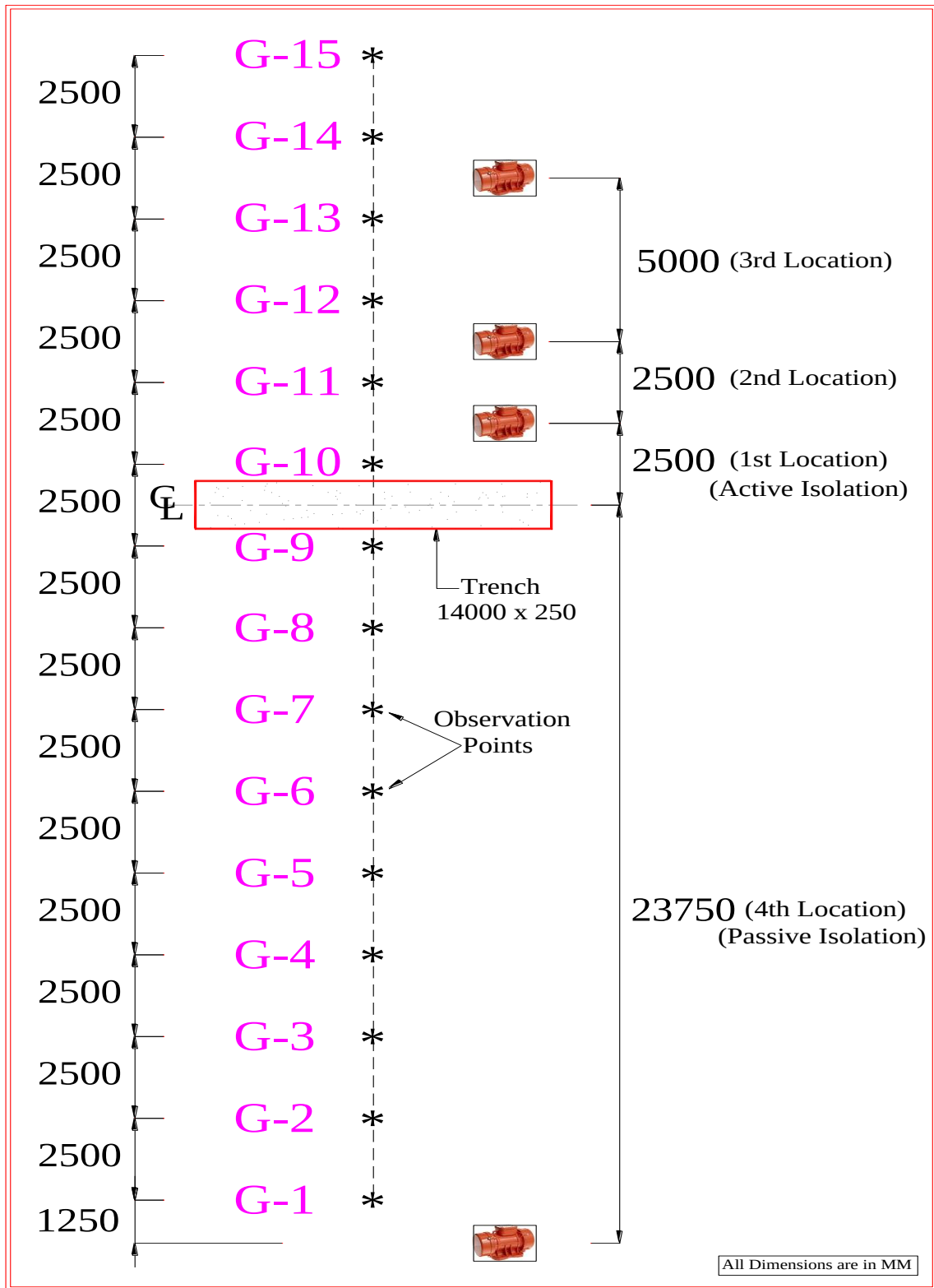


4.3.2 Field Test Procedure

A dynamic excitation comprising of a sinusoidal vertical harmonic load was induced by using an electro-mechanical oscillator (SOV). The excitation force was quadratic and characterized by harmonic forces proportional to the square of the driving frequency. This resulted in having surface waves with different wavelengths. The first stage of testing consisted of exciting the ground with loads at varying frequencies at 10, 20, 30, 40 and 50Hz and recording measurements of ground motion at specified positions as indicated in Figure-5 before digging the trench. An incremental digging technique by a depth of 0.40 m was adopted in digging the trench wall by using a JCB excavator with required width of blade i.e. 0.250 m in order to check and maintain the stability of trench as shown in Figure 29. Second stage of testing consisted of exciting the ground after constructing the trench (i.e. empty trench) and recording the measurements of ground motion for the same frequencies at the same selected locations in first stage. In third stage, the in-filled material as Crumbed tyre rubber, Rice husk and Saw dust was back-filled in the empty trench and compacted in stages up to optimum density. After the compaction process was complete, the harmonic excitation was applied and ground motion measurements were recorded for the same frequencies and at the same specified locations. To assess the system effectiveness, the recorded time history of vertical soil particles velocities at pickup points was converted to the frequency domain, analyzed and discussed in subsequent text.



Figure 29: Excavation of wave barrier trench at test site location with JCB excavator



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4.3.3 Instrumentation and Test setup description

This study investigates vibration scattering using empty and in-filled trench wave barriers with Crumbed tyre rubber, Rice husk and Saw dust as in-filled materials by conducting a parametric experimental study. Therefore, all test parameters and the results of testing is presented in dimensionless format. A trench wall of 14m length, 0.25m width and 2m depth were constructed. Since, the ratio of the trench wall width to its depth is very small, it is quite possible to dig such thin trenches using the classical techniques. The trench was dig by the incremental digging in the stages of 0.40m by using a JCB excavator. The stability was checked again and again and it was found that stability was maintained at the considered depth. Because the water table was well below the target depth and due to the nature of soil, stiff sandy silt to silty clay, the excavated trench can stay stable without collapse. That means the ground can be excited and measurements can be taken while the trench is open in order to compare the protective effectiveness of empty and in-filled trench barriers for the same soil profile and testing conditions.

The source of excitation was an electro-mechanical oscillator (SOV) consists of vibro-motor with RCC footing base, speed controller in form of Variable frequency drive (VFD) and associated with electrical connections. The vibro-motor comprises of a motor with eccentric masses at both the ends of rotating shaft. The eccentric masses in motor generate the harmonic excitation. The oscillator was driven by a 3.0HP 220V three phase motor capable of generating sinusoidal force of 23.50kN peak-to-peak as detailed in Annexure-1. The speed of the motor was controlled by an AC variable frequency speed drive, yielding stable operating speeds between 5 to 50Hz. The vibro-motor was installed on top of the RCC cuboidal block of dimension 0.50m x 0.50m x 0.70m. The fixtures for holding the vibro-motor on the block were pre-embedded in the concrete which was integrally welded to the rebar cage of the concrete block before casting. Design calculations for the concrete block footing has been carried out considering the generation of requisite force. The maximum operating speed of the oscillator is 3000rpm with no loads. To simulate the

machine foundation case and to keep the system acceleration during the excitation less than 1g, the vibro-motor was placed centrally on top of RCC concrete block footing as shown in Figure 31. Thus, the center of gravity (CG) of the electro-mechanical oscillator (where the dynamic force is applied) was above the geometric center of its base. The plates were bolted together using four threaded steel rods. To ensure good contact between the electro-mechanical oscillator and the ground, the concrete block footing was embedded about 0.30m in the ground with reference to ground surface. The portability of the oscillator was taken care by the tripod.



Figure 31: View of Electro-Mechanical oscillator, tripod and Variable Frequency Drive (VFD)

Five loading events with different frequencies were utilized in this experiment. The frequencies considered were 10, 20, 30, 40 and 50Hz. All the geometrical parameters of the experiment are normalized in terms of Rayleigh wavelength (L_R) which is a function of the excitation frequency. The resulting Rayleigh wavelength, the barrier dimensionless geometry and the distance between source of vibration and trench barrier were calculated and listed in Table 8 and are shown in Figure 32. Geophones (10Hz) were installed on the observation points over a line perpendicular to the centre of the wave trench barrier at an interval of 2.5m throughout. The experimental layout and geophones numbering are illustrated in Figure 30.

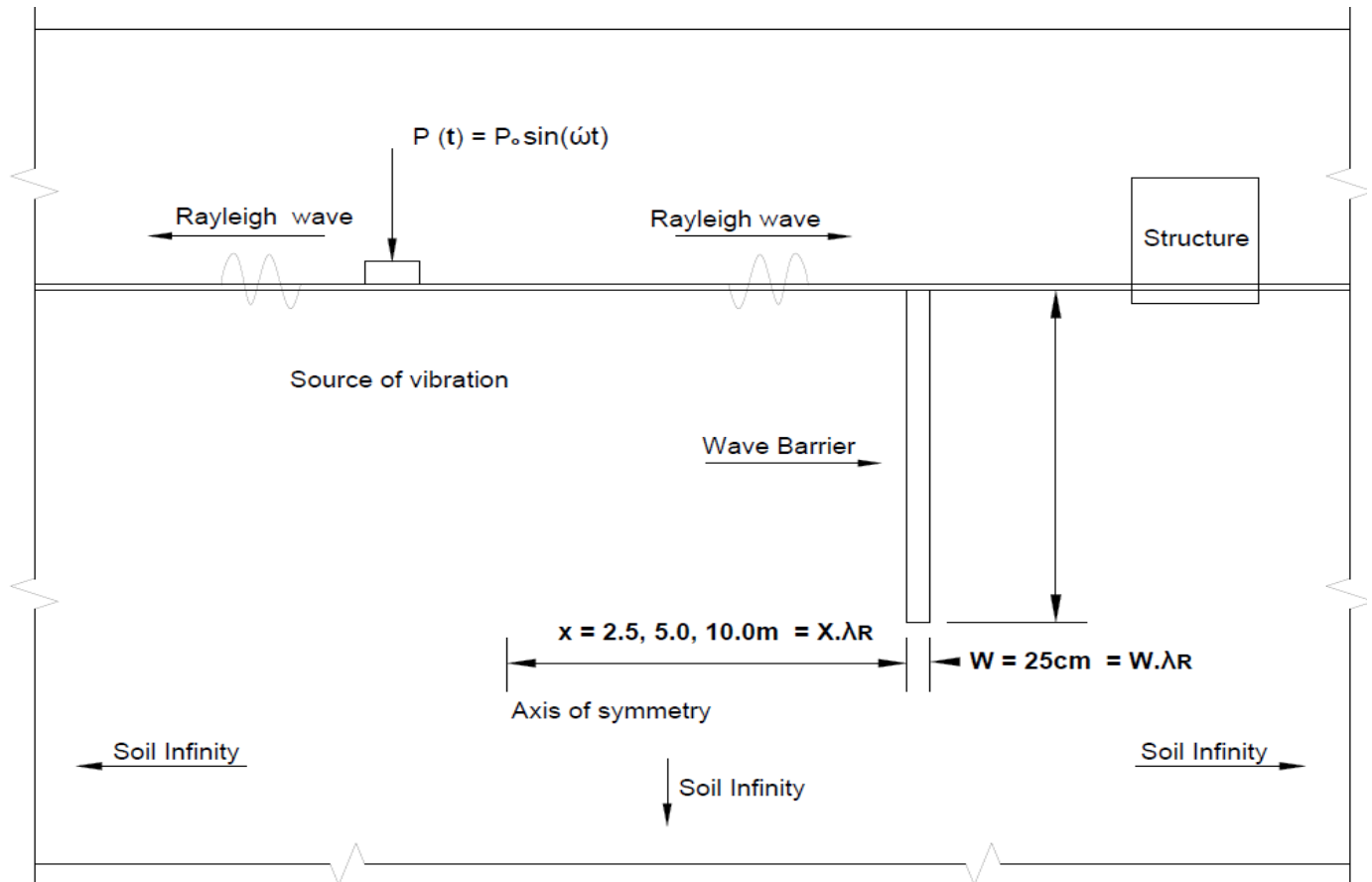


Figure 32: Schematic view of the vibration isolation system and geometrical parameters

The geophones were connected to a 32 channel OROS data acquisition system (DAQ). A laptop equipped with the DAQ was used to control the acquisition system through NV Gate software. For every selected frequency, tests after stabilizing the response to a duration of 5 to 10 seconds, measurements of soil particles amplitudes and velocities was recorded using vertical component geophones with a 1 millisecond sample interval which results in have 10000 data points. To study the influence of the proximity of the source of disturbance to the isolation system on its protective effectiveness, three locations were chosen to place the excitation system: 2.5, 5 and 10m from the centre of the trench wave barrier as shown in Figure 32.

**Table 8:** Dimensionless geometrical parameters of experiment:

Frequency of exciter (Hz)	Rayleigh wavelength (m)	Barrier dimensionless or Normalized depth	Dimensionless distance between vibration source and wave barrier		
			1 st location	2 nd location	3 rd location
	L_R, m	$D=d/L_R$	$X_1=x_1/L_R$	$X_2=x_2/L_R$	$X_3=x_3/L_R$
10	19.86	0.05	0.13	0.25	0.50
20	9.93	0.10	0.25	0.50	1.01
30	6.62	0.15	0.38	0.76	1.51
40	4.96	0.20	0.50	1.01	2.02
50	3.97	0.25	0.63	1.26	2.52

Measurements were taken at the five excitation frequencies for every location for the five conditions (without trench, empty trench, trench filled with material such as Crumbed tyre rubber, Rice husk and Saw dust) as shown in Figure 33 and Figure 34. Table 9 presents the experimental parameters, including geometrical dimensions of barrier, its distance from source of disturbance, and loading frequencies considered.

Table 9: Experimental parametric test:

Wave Trench Barrier width	w	0.25 m
Wave Trench Barrier depth	d	1m & 2.0 m
Distance between the Oscillator and the trench	x	2.5m, 5m, 10 m & 23.75m
Exciting frequency Values	f	10, 20, 30, 40 & 50Hz

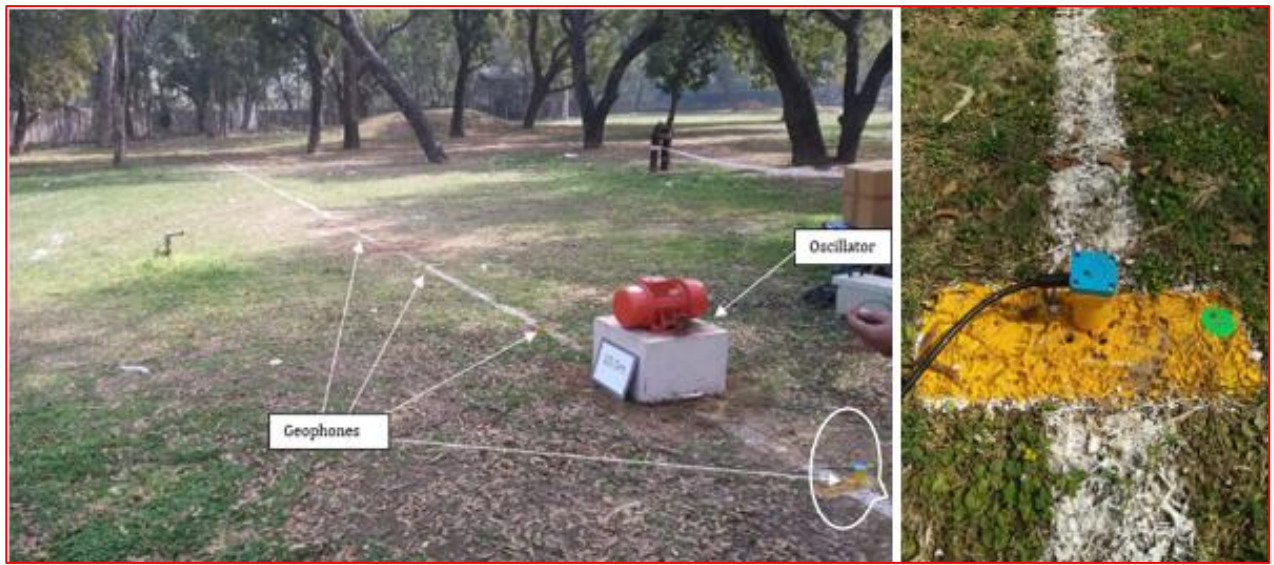


Figure 33: Instrumentation set up showing placement of Oscillator and installed geophones (inset)



(i) Crumbed tyre rubber

(ii) Rice husk

(iii) Saw dust

Figure 34: In-filled trenches with Crumbed tyre rubber, Rice husk and Saw dust

In addition to all the above cases, one more case of trench filled with sand as shown in Figure 35, has been tested to ascertain the performance aspect of presently carried out practices at some of the locations in Delhi. The results will also be discussed as an additional case along with the observation of the core experiment



Figure 35: Aerial view of In-filled trench wave barrier

4.3.5 Measurements for Vibration Isolation:

The evaluation of performance of in-filled materials in terms of screening effectiveness precisely depends on the trench barrier in-filled material stiffness. Hence, a series of experiments were necessary to understand the propagating characteristics of the waves. The test layout for both active and passive isolation cases is shown in Figure 36. The layout consists of an electro-mechanical oscillator mounted over RCC block footing, trench wave barrier and 15nos. of observation points on a centre line where Geophones was instrumented to acquire the response at these specific points. The electro-mechanical oscillator, which induces a sinusoidal motion, is used as a stationary vibration source to produce vertical harmonic force of maximum up to 23.50kN in a frequency range of practical importance of 10 to 50Hz. The excitation frequencies were increased progressively in $\Delta f = 10$ Hz incremental steps. The oscillator comprised of vibro-motor mounted on RCC block and placed centrally above the rigid rectangular footing such that centre of

gravity of vibro-motor and block lie on the same axis in order to excite only vertical vibrations. For this study, a rectangular trench with a 2m depth, 0.25m width and 14m length is excavated transversely to the center line. The installed source on footing is placed at a distance of $L_1 = 2.5\text{m}$, $L_2 = 5\text{m}$ & $L_3 = 10\text{m}$ from the centre line of the trench for the measurement of active isolation case and a distance of $L_4 = 23.75\text{ m}$ i.e. on the other side of the trench for measurement of performance in passive isolation. The vertical components of harmonic vibrations are recorded with those geophones located on the centre line, which corresponds to a time interval of $\Delta t = 0.0005\text{ sec}$. The displacement amplitudes and velocity at different observation points are directly obtained from the acquired data. The screening performance of the material stiffness of the trench compared to soil and the excitation frequency range are investigated by conducting a series of field tests of source and receiver isolation barrier, namely active and passive vibration screens. The active isolation cases have been investigated by varying the locations of oscillator as 2.5m, 5.0m and 10m from the centre line of the trench. The passive case has been studied by the keeping the oscillator at 23.75m from the centre line of the trench. The considered parameters are summarized in Table 9. The length of Rayleigh (L_R) wave of the generated vibration is one of the most critical factors to determine the screening effectiveness of wave barriers. Provided that the minimum depth of open trench should be at least $0.6 L_R$ at a point $10 L_R$ away from such trench for active isolation and $1.33 L_R$ for the passive when the measurement point is located at a distance between $2L_R$ and $7L_R$ from the wave barrier. The trench width has built between $0.1L_R$ and $0.5L_R$ to accomplish such remarkable reduction in vertical soil vibrations [54,55,56]. The predominant values of the applied excitation frequencies in this study and the related Rayleigh wavelengths are given in Table 8 in order to determine the optimum geometric parameters of the trench barrier and average for an effective protection and to avoid the difficulties in their practical applications such as instability of soil high water table levels and high costs.

4.3.6 General Properties of the Responses:

To assess the effects of the barrier geometry on the screening effectiveness, all vibration tests were conducted with the same initial conditions and with the specified vibrating frequencies.

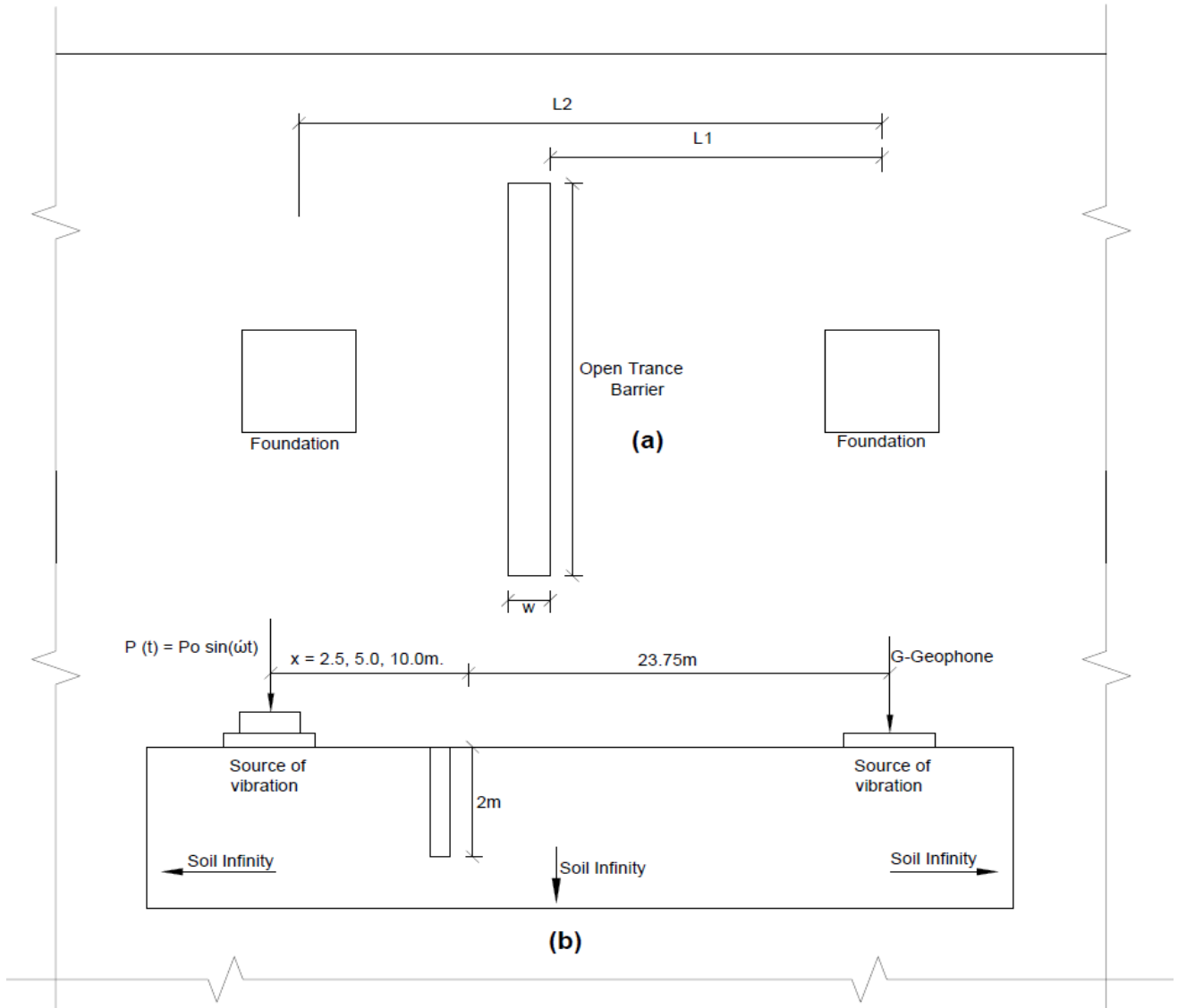


Figure 36: Field test model for active and passive isolation cases (a) Plan (b) Sectional elevation

The vibratory system is controlled using a Variable Frequency Drive (VFD). To ensure accurate and consistent vibration frequency at each testing frequency during the three stages, a vibro-meter is used to check real vibrating frequency with an accuracy of about $\pm 0.25\text{ Hz}$ before recording the responses. Figure

37 to Figure 39 shows a typical time history of soil particle displacement and the corresponding Fast Fourier Transform (FFT) of the recorded signals that are measured on the ground along the monitoring path during stage one and the vibrating source is at first location. The different channels used in the data acquisition system (DAQ) represent the ground response at different locations on centre line. The obtained results displayed high quality signals for the harmonic excitations with different input frequencies. On the other hand, the Fourier spectrum indicates clearly that the ground response has the same dominant frequency as the frequency of the applied dynamic load.

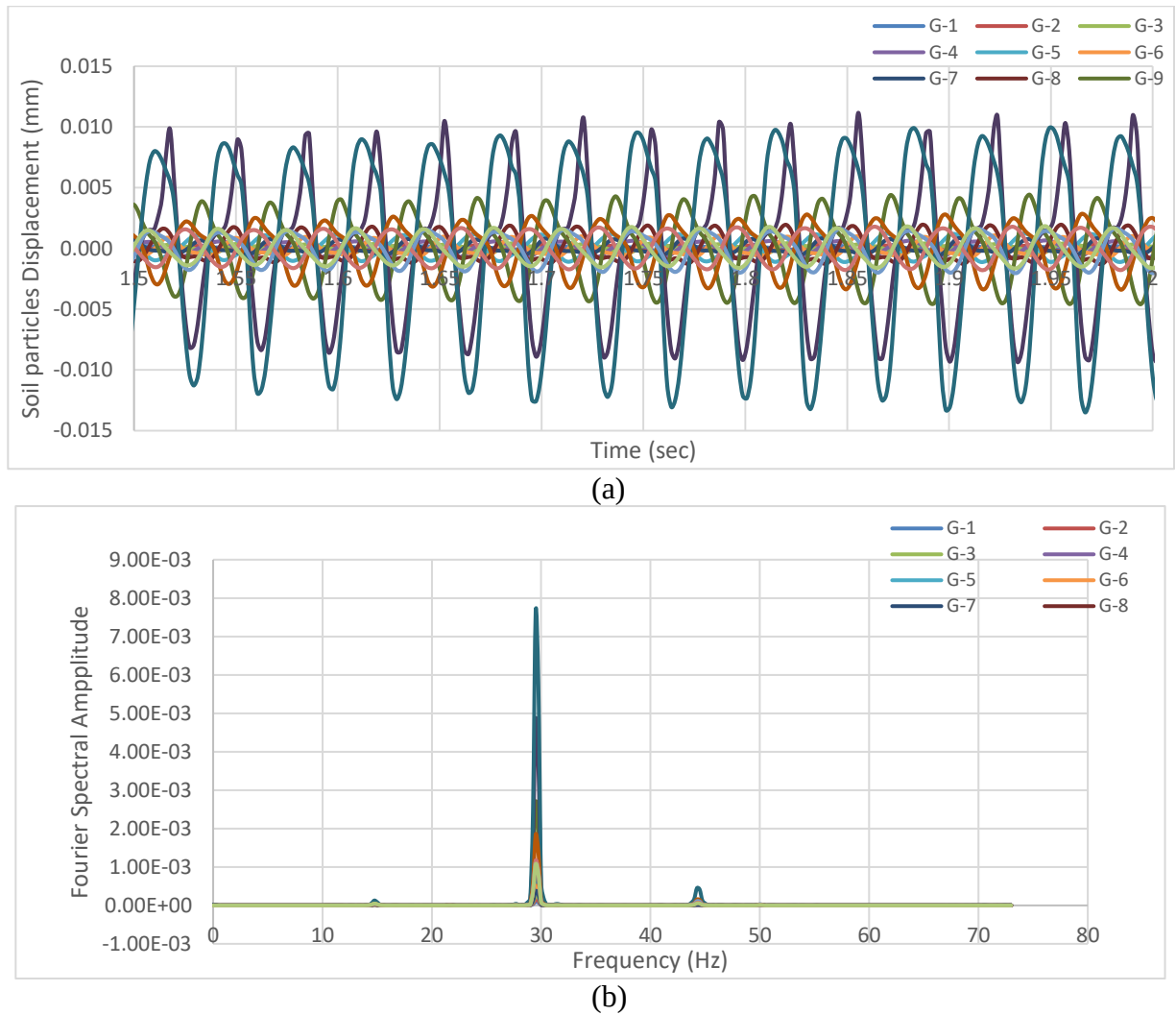
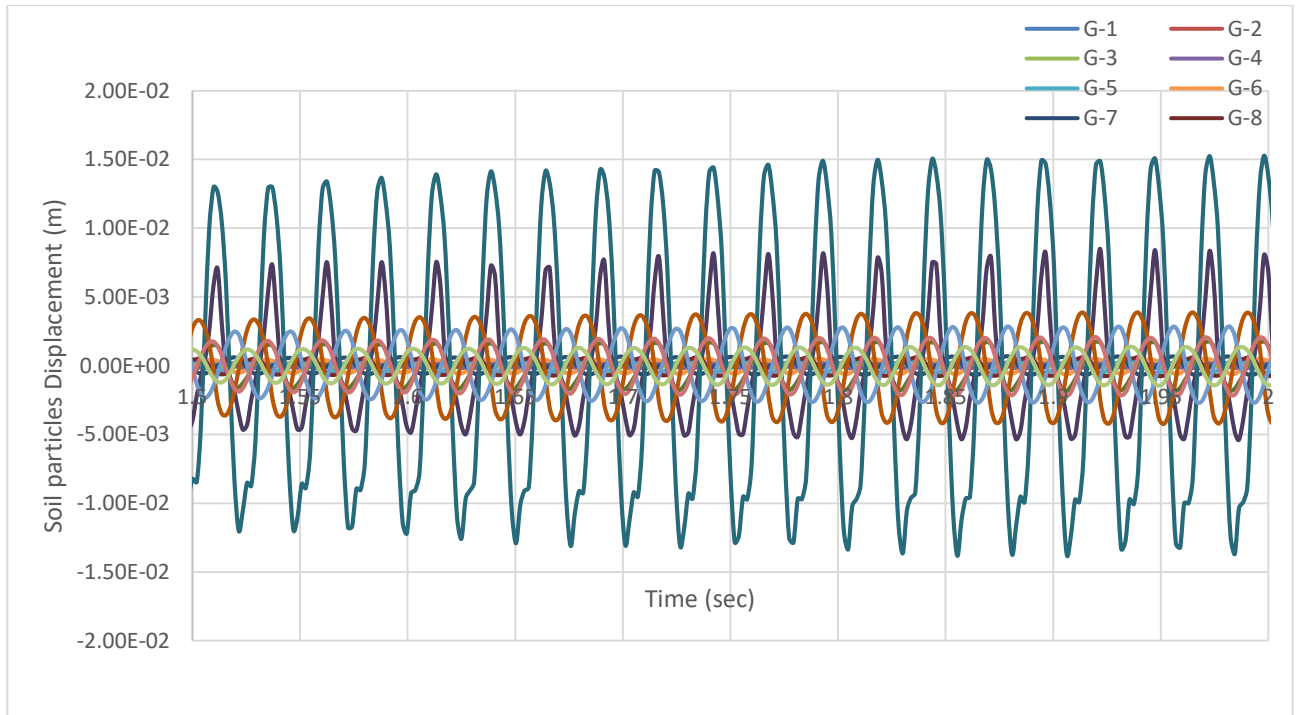
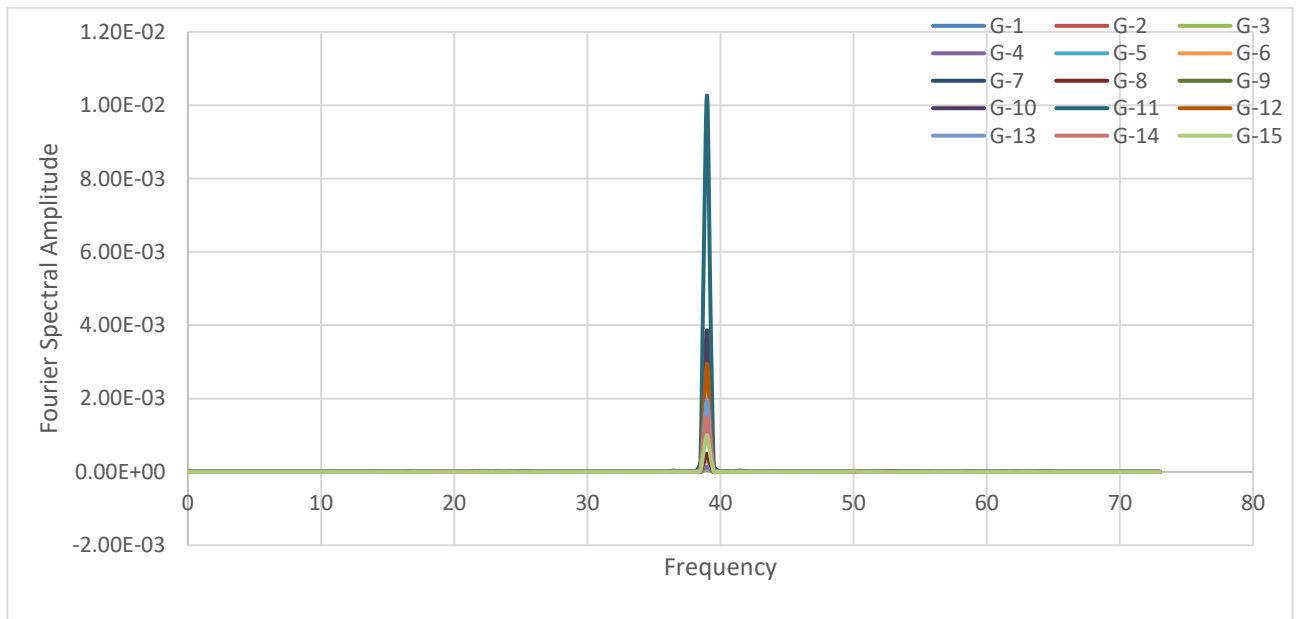


Figure 37: Measured soil particles displacement during the first stage in time domain (a) Response at observation points in No Trench case when oscillator is at 2.5m from trench (b) corresponding FFT at exciting frequency of $f = 30\text{Hz}$

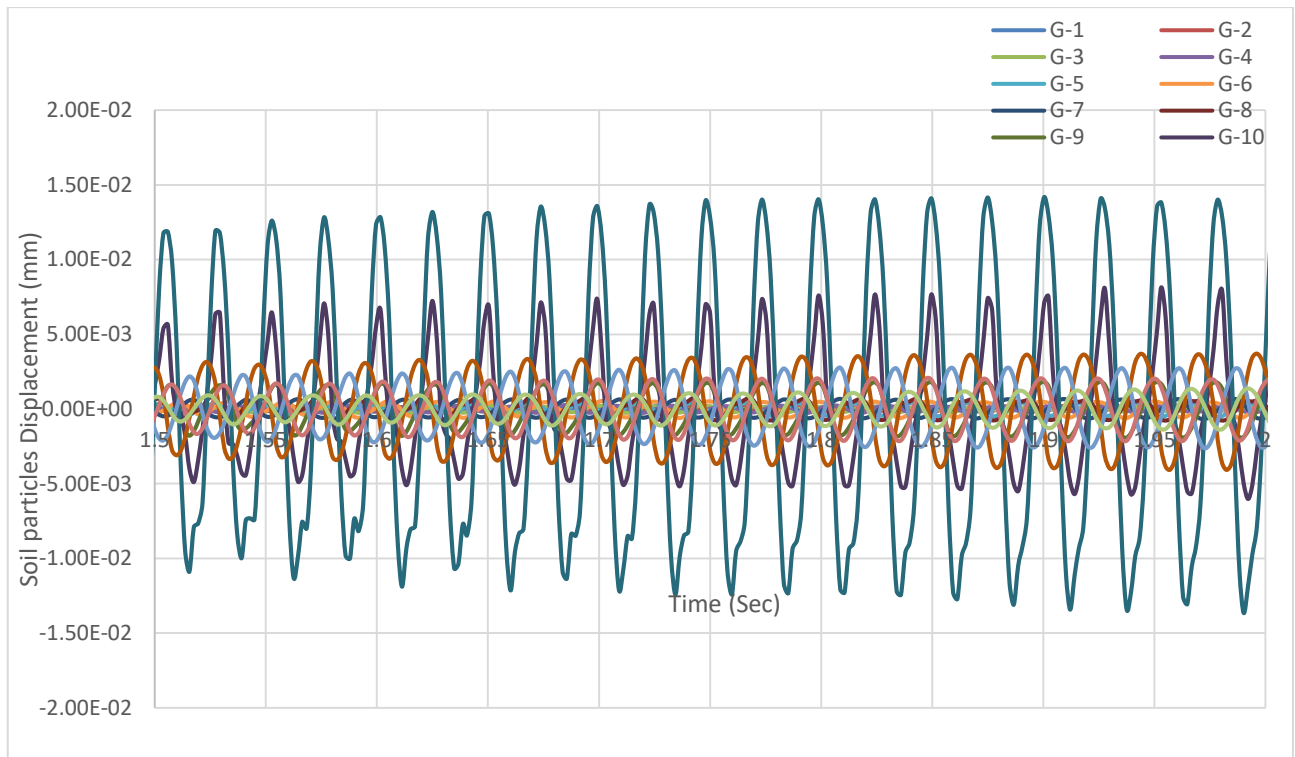


(a)

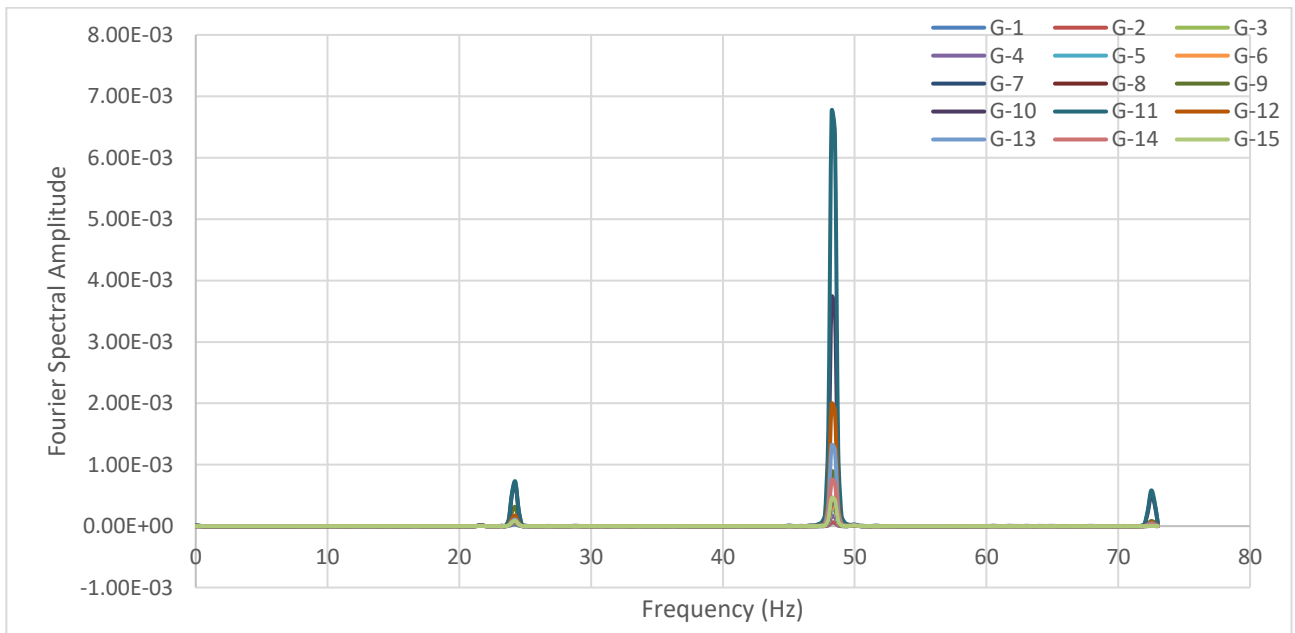


(b)

Figure 38: Measured soil particles displacement during the first stage in time domain (a) Response at observation points in No Trench case when oscillator is at 2.5m from the trench (b) corresponding FFT at exciting frequency of $f=40\text{Hz}$



(a)



(b)

Figure 39:: Measured soil particles displacement during the first stage in time domain (a) Response at observation points in No Trench case when oscillator is at 2.5m from the trench (b) corresponding FFT at exciting frequency of $f=50\text{Hz}$

4.3.7 Amplitude Reduction Ratio:

The source of vibration simulates the case of machine foundation vibration, which results in a steady state response. The system effectiveness can be evaluated based on either the observed displacement, velocity or acceleration with and without the vibration barrier. In most of the published literature, the system effectiveness was evaluated in terms of the achieved reduction in response amplitude of soil particle. In practice, the effect of transmitted vibration is usually evaluated in terms of soil particles velocity at points of interest. Since displacement pickups were used to measure the soil particles amplitude in terms of vertical displacement, the system effectiveness can be presented in terms of reduction in soil particle amplitude. Therefore, the results are presented in the form of amplitude reduction ratio, A_r , which is calculated by normalizing the post-trench installation maximum spectral velocity amplitude $(A_r)_{After}$ by the maximum spectral velocity amplitude before trench installation $(A_r)_{Before}$ measured on the ground surface. The maximum spectral amplitude can be obtained from Fourier curves, which are established from applying FFT on the time history records at the points of interest. The amplitude reduction ratio is then given by:

$$Ar = \frac{(Ar)_{After}}{(Ar)_{Before}} \quad (4.1)$$

To evaluate the system effectiveness (screening effectiveness) of the wave barrier system, the averaged amplitude reduction ratio (A_r) over a distance of interest $x_{measured}$ behind the wave barrier can be calculated using the following equation:

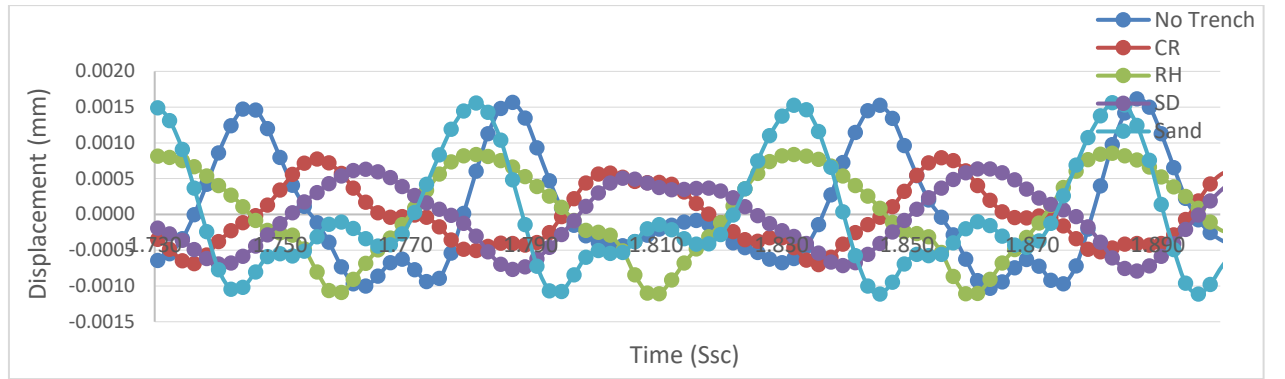
$$Ar = \frac{1}{x} \int Ar \, dx \quad (4.2)$$

Thus, the system effectiveness is calculated using Equation 3-4 as follows:

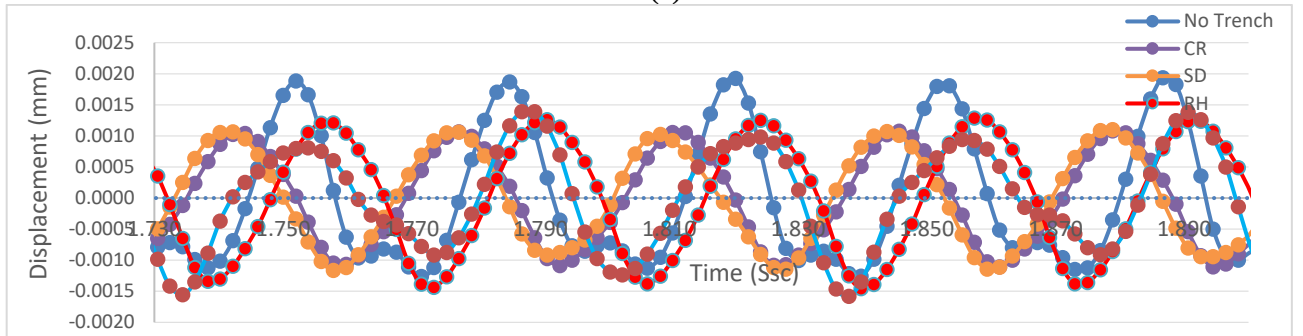
$$Eff = (1 - Ar) \times 100 \quad (4.3)$$

4.3.8 Measurements for Active Isolation:

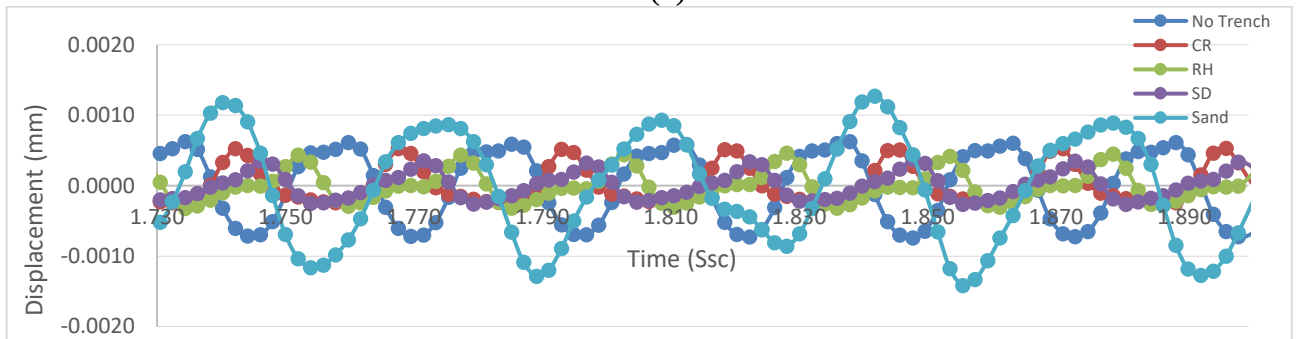
The resulting time histories of the vertical response as amplitude at observation points G1 to G15 for active isolation measures in case of no trench, rectangular empty trench and trenches with in-filled materials are compared in Figure 40, Figure 41 and Figure 42. The comparison of the vertical displacement vs time histories in all the cases at one of the observations point i.e. G-8 for active isolation measures due to exciting frequency of 20, 30, 40 and 50Hz when the source vibrator location 2.5m from centre of trench is shown in Figure 40. The comparison of the vertical displacement vs time histories in all the cases at observation point G-8 for active isolation measures due to exciting frequency of 20, 30, 40 and 50 Hz when the source vibrator location 5m from centre of trench is shown in Figure 41. The comparison of the vertical displacement vs time histories in all the cases at observation point G-8 for active isolation measures due to exciting frequency of 20, 30, 40 and 50Hz when the source vibrator location 10 m from centre of trench is shown in Figure 42. The wave propagation pattern of the transmitted vibrations in the case of both open and in-filled trench barriers is similar to the case of no trench. The amplitude reduction factor (A_r) is defined as the vertical displacement amplitude after the presence of the trench barriers relative to the amplitude on the undisturbed site (without trench barriers). An effective screening exists when the calculated reduction factor from the experimental data is less than 0.6 for the applied excitation frequencies. The Amplitude reduction ration A_r for all the cases under different exciting frequencies has calculated separately and tabulated in Table 10, Table 11 and Table 12. Average Spectral Amplitude reduction factor as a function of excited frequencies for active isolation when the source of vibration is at 2.5m.



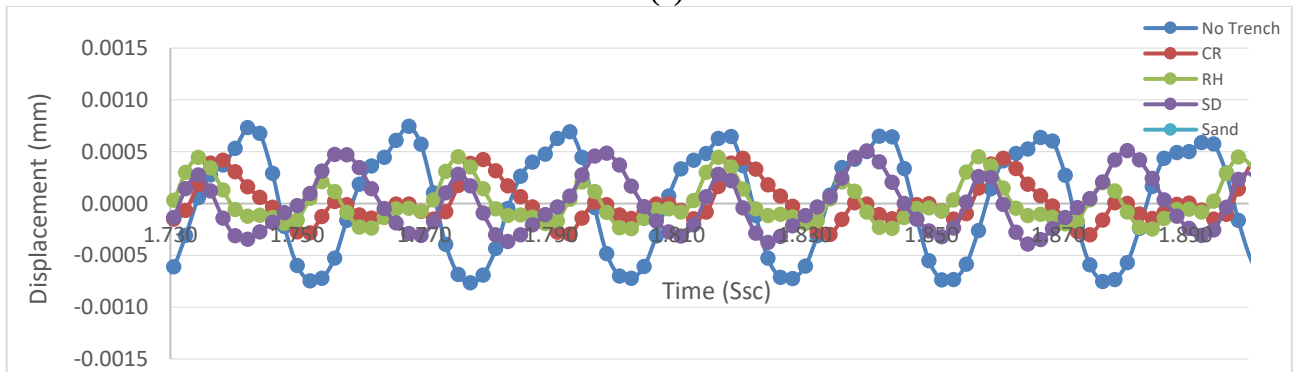
(a)



(b)



(c)



(d)

Figure 40: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to frequency of (a) 20 Hz (b) 30 Hz (c) 40 Hz & (d) 50 Hz at the source vibrator location 2.5m from centre of trench

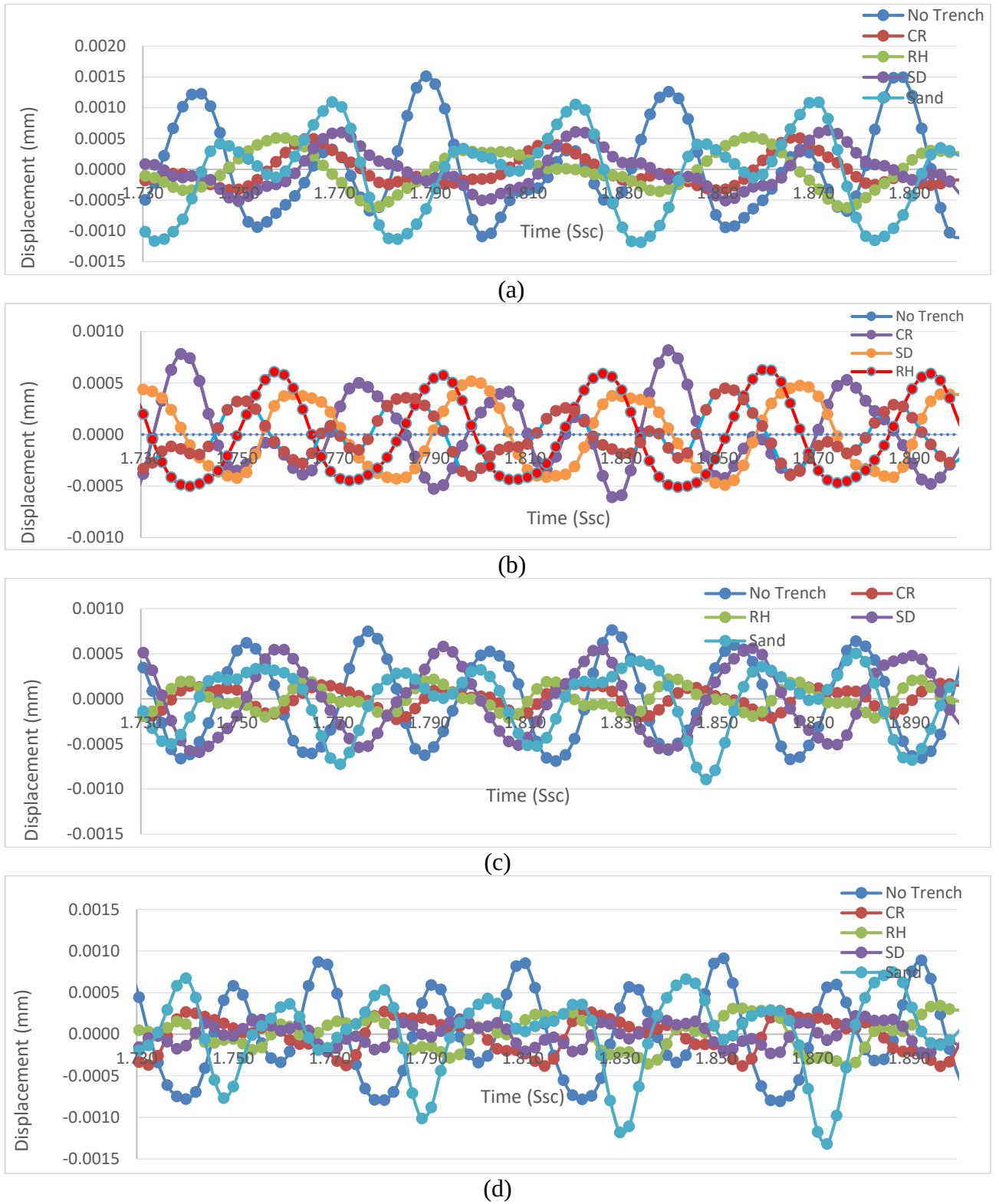
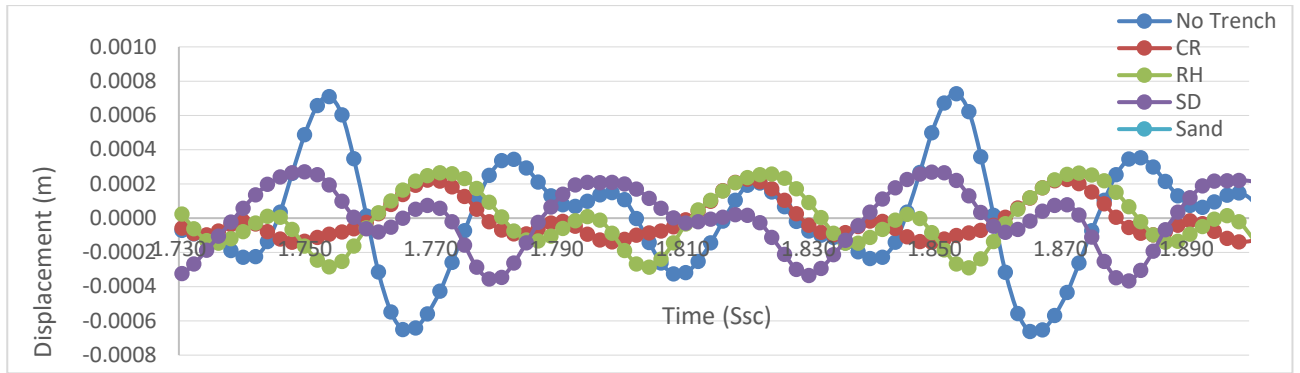
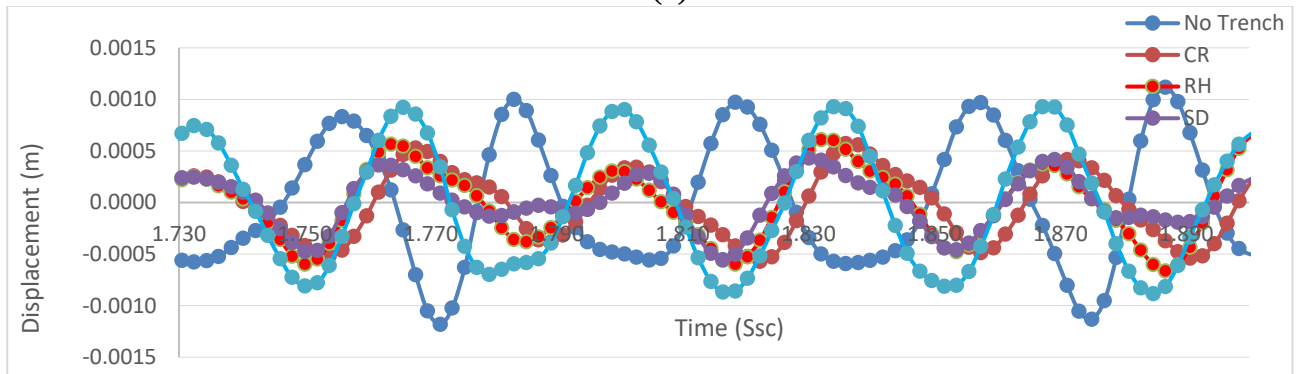


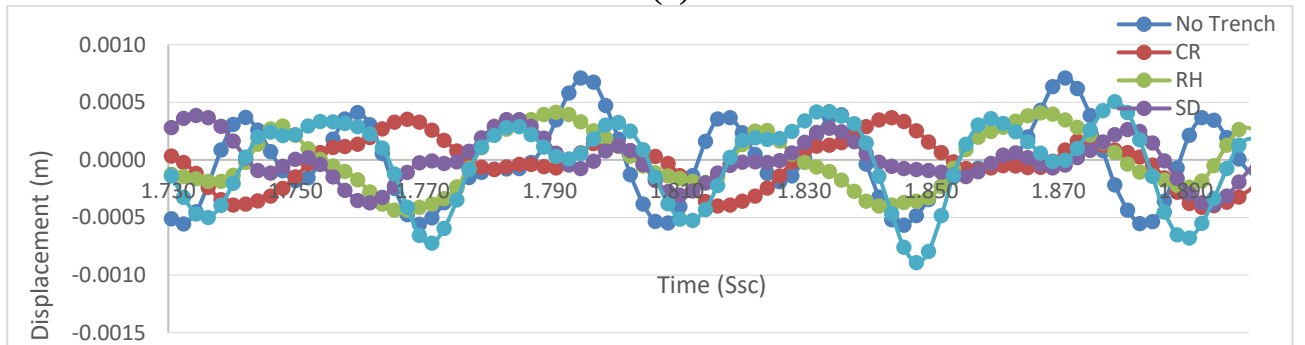
Figure 41: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to exciting frequency of (a) 20Hz (b) 30Hz (c) 40Hz & (d) 50Hz at the source vibrator location 5m from centre of trench



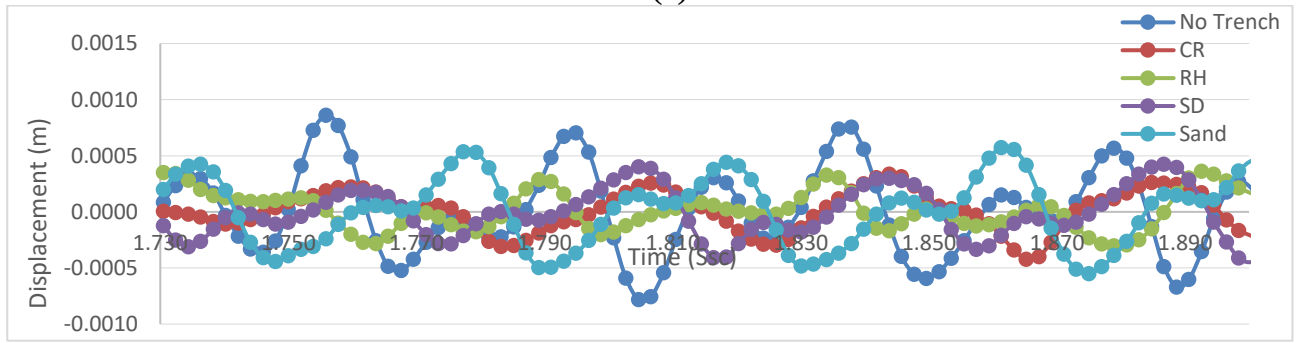
(a)



(b)



(c)



(d)

Figure 42: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to exciting frequency of (a) 20Hz (b) 30Hz (c) 40Hz & (d) 50Hz at the source vibrator location 10 m from centre of trench

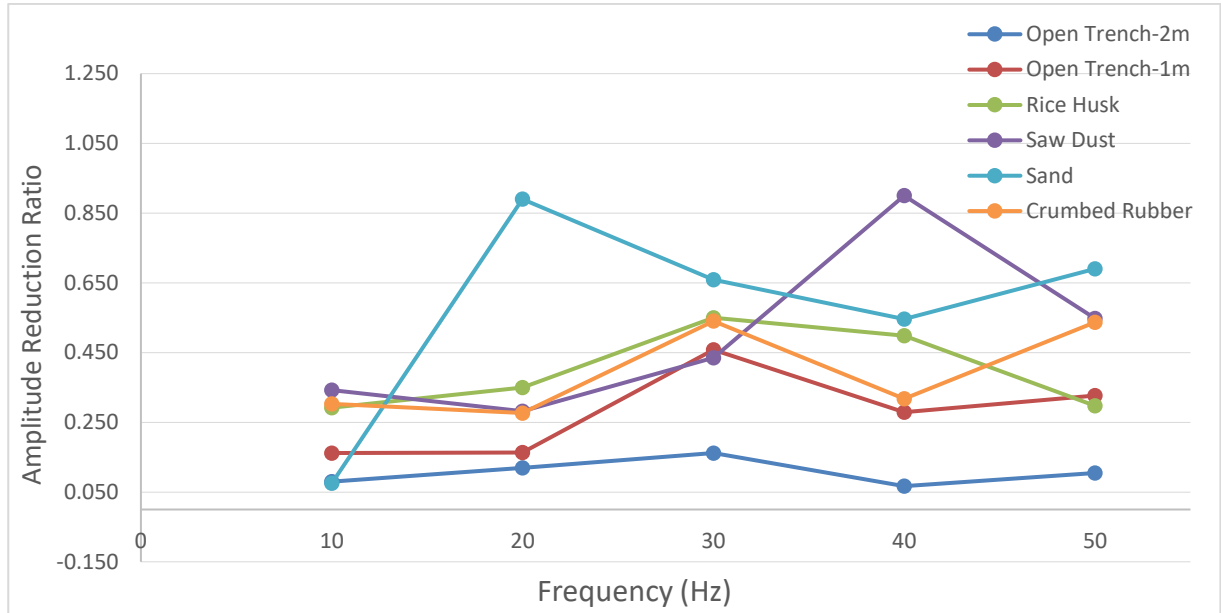


Figure 43: Variation of Attenuation of vibration as a function of excited frequencies for active -isolation at observation point G9 when the source of vibration is at 5 m

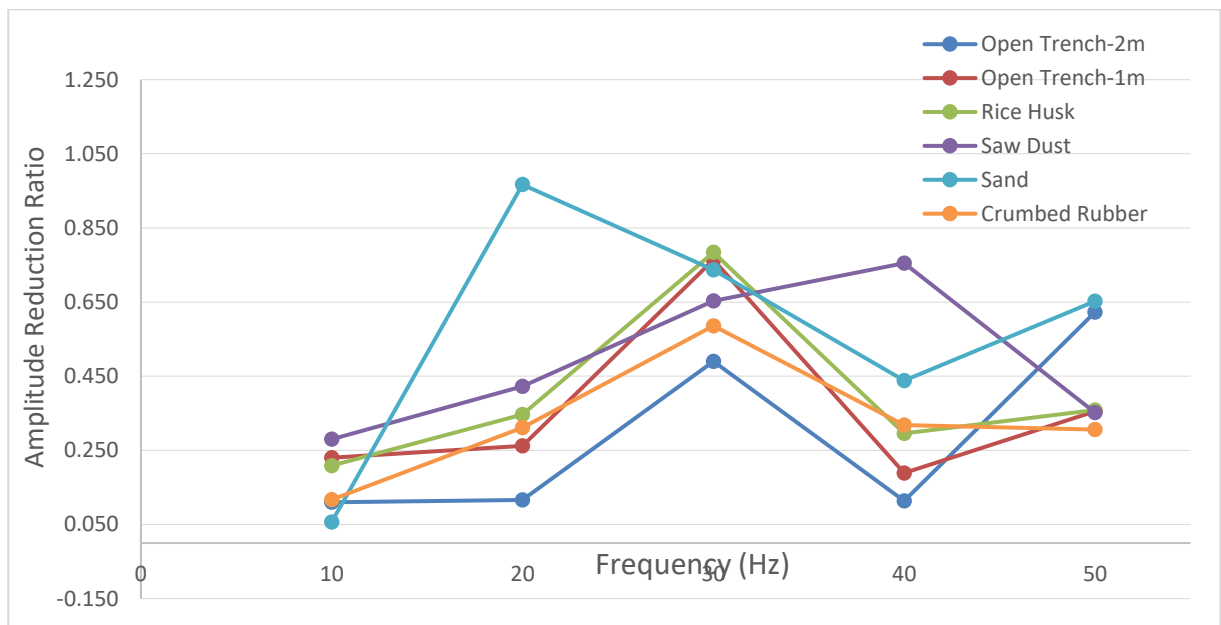


Figure 44: Variation of Attenuation of vibration as a function of excited frequencies for active -isolation at measurement point G8 when the source of vibration is at 5m

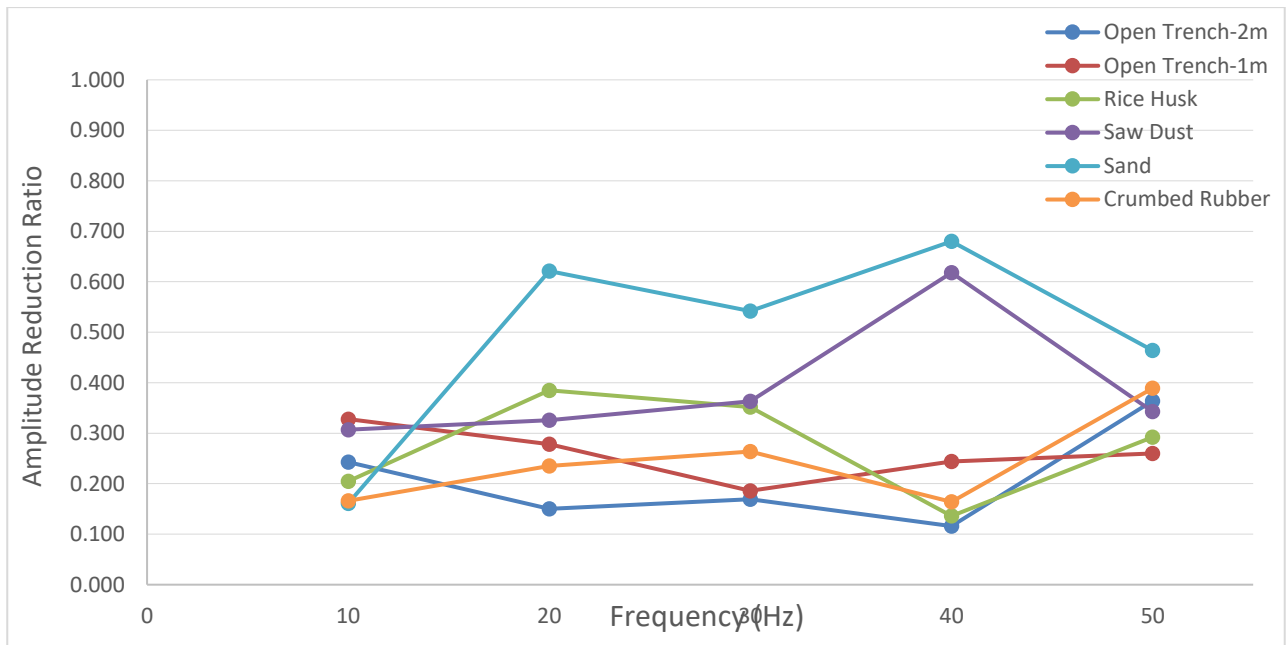


Figure 45: Variation of Attenuation of vibration as a function of excited frequencies for active - isolation at measurement point G7 when the source of vibration is at 5 m

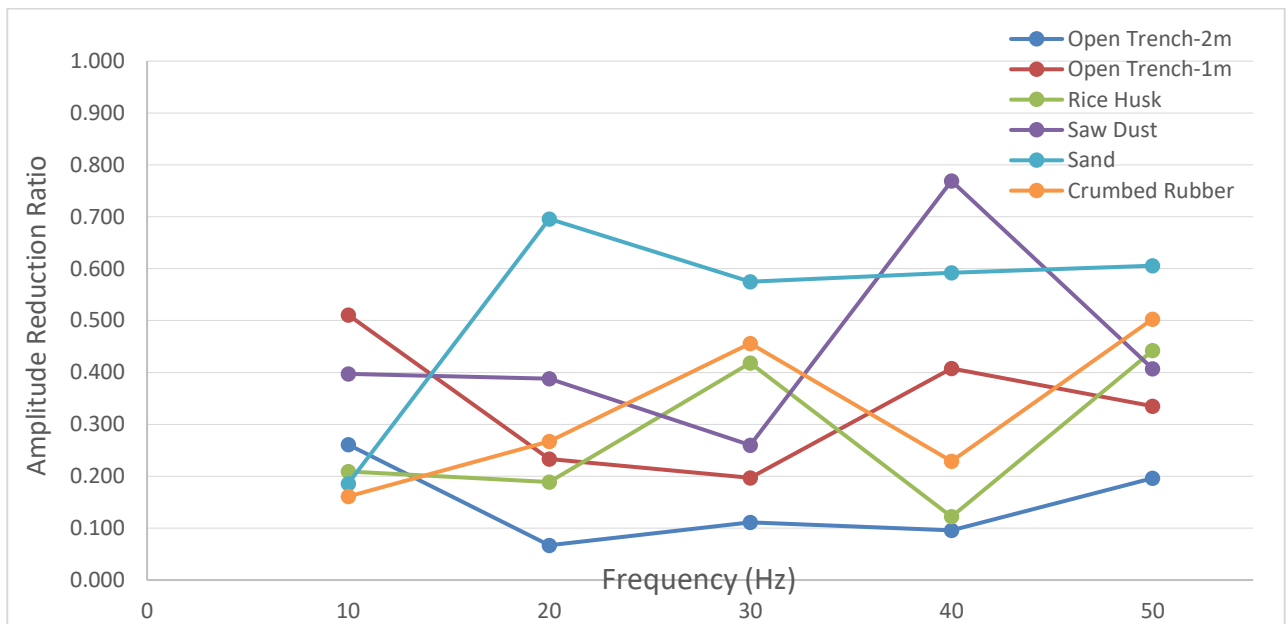


Figure 46: Variation of Attenuation of vibration as a function of excited frequencies for active - isolation at measurement point G6 when the source of vibration is at 5m

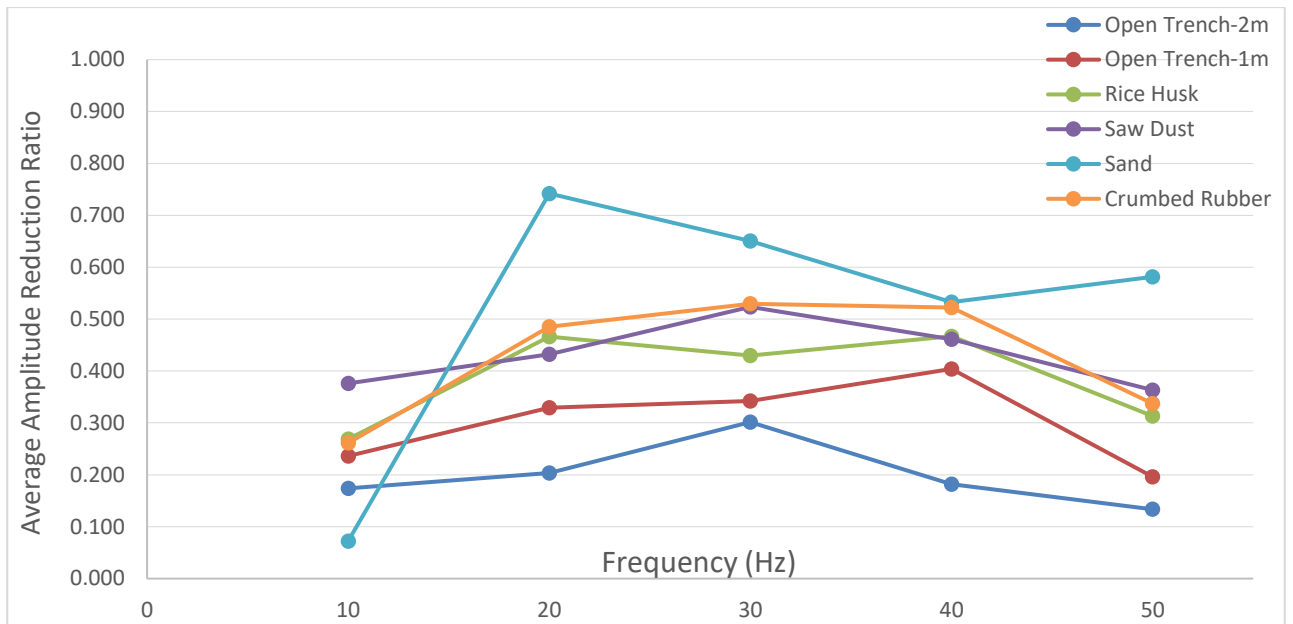


Figure 47: Average Spectral Amplitude reduction factor as a function of excited frequencies for active - isolation when the source of vibration is at 2.5m

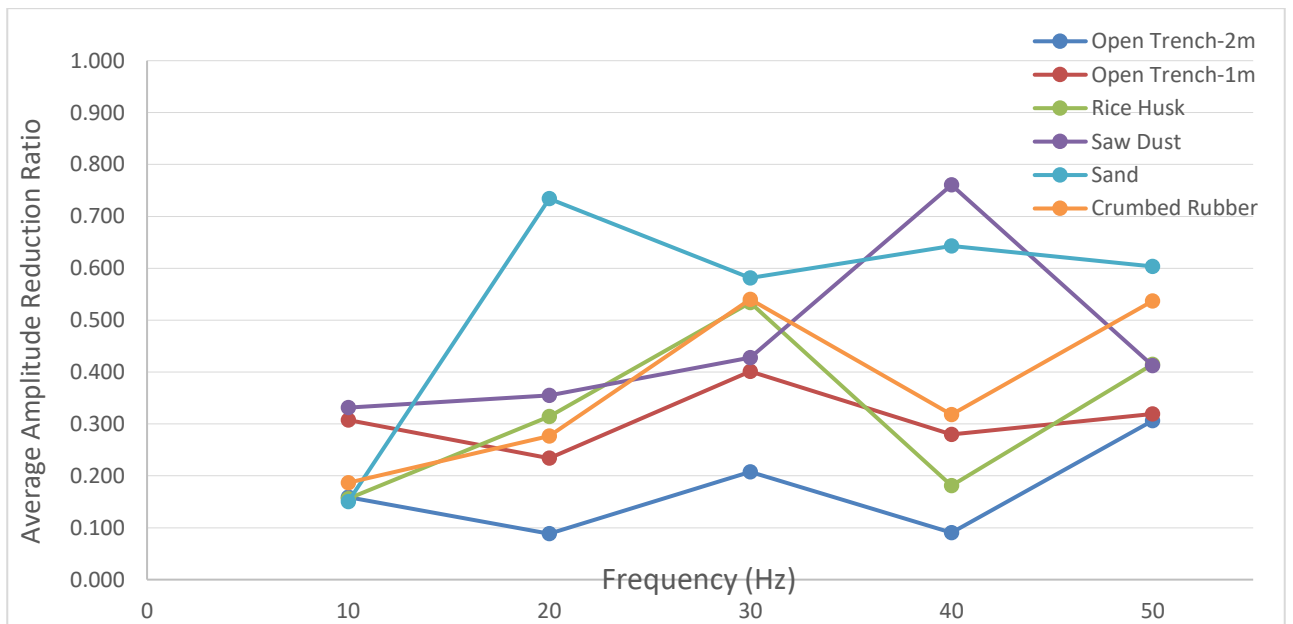


Figure 48: Average Spectral Amplitude reduction factor as a function of excited frequencies for active - isolation when the source of vibration is at 5m

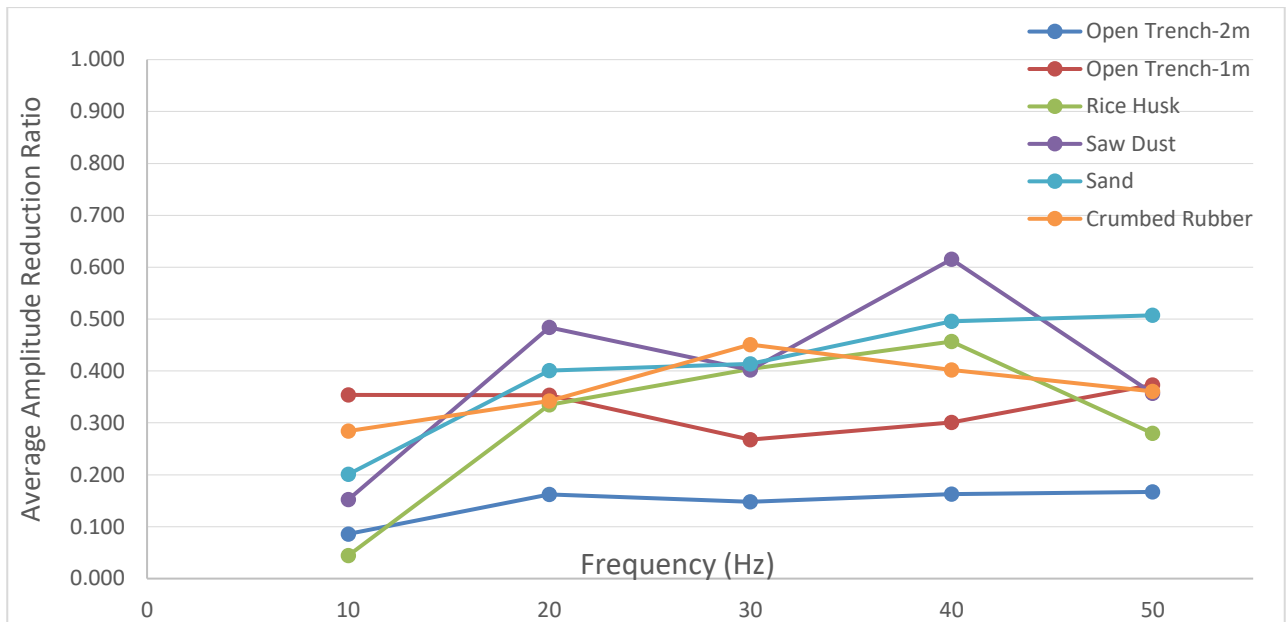


Figure 49: Average Spectral Amplitude reduction factor as a function of excited frequencies for active -isolation when the source of vibration is at 10m

The variation of attenuation of vibration as a function of excited frequencies for 10Hz, 20Hz, 30Hz, 40Hz and 50Hz for active -isolation at measurement point G9, G-8, G7 and G6 in the case when the source of vibration is located at 5 m from the centre of trench has been presented in Figure 43 to Figure 46. It reflects the variation of attenuation of vibration due to different in-filled materials. The average spectral amplitude reduction factor calculated as a function of excited frequencies for 10Hz, 20Hz, 30Hz, 40Hz and 50Hz for active -isolation is presented in Figure 47 when the source of vibration is at 2.5m, in Figure 48 when the source of vibration is at 5m and Figure 49 when the source of vibration is located at 10m from the centre of trench. It may be noted that sand is also used in the barrier but it is not used as a part of research here.



Table 10: Amplitude reduction ratio (A_r) in presence of wave barriers when $X_1=2.5$ m

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIOT2.5/10	10 Hz	0.080	0.174	0.244	0.198	0.174
AIOT2.5/20	20Hz	0.119	0.277	0.257	0.161	0.204
AIOT2.5/30	30Hz	0.162	0.381	0.533	0.130	0.302
AIOT2.5/40	40Hz	0.067	0.279	0.185	0.196	0.182
AIOT2.5/50	50 Hz	0.105	0.122	0.157	0.150	0.134
2. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIOT2.5/10	10 Hz	0.062	0.288	0.327	0.267	0.236
AIOT2.5/20	20Hz	0.084	0.462	0.374	0.398	0.330
AIOT2.5/30	30Hz	0.124	0.540	0.565	0.140	0.342
AIOT2.5/40	40Hz	0.307	0.453	0.385	0.471	0.404
AIOT2.5/50	50 Hz	0.079	0.162	0.246	0.298	0.196
3. CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AICR2.5/10	10 Hz	0.666	0.125	0.132	0.122	0.261
AICR2.5/20	20Hz	0.496	0.485	0.525	0.435	0.485
AICR2.5/30	30Hz	0.760	0.564	0.405	0.389	0.530
AICR2.5/40	40Hz	0.680	0.347	0.491	0.570	0.522
AICR2.5/50	50 Hz	0.465	0.335	0.363	0.186	0.337
4. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIRH2.5/10	10 Hz	0.292	0.326	0.260	0.197	0.269
AIRH2.5/20	20Hz	0.350	0.519	0.573	0.423	0.466
AIRH2.5/30	30Hz	0.550	0.485	0.332	0.352	0.430



AIRH2.5/40	40Hz	0.498	0.452	0.385	0.533	0.467
AIRH2.5/50	50 Hz	0.297	0.413	0.303	0.239	0.313
5. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD2.5/10	10 Hz	0.480	0.383	0.301	0.341	0.376
AISD2.5/20	20Hz	0.290	0.397	0.512	0.529	0.432
AISD2.5/30	30Hz	0.630	0.604	0.598	0.262	0.524
AISD2.5/40	40Hz	0.400	0.597	0.368	0.479	0.461
AISD2.5/50	50 Hz	0.352	0.475	0.372	0.254	0.363
6. SAND:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIS2.5/10	10 Hz	0.049	0.057	0.100	0.083	0.072
AIS2.5/20	20Hz	0.570	0.967	0.588	0.843	0.742
AIS2.5/30	30Hz	0.420	0.737	0.682	0.764	0.651
AIS2.5/40	40Hz	0.385	0.438	0.829	0.479	0.533
AIS2.5/50	50 Hz	0.630	0.652	0.593	0.452	0.582

**Table 11:** Amplitude reduction ratio (A_R) in presence of wave barrier when $X_2 = 5\text{m}$

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIOT5/10	10 Hz	0.022	0.110	0.243	0.261	0.159
AIOT5/20	20Hz	0.021	0.116	0.150	0.067	0.089
AIOT5/30	30Hz	0.061	0.490	0.169	0.111	0.208
AIOT5/40	40Hz	0.037	0.114	0.116	0.096	0.091
AIOT5/50	50 Hz	0.042	0.623	0.364	0.196	0.306
2. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIOT5/10	10 Hz	0.162	0.230	0.328	0.511	0.308
AIOT5/20	20Hz	0.163	0.262	0.278	0.233	0.234
AIOT5/30	30Hz	0.458	0.764	0.186	0.197	0.401
AIOT5/40	40Hz	0.279	0.189	0.244	0.408	0.280
AIOT5/50	50 Hz	0.327	0.355	0.260	0.335	0.319
3. CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AICR5/10	10 Hz	0.303	0.117	0.166	0.161	0.187
AICR5/20	20Hz	0.294	0.311	0.235	0.267	0.277
AICR5/30	30Hz	0.855	0.586	0.264	0.456	0.540
AICR5/40	40Hz	0.560	0.318	0.164	0.229	0.318
AICR5/50	50 Hz	0.950	0.306	0.389	0.503	0.537
4. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIRH5/10	10 Hz	0.001	0.209	0.205	0.209	0.156
AIRH5/20	20Hz	0.336	0.347	0.385	0.189	0.314
AIRH5/30	30Hz	0.581	0.784	0.352	0.418	0.534



AIRH5/40	40Hz	0.171	0.296	0.136	0.122	0.181
AIRH5/50	50 Hz	0.566	0.359	0.292	0.442	0.415
5. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD5/10	10 Hz	0.342	0.280	0.307	0.397	0.332
AISD5/20	20Hz	0.282	0.423	0.326	0.388	0.355
AISD5/30	30Hz	0.435	0.653	0.363	0.260	0.428
AISD5/40	40Hz	0.900	0.755	0.618	0.769	0.761
AISD5/50	50 Hz	0.548	0.352	0.343	0.407	0.413
6. SAND:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIS5/10	10 Hz	0.075	0.179	0.161	0.186	0.150
AIS5/20	20Hz	0.890	0.729	0.621	0.696	0.734
AIS5/30	30Hz	0.659	0.550	0.542	0.575	0.582
AIS5/40	40Hz	0.546	0.754	0.680	0.592	0.643
AIS5/50	50 Hz	0.690	0.654	0.464	0.606	0.604



Table 12: Amplitude reduction ratio (A_r) in presence of wave barrier when $X_3 = 10\text{m}$

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIOT10/10	10 Hz	0.019	0.083	0.149	0.093	0.086
AIOT10/20	20Hz	0.035	0.175	0.213	0.225	0.162
AIOT10/30	30Hz	0.037	0.165	0.197	0.193	0.148
AIOT10/40	40Hz	0.018	0.184	0.241	0.207	0.163
AIOT10/50	50 Hz	0.029	0.272	0.210	0.157	0.167
2. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIOT10/10	10 Hz	0.073	0.846	0.230	0.266	0.354
AIOT10/20	20Hz	0.193	0.373	0.307	0.540	0.353
AIOT10/30	30Hz	0.341	0.254	0.252	0.224	0.268
AIOT10/40	40Hz	0.173	0.343	0.440	0.248	0.301
AIOT10/50	50 Hz	0.271	0.537	0.368	0.317	0.373
3. CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AICR10/10	10 Hz	0.224	0.312	0.250	0.351	0.284
AICR10/20	20Hz	0.272	0.193	0.313	0.592	0.343
AICR10/30	30Hz	0.435	0.477	0.439	0.453	0.451
AICR10/40	40Hz	0.306	0.517	0.351	0.435	0.402
AICR10/50	50 Hz	0.397	0.383	0.327	0.337	0.361
4. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_r
AIRH10/10	10 Hz	0.003	0.043	0.051	0.080	0.044
AIRH10/20	20Hz	0.001	0.369	0.376	0.594	0.335
AIRH10/30	30Hz	0.001	0.560	0.546	0.508	0.404



AIRH10/40	40Hz	0.002	0.704	0.586	0.535	0.457
AIRH10/50	50 Hz	0.001	0.345	0.391	0.382	0.280
5. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD10/10	10 Hz	0.176	0.130	0.114	0.188	0.152
AISD10/20	20Hz	0.586	0.372	0.413	0.566	0.484
AISD10/30	30Hz	0.421	0.400	0.401	0.385	0.402
AISD10/40	40Hz	0.634	0.631	0.609	0.587	0.615
AISD10/50	50 Hz	0.440	0.392	0.299	0.296	0.357
6. SAND:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIS10/10	10 Hz	0.234	0.152	0.160	0.257	0.201
AIS10/20	20Hz	0.390	0.716	0.243	0.254	0.401
AIS10/30	30Hz	0.528	0.417	0.377	0.334	0.414
AIS10/40	40Hz	0.680	0.652	0.441	0.210	0.496
AIS10/50	50 Hz	0.678	0.602	0.418	0.331	0.507

4.3.9 Measurements for Passive Isolation:

For carrying out measurement in case of passive isolation, the source of vibration was located at a distance of 23.75m from the centre of trench. The observation points G1 to G15 were remained identical as in case of active isolation. The resulting time histories of the vertical response as amplitude at observation points G1 to G15 for passive isolation measures in case of no trench, rectangular empty trench and trenches with in-filled materials are compared in Figure 50. The comparison of the vertical displacement vs time histories in all the cases at observation point G10 for passive isolation measures due to exciting frequency of 20, 30, 40 & 50Hz when the source vibrator location 23.75m from center of trench is shown in Figure 50. The wave propagation pattern of the transmitted vibrations in the case of both open and in-filled trench barriers is similar to the case of no trench. The average amplitude reduction factor (A_r) in case of no trench and trench wave barrier with in-filled materials under different exciting frequencies has calculated separately and tabulated in Table 12. The variation of attenuation of vibration as a function of excited frequencies for 10Hz, 20Hz, 30Hz, 40Hz and 50Hz for active isolation at measurement point G10, G-11 and G12 in the case when the source of vibration is located at 23.75m from the centre of trench has been presented in Figure 51 to Figure 53. The average vertical amplitude reduction ratio as a function of excited frequencies for passive isolation when the source of vibration at 23.75m is shown in Figure 54.

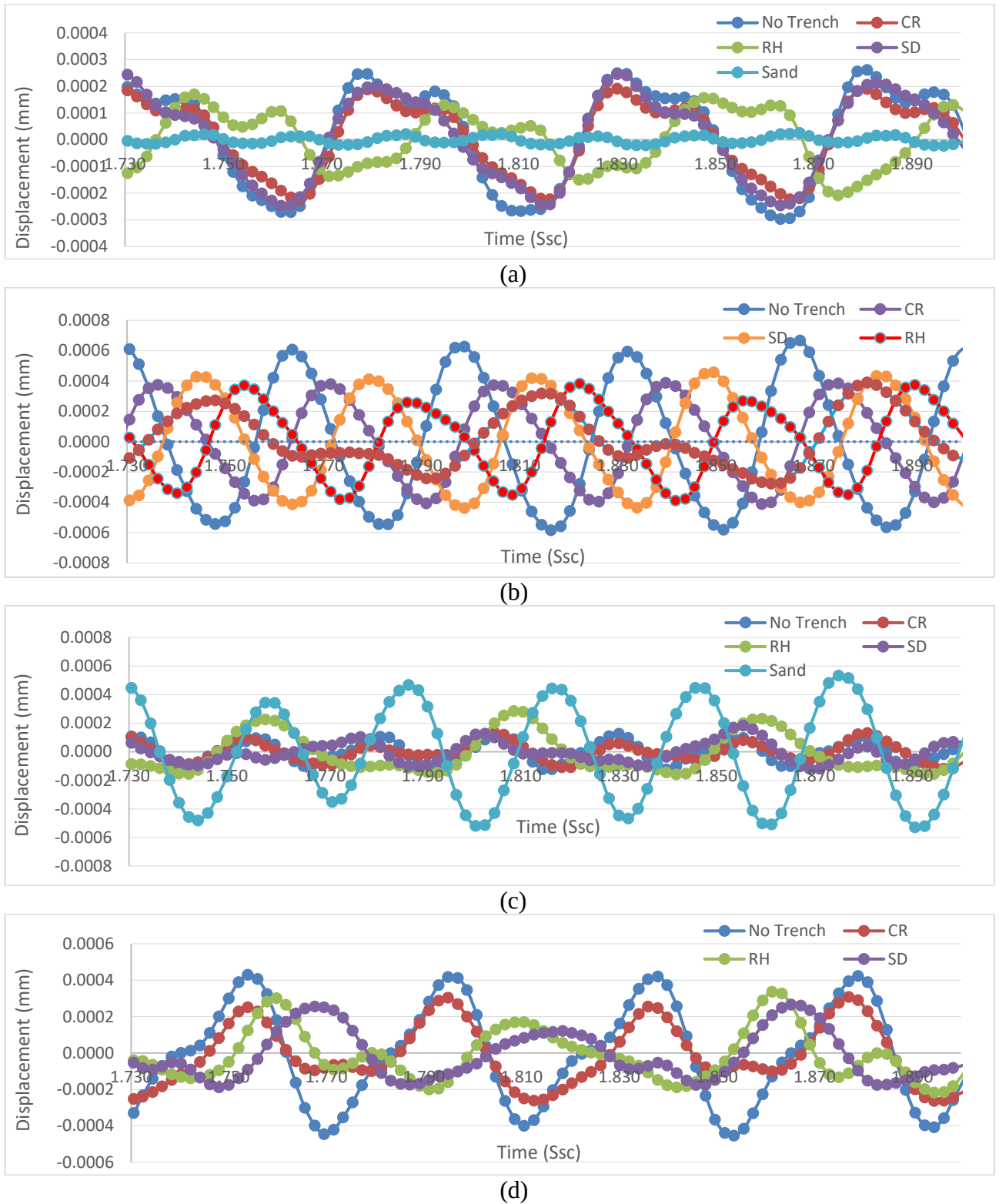


Figure 50: Comparison of the spectral amplitude vs time histories at observation point G-10 for passive isolation measures due to exciting frequency of (a) 20 Hz (b) 30 Hz (c) 40 Hz & (d) 50 Hz at the source vibrator location 23.75m from centre of trench

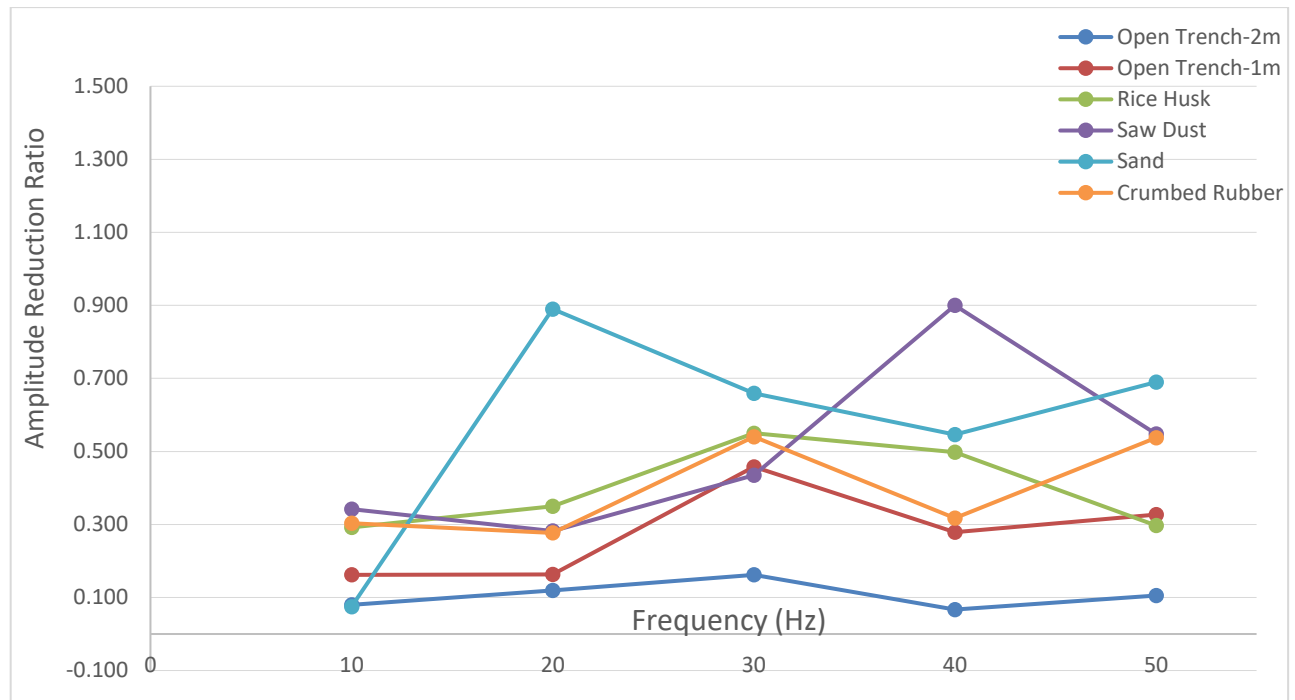


Figure 51: Variation of Attenuation of vibration as a function of excited frequencies for passive -isolation at observation point G10 when the source of vibration is at 23.75 m

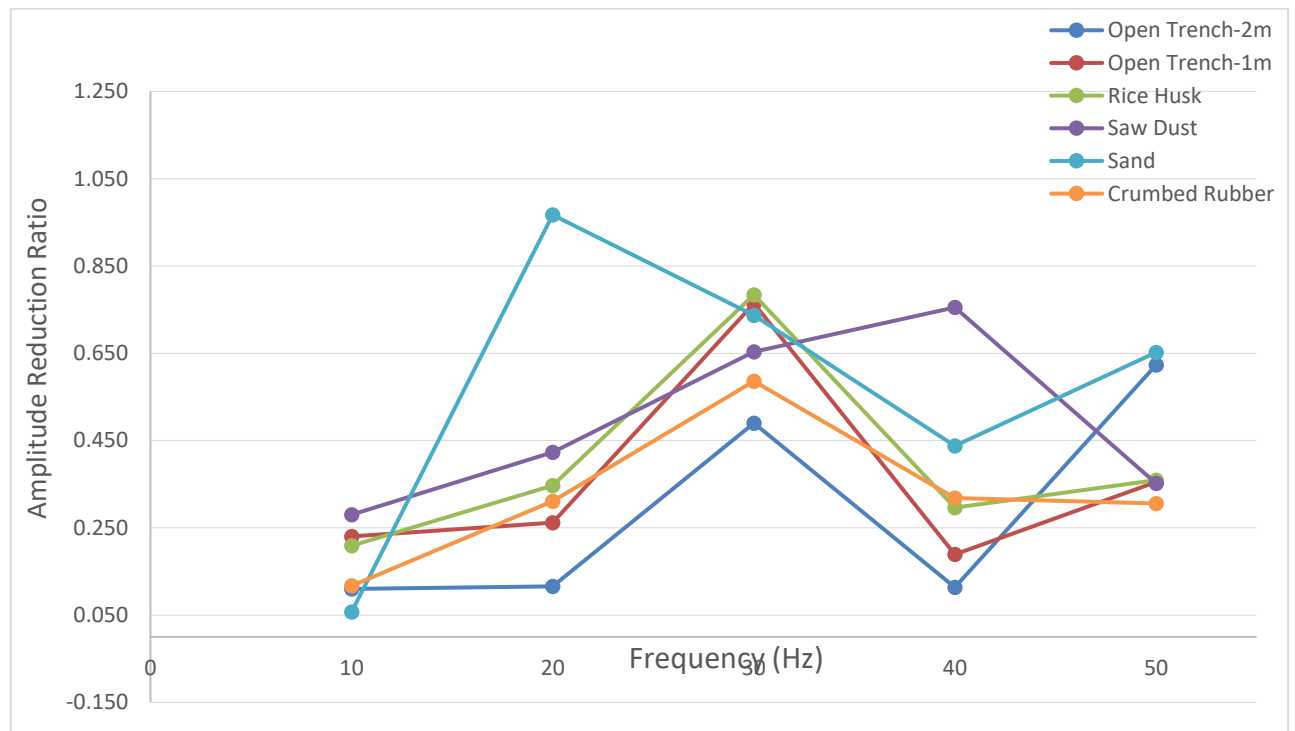


Figure 52: Variation of Attenuation of vibration as a function of excited frequencies for passive -isolation at measurement point G11 when the source of vibration is at 23.75 m

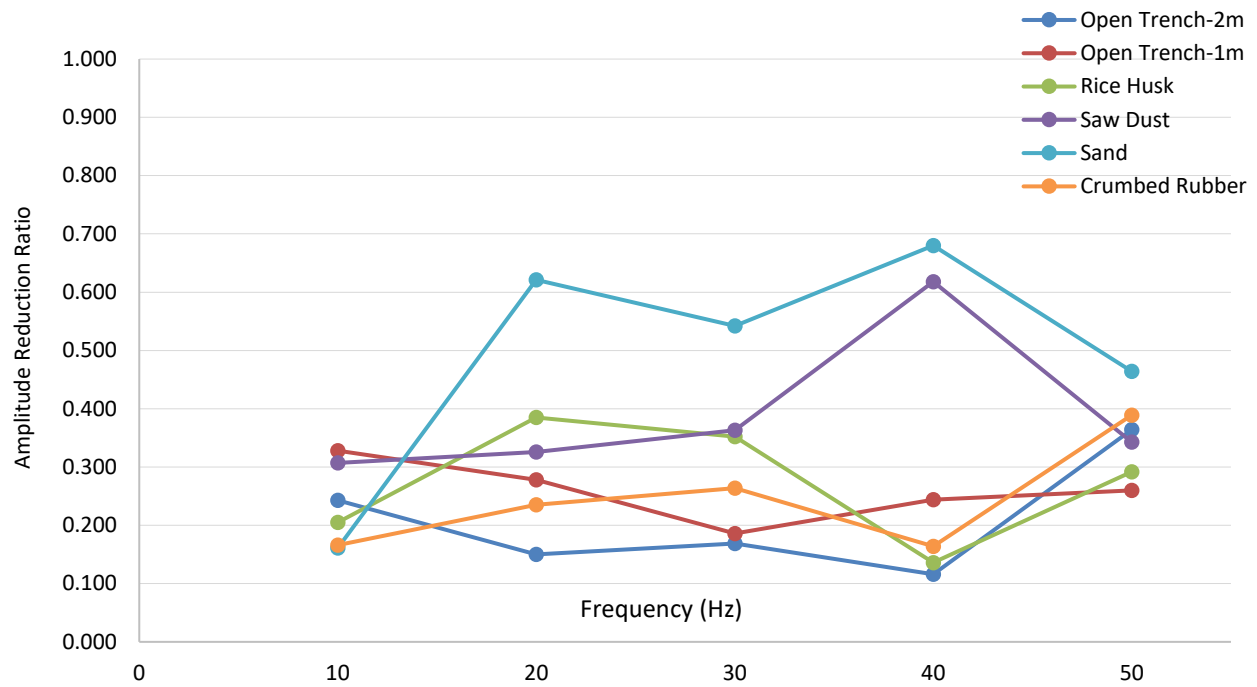


Figure 53: Variation of Attenuation of vibration as a function of excited frequencies for passive -isolation at measurement point G12 when the source of vibration is at 23.75 m

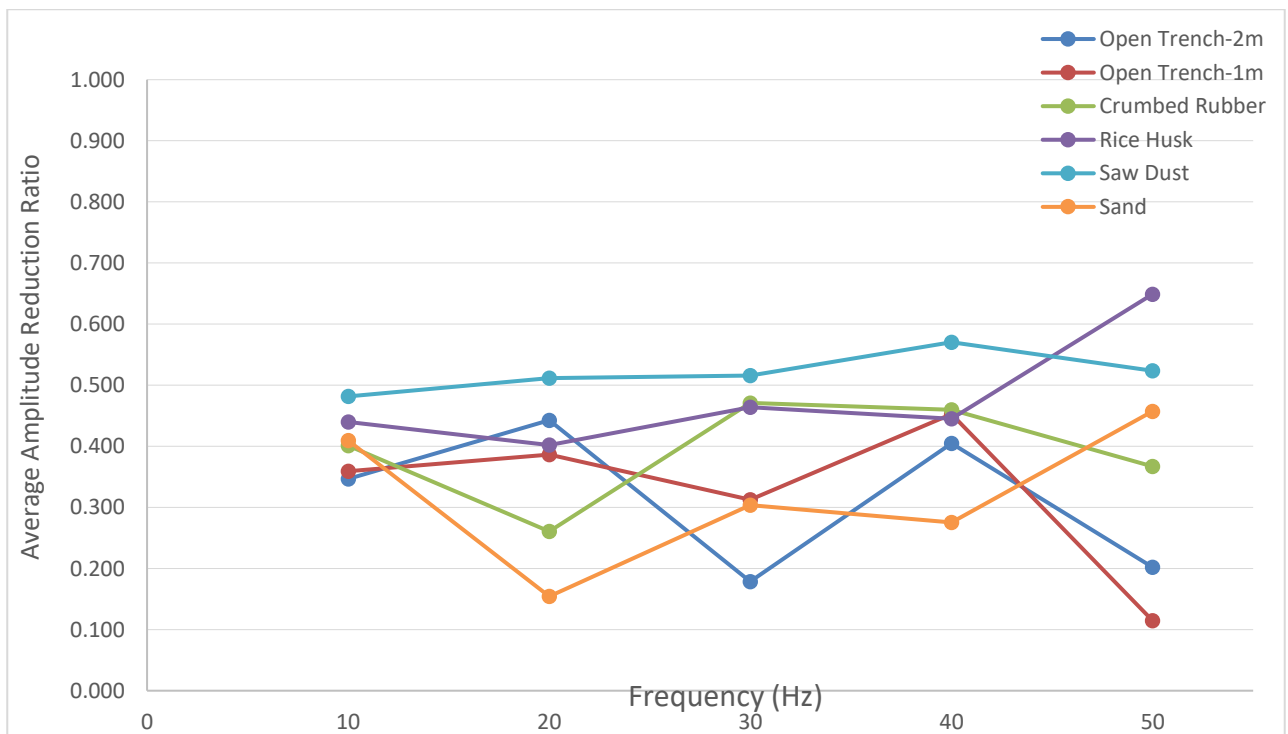


Figure 54: Average vertical amplitude reduction ratio as a function of excited frequencies for passive isolation when the source of vibration at 23.75 m



Table 13: Amplitude reduction ration (A_r) in presence of wave barriers when $X_1=23.75m$

1. OPEN TRENCH:					
Case ID	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIOT2.5/10	10 Hz	0.304	0.526	0.210	0.347
PIOT2.5/20	20Hz	0.340	0.488	0.500	0.443
PIOT2.5/30	30Hz	0.224	0.180	0.132	0.179
PIOT2.5/40	40Hz	0.342	0.342	0.531	0.405
PIOT2.5/50	50 Hz	0.214	0.193	0.200	0.202
2. OPEN TRENCH:					
Case ID	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIOT2.5/10	10 Hz	0.413	0.495	0.170	0.359
PIOT2.5/20	20Hz	0.315	0.609	0.236	0.387
PIOT2.5/30	30Hz	0.339	0.357	0.242	0.313
PIOT2.5/40	40Hz	0.693	0.253	0.412	0.453
PIOT2.5/50	50 Hz	0.165	0.047	0.132	0.115
3. CRUMBED RUBBER:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PICR2.5/10	10 Hz	0.351	0.550	0.303	0.401
PICR2.5/20	20Hz	0.308	0.119	0.355	0.261
PICR2.5/30	30Hz	0.580	0.430	0.403	0.471
PICR2.5/40	40Hz	0.402	0.392	0.586	0.460
PICR2.5/50	50 Hz	0.547	0.430	0.124	0.367
4. RICE HUSK:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIRH2.5/10	10 Hz	0.223	0.508	0.589	0.440
PIRH2.5/20	20Hz	0.434	0.241	0.531	0.402
PIRH2.5/30	30Hz	0.574	0.448	0.370	0.464



PIRH2.5/40	40Hz	0.428	0.454	0.453	0.445
PIRH2.5/50	50 Hz	0.695	0.622	0.630	0.649
5. SAW DUST:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PISD2.5/10	10 Hz	0.345	0.412	0.688	0.482
PISD2.5/20	20Hz	0.285	0.633	0.617	0.512
PISD2.5/30	30Hz	0.677	0.413	0.458	0.516
PISD2.5/40	40Hz	0.695	0.653	0.363	0.570
PISD2.5/50	50 Hz	0.595	0.397	0.579	0.524
6. SAND:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIS2.5/10	10 Hz	0.292	0.351	0.585	0.409
PIS2.5/20	20Hz	0.090	0.156	0.217	0.154
PIS2.5/30	30Hz	0.227	0.334	0.350	0.304
PIS2.5/40	40Hz	0.205	0.315	0.306	0.275
PIS2.5/50	50 Hz	0.379	0.490	0.503	0.457

4.4 RESULTS AND DISCUSSION:

Because of the large number of vibration tests conducted, only a sample from the results will be presented in a compact format. A characterization of the source of disturbance is followed by a discussion on the influence of the barrier dimensionless geometry on its screening effectiveness as well as the influence of the barrier depth and its proximity to the source of disturbance. The results are presented in terms of the amplitude reduction ratio (A_R). To assess the effects of the barrier geometry on the screening effectiveness, all vibration tests were conducted with the same initial conditions and the same vibrating frequencies. The vibratory system is controlled using an AC variable frequency drive. To ensure accurate and consistent vibration frequency at each frequency level during the five stages viz. 10, 20, 30, 40 and 50Hz, a vibro-

meter was used to check real vibrating frequency with an accuracy of about $\pm 0.25\text{Hz}$ before recording the responses. Figure 40, Figure 41, Figure 42 and Figure 50 show a typical time history and the corresponding Fast Fourier Transform (FFT) of the recorded signals that are measured on the ground along the monitoring path during stage one and the vibrating source is at first location i.e. $x = 2.5\text{m}$. The response at various channels G1 to G15, represented the ground response at specified observation at different locations. The obtained results displayed high quality signals for the harmonic excitations with different input frequencies. On the other hand, the Fourier spectrum indicates clearly that the ground response has the same dominant frequency as the frequency of the applied dynamic load.

4.4.1 Attenuation due to the Presence of Barriers:

The observations for attenuation due to barriers derived are as follows:

1. The field results show that the in-filled wave trench barrier can be considered as a practical alternative for wave scattering; and the observed protective effectiveness was up to 65% or higher.
2. The wave barriers protective effectiveness is influenced by the barriers normalized depth and the barrier's proximity to the source of disturbance. The barriers are found to be generally more effective when $D \geq 0.60$ (i.e. an optimum barrier normalized depth) for both open and in-filled trench barriers with in-filled material as Crumbed rubber, Rice husk and Saw dust. For x/d of about 0.79, 1.63 and 3.29, the normalized distance X of 0.45, 0.92 and 1.64 are the optimum barrier locations corresponding to the optimum normalized depth D of about 0.60.
3. The results show that a deeper trench is required as the ratio x/d increases to achieve the same improvement in the system's effectiveness. As the ratio x/d increased, the open trench barrier effectiveness decreased while no significant change was observed in the case of in-filled trench barrier effectiveness.
4. The experimental observations made in this study are valid for soil profiles considered in this study.



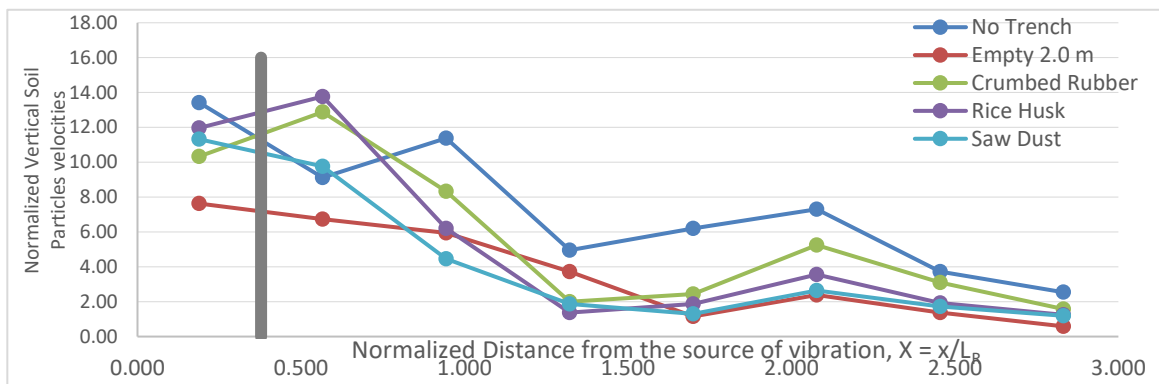
5. As shown in Figure 55 to 57, the measured soil particle velocities normalized by the soil particle velocity at one of the observation points (i.e. attenuation curves for vertical soil particles velocities) for the cases of No trench, Empty Trench and in-filled trenches for frequencies 30Hz, 40Hz and 50Hz. The results are presented for all the locations of source of vibration i.e. $x = 2.5\text{m}$, $x = 5\text{m}$ and $x = 10\text{m}$.
6. The recorded measurements follow the expected trends in terms of amplitude versus distance for all applied exciting frequencies. The results show a very abrupt decay, which indicates that the soil damping is high. This means that the ground motion is damped both geometrically and materially.
7. It is worth mentioning that as the frequency of the excitation increases, the geometric damping increases as well, which results in further attenuation of the generated surface waves.
8. It is observed from Figure 59 to Figure 63 and the calculated data that the observation points located up to 18m from the source of vibration is significant but beyond 18m from the source of disturbance, the attenuated velocity amplitude is less than 4-5% of that at the source for the ground conditions at this site. Therefore, the analysis of Ar and barrier effectiveness will be limited to a distance 18.0m from the source, as the amplitudes at larger distances are negligible, even without any wave barrier. Hence, the measured responses will not allow reliable and meaningful evaluation of the barrier effectiveness at distant points.
9. Also, Figure 59 to Figure 63 show the calculated amplitude reduction ratios for the three locations of the disturbance source for the exciting frequencies of 10, 20, 30, 40 and 50Hz in case of no trench and in-filled trenches. As it can be noted from the Figures, the amplitude reduction ratio changes randomly as the distance from the trench exceeds about 15.0m ($3.9L_R$ to $5.7L_R$). This may be attributed to two reasons: first, the reflected waves at the soil layers interfaces, which pass beneath the barrier are in-phase or out-of-phase; second, the vibration amplitudes are very negligible even without the barrier, and any variation in the response represents a large change in the ratio.



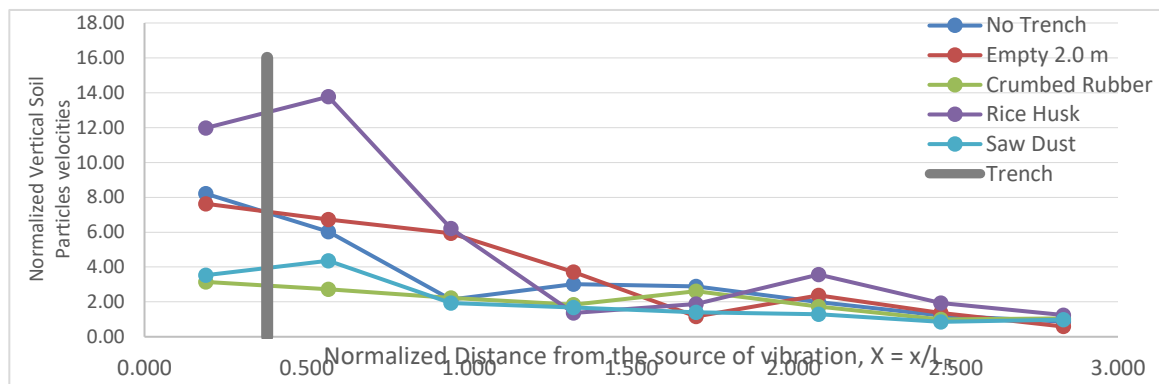
10. The in-phase and out-of-phase behaviour arises from the phenomena of minima and maxima. In other words, these are the points where waves are closest to exactly in-phase and out-of-phase with each other causing maximum and minimum A_r . This behaviour was documented by Woods [44] in his experimental study on open trenches, Baker [57] in his experimental on in-filled trenches and by Beskos [20]. In his study of sheet pile barriers as vibration isolators. It was noted that the distance to the principal minima decreases as the barrier depth increases, i.e. by increasing the exciting frequency. A similar behaviour is observed in this study. For example, Figure 57 shows clear minima immediately behind the barrier resulting in having a quiet area.
11. Local soil in-homogeneity and high soil damping can be considered the reasons of having many maxima as we move away from the barrier resulting in the random nature of the calculated A_r . On the other hand, as the distance away from the barrier increased, the vibration amplitudes were much smaller and thus the distant geophones measured negligible velocity values, which were possibly mixed with ground noise. When these small values are used to evaluate the amplitude reduction ratio, significant numerical errors are likely to occur. As a result, the large A_r values are suspect and are considered misleading and unreliable. Therefore, the readings of channels located within a distance of about 18m from the source will be included only when calculating the averaged amplitude reduction.
12. In case of Passive isolation tests, from the Figure 58, which shows the normalized vertical soil particles velocities, it is derived that the amplitude reduction ratio quite very good and the performance in terms of efficiency in all the cases ranging from 68% to 90%. It may be due to the reason that due to damping in materials, the amplitude reduces too much at farther locations from the source of vibration. And reduced energy has lesser impact on the propagation of waves. Overall, the performance in case of passive isolation is better than that of active isolation.
13. The screening effectiveness in terms of % age efficiency is presented in Table 13.

Table 14: Protective Efficiency of Barriers (%age) based on experimental study:

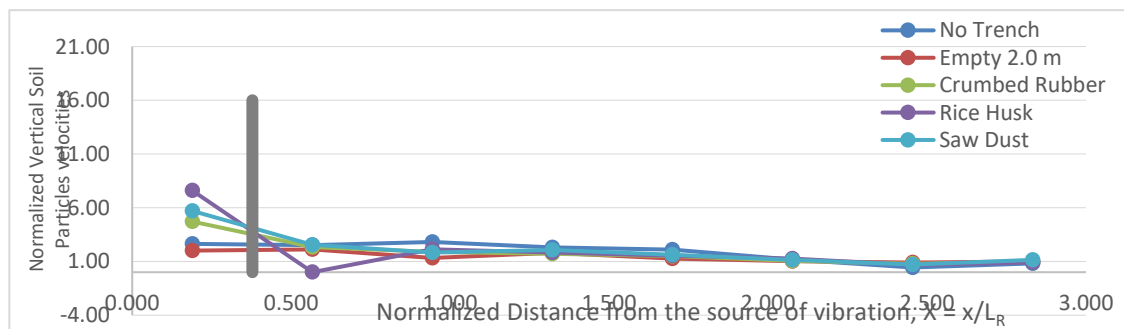
Trench Type	1 st Location	2 nd Location	3 rd Location	Average
1. Open Trench	80.10%	83.00%	85.50%	82.86%
2. Crumbed Rubber	57.30%	62.80%	63.20%	61.10%
3. Rice Husk	64.10%	68.00%	69.60%	67.23%
4. Saw Dust	56.90%	54.30%	59.80%	57.00%



(a)

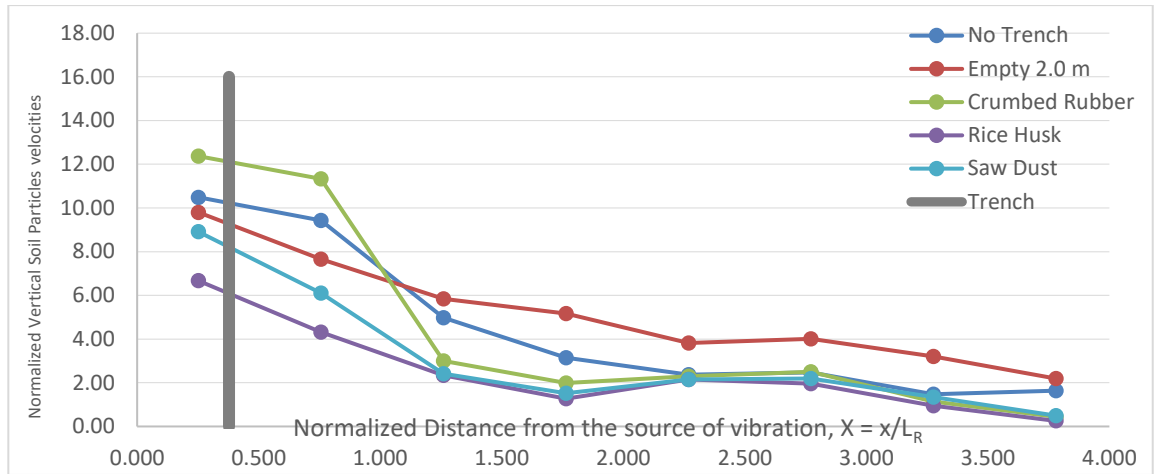


(b)

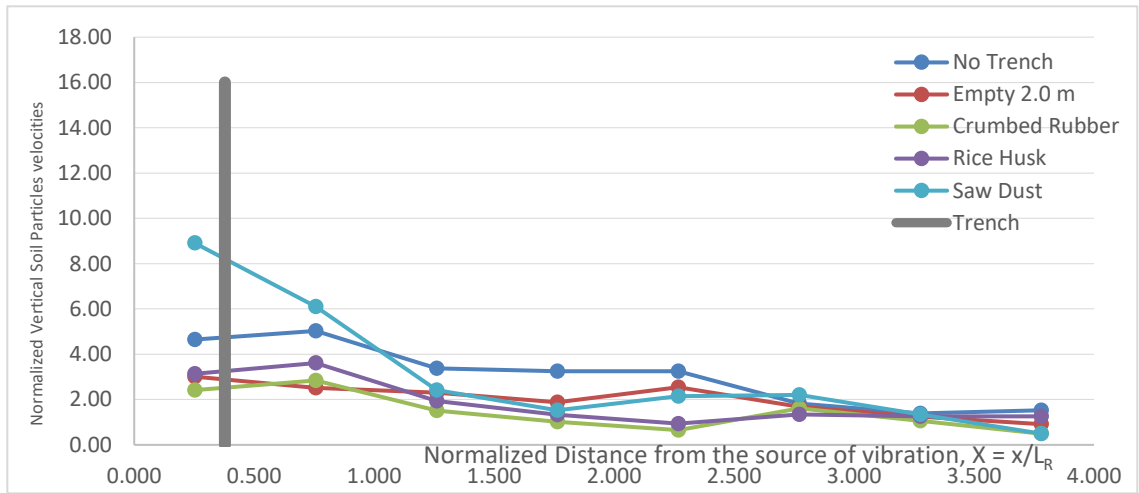


(c)

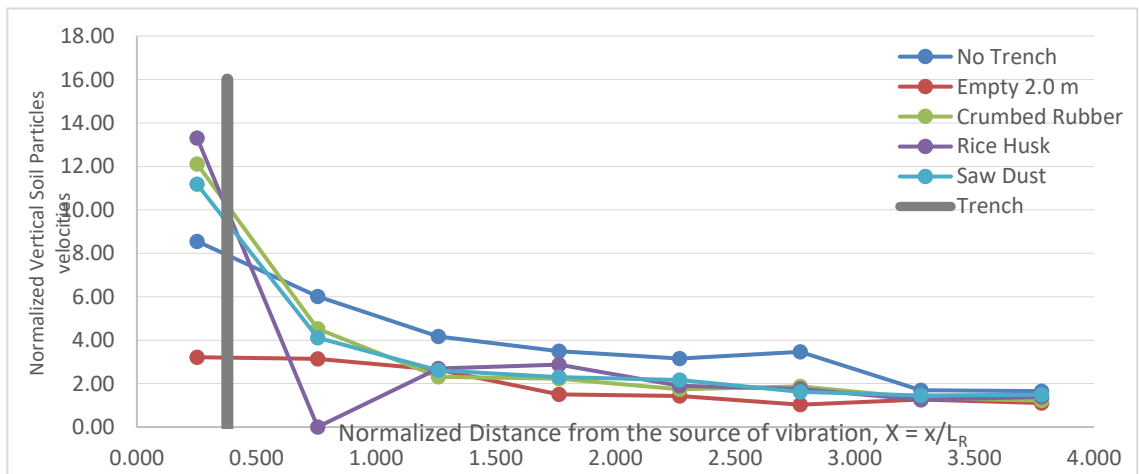
Figure 55: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 30\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from Centre of trench in active isolation



(a)

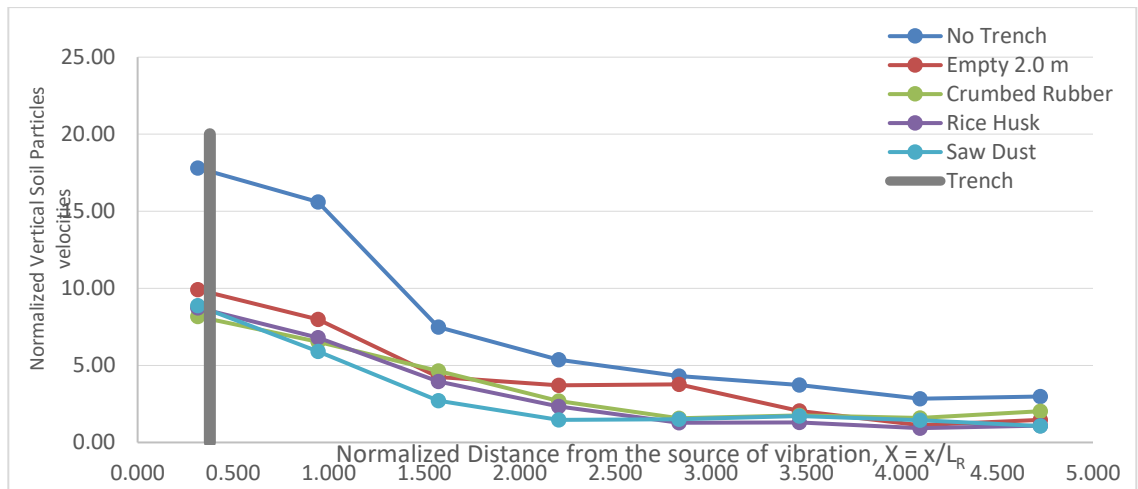


(b)

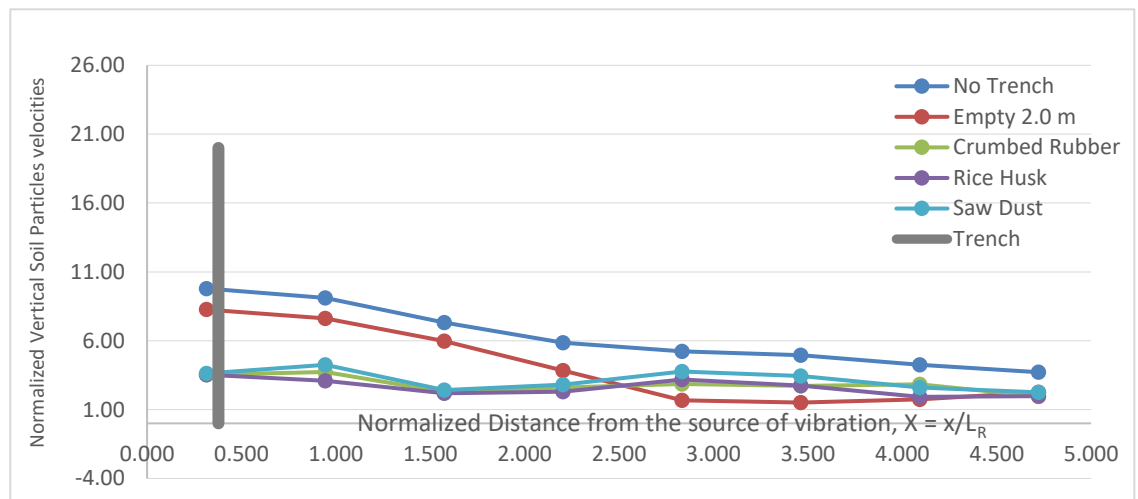


(c)

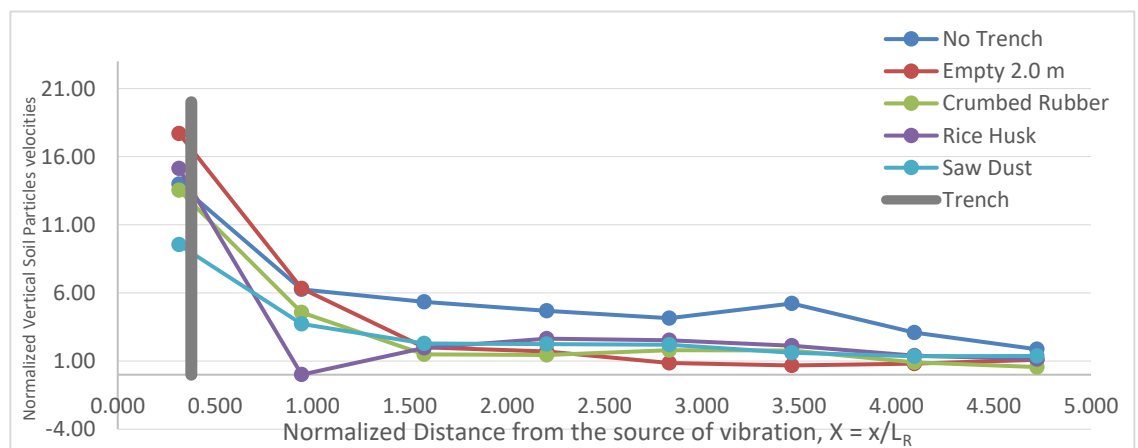
Figure 56: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 40\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from Centre of trench in active isolation



(a)

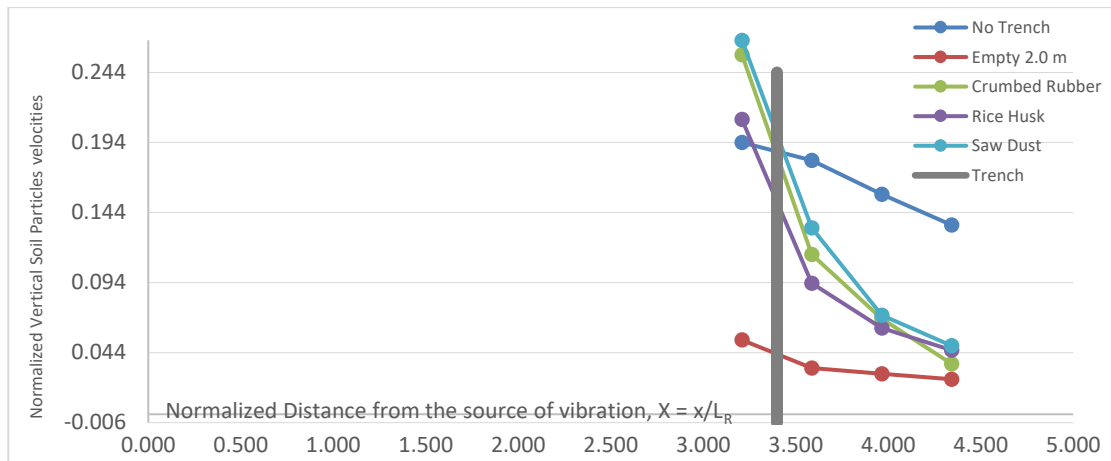


(b)

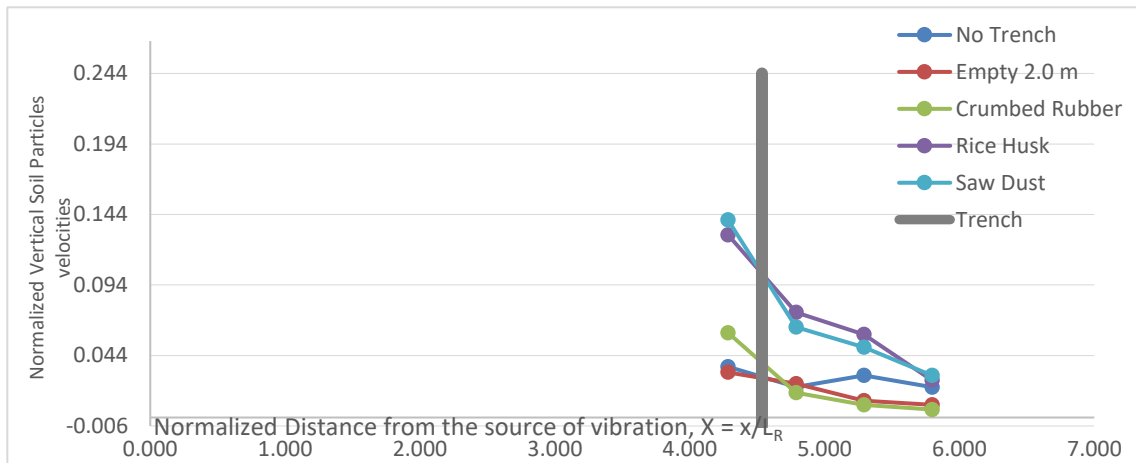


(c)

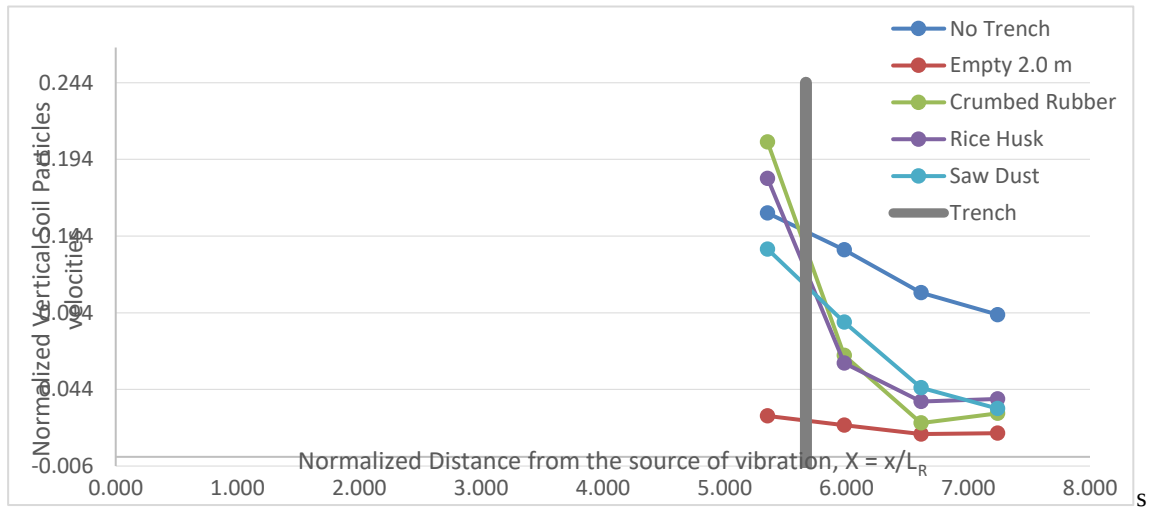
Figure 57: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 50\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from Centre of trench in active isolation



(a)



(b)



(c)

Figure 58: Normalized ground motion (G9 to G12) due to exciting frequency of (a) $f = 30\text{Hz}$ (b) $f = 40\text{Hz}$, $f = 50\text{Hz}$ when source of vibration at 23.75 m from Centre of trench in passive isolation

4.4.2 Effect of Barriers Dimensions and Location on Trench wave barrier performance:

The Rayleigh wavelength, L_R , decreases as the excitation frequency increases. Consequently, an increase in the frequency leads to an increase in the normalized barrier dimensions and the normalized distance, X , because all dimensions are normalized by L_R . However, the distance x is constant for every location but varied as the source of disturbance was moved from one location to another. Accordingly, the influence of the barrier normalized depth as well as the coupled effect of the barrier location to its depth will be discussed. All previously published experimental studies have been conducted on constant distance to depth ratios and only few studies had considered varying distance locations, which means the coupled effect of barrier location and depth together has not been taken into consideration. The influence of barrier normalized width is not the part of this field investigation since the proposed practical width to construct this type of in-filled trench wave barrier systems is 0.25m, which was found to provide excellent performance in scattering the induced ground vibration as described previously [39]. Therefore, the barrier performance will be assessed according to its normalized depth and the ratio of barrier-source distance to barrier depth. The normalized barrier dimensions & barrier-source distances are listed in Table 8.

Figure 55 & Figure 58 demonstrate the influence of the distance of source of vibration to the trench barrier normalized vs amplitude reduction ration i.e. on the effectiveness of open and three types of in-filled trench wave barrier systems. It is observed that as the normalized depth, D , is increased, the average amplitude ratio A_r (avg.) decreased. It shows the performance of screening improvised. The results show that a significant effectiveness can be achieved when the normalized depth is greater than or equal to 0.25. Therefore, the normalized depth of 0.25 can be considered as optimum depth for all the type of barriers. An overall amplitude reduction ratio of about 0.20 to 0.55 achieved for all type of barriers. As observed, the vibration amplitudes are reduced by or barrier effectiveness is 83% for open trench, 61% for Crumbed rubber, 67% for Rice Husk and 57% for Saw dust trench barriers respectively. Also in Figure 58, the effect



of barrier location normalized by its depth on the effectiveness of open and all types of barriers under investigation is shown. The adopted ratios of x/d are 1.25, 2.5, and 5.00 for the 1st, 2nd and 3rd locations respectively. It can be observed that as the distance between the barrier and the vibration source increases, a deeper trench is required in order to achieve a significant improvement in the system effectiveness. For example, in the case of an open trench barrier system, when $x/d = 1.25$ (first location), a significant improvement can be gained by placing the barrier at a normalized distance, $X \geq 0.25$ with $D \geq 0.15$. Meanwhile, for $x/d = 5.00$ (third location), similar improvement can be achieved by placing the barrier at $X \geq 1.50$ with $D \geq 0.25$. The same trend is observed in the case of Crumbed Rubber, Rice Husk and Saw Dust filled trench wave barriers. This means average system effectiveness of 80%, 57%, 61% and 57% can be achieved by placing the barriers at $X = 1-1.5$ for the cases of open and in-filled trench barriers respectively. Secondly, when $x/d = 2.50$, for average system effectiveness of 83%, 63%, 68% and 53% can be achieved by placing the barriers at $X = 1.64-2.75$ for the cases of open and three types of in-filled trench barriers, respectively. Furthermore, average system effectiveness of 85%, 63%, 70% and 5% can be achieved when $x/d = 5.00$ and $D = 0.50 - 0.84$ by placing the barriers at $X = 1.64-2.75$ for the cases of open and three types of in-filled trench barriers, respectively. It can be concluded that as x/d decreases, a shallower barrier can be used to achieve the same improvement in system effectiveness reason of choosing the present methodology in calculating A_r is that the trench had sufficient length (14 m) and was narrow, which means the edge effects can be ignored, especially at higher frequencies. On the other hand, published literature revealed that all the experimental studies were performed using small scale models while the experiments conducted in this investigation involves a large (full) scale setup in which the soil layering effects is expected to influence the results. Therefore, no strict and direct comparisons can be made between the present and previously published results.

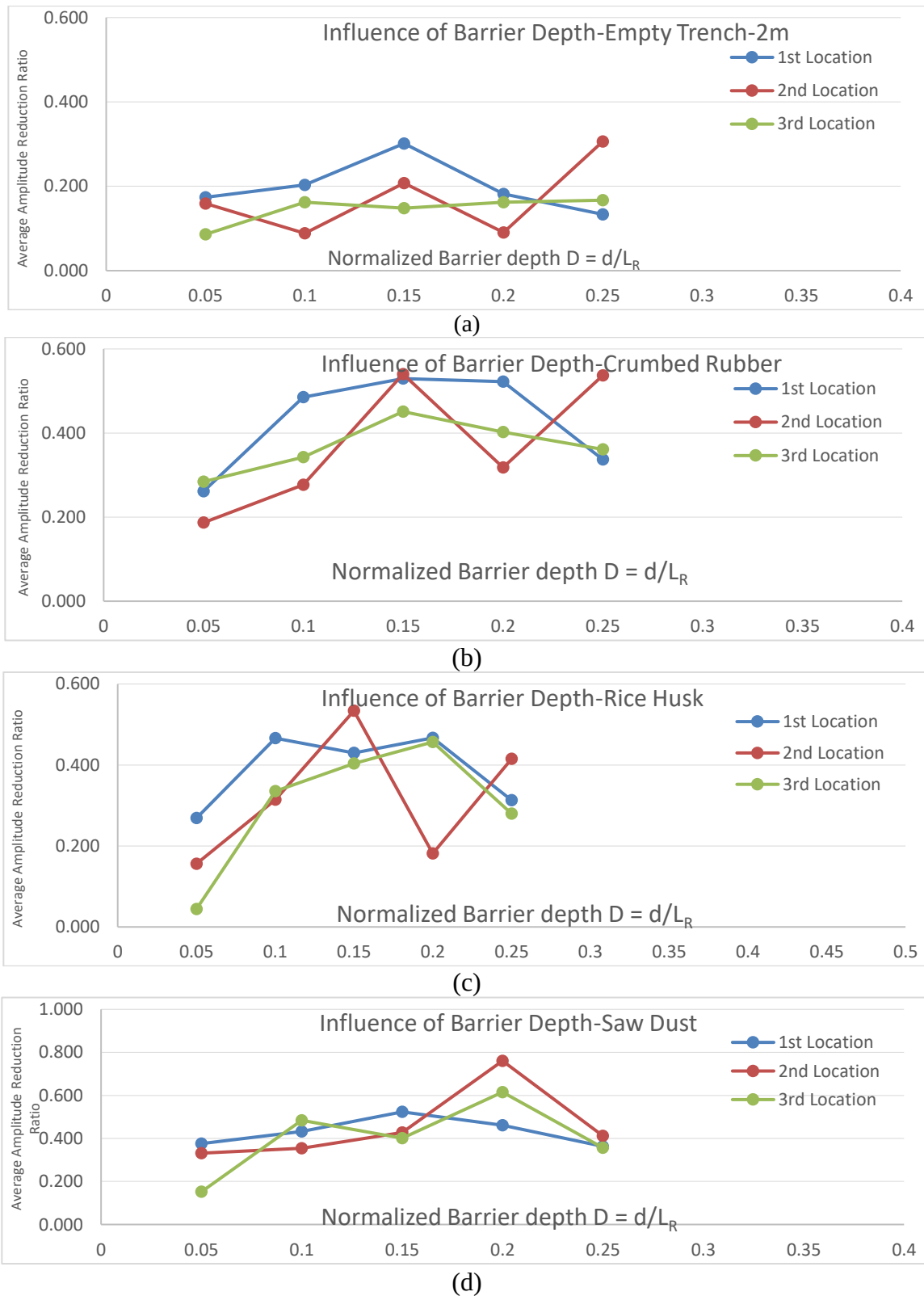
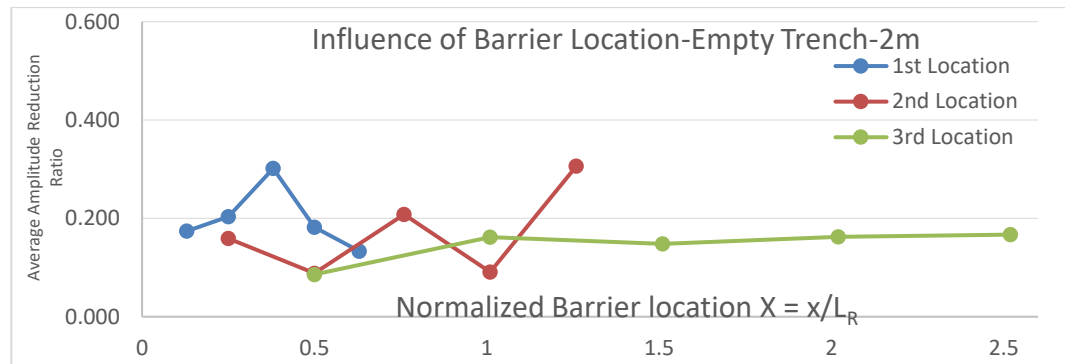
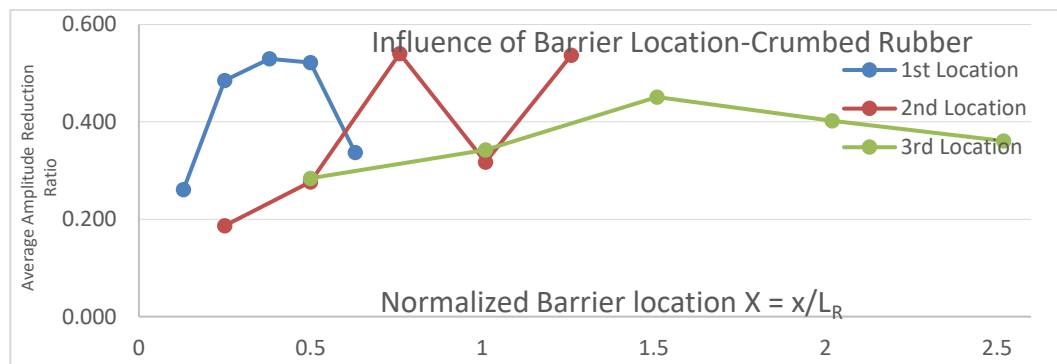


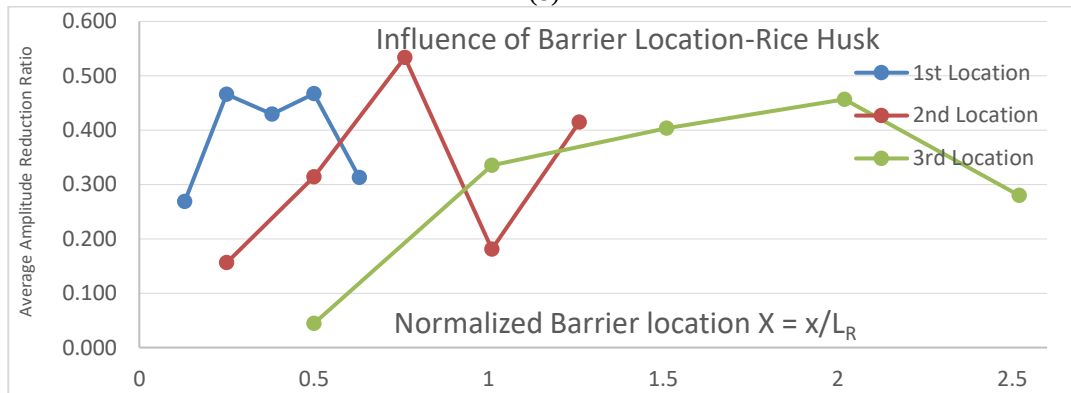
Figure 59: Effect of the normalized depth for barrier placed at different locations (a) Empty trench, (b) Crumbed Rubber (c) Rice Husk (d) Saw Dust



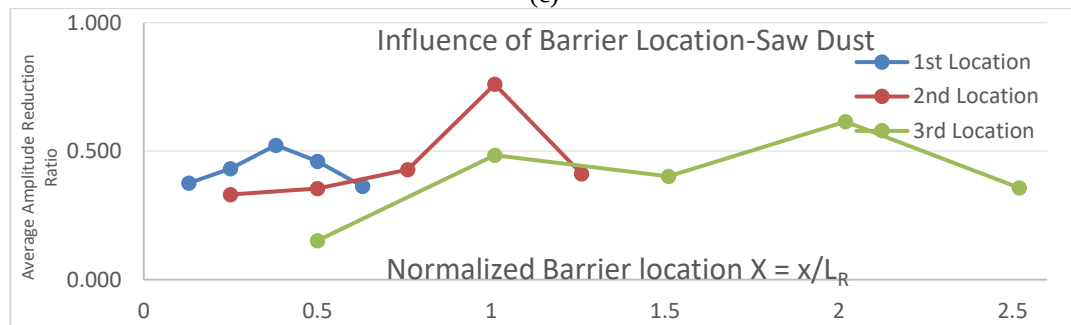
(a)



(b)



(c)



(d)

Figure 60: Influence of the normalized distance for barriers placed at different locations (a) Empty trench, (b) Crumbed Rubber (c) Rice Husk (d) Saw Dust

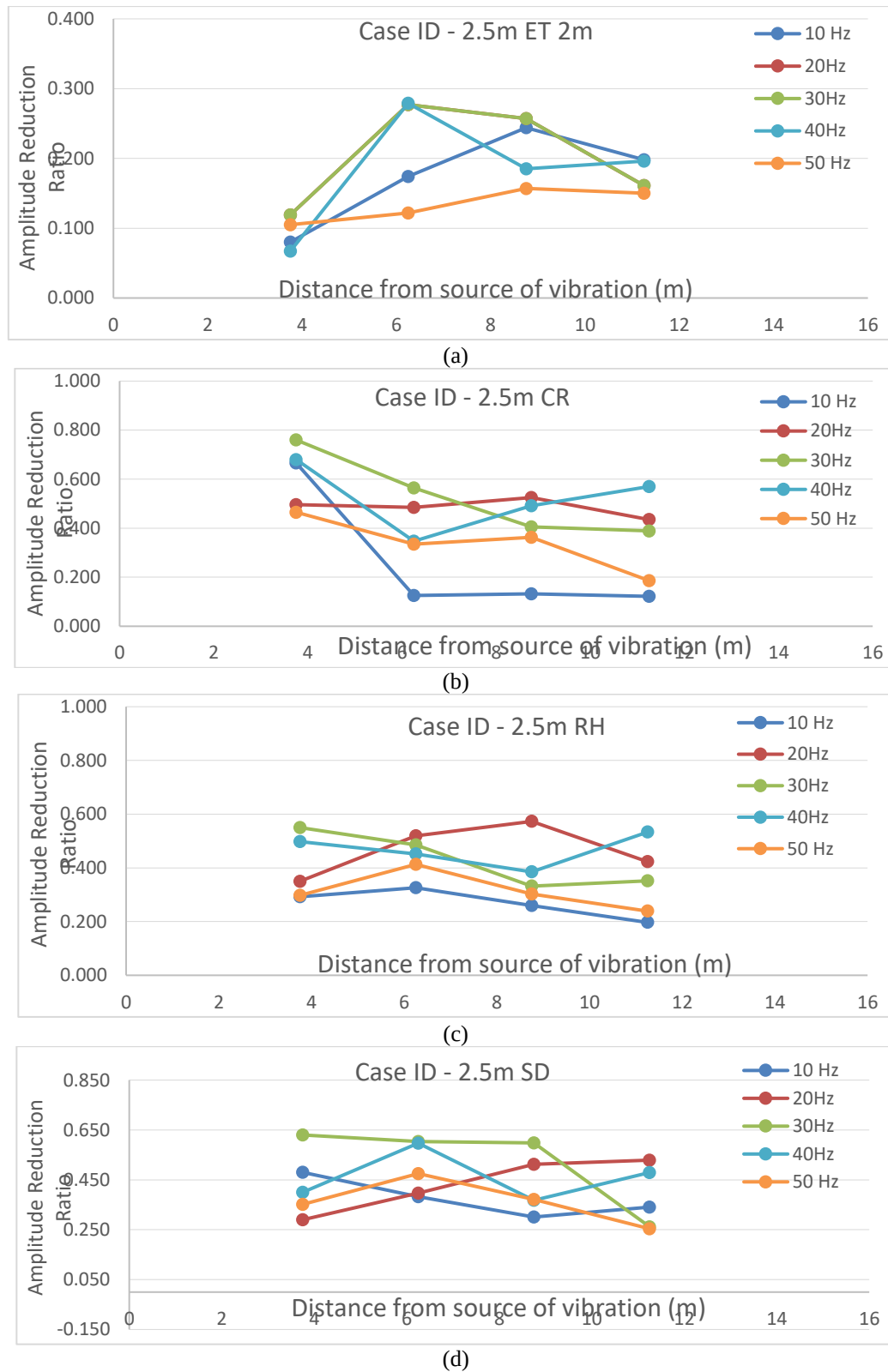


Figure 61: Amplitude reduction ratio for a trench at first location (x=2.5 m) (a) Empty trench-2m, (b) Crumbed rubber (c) Rice Husk (d) Saw Dust

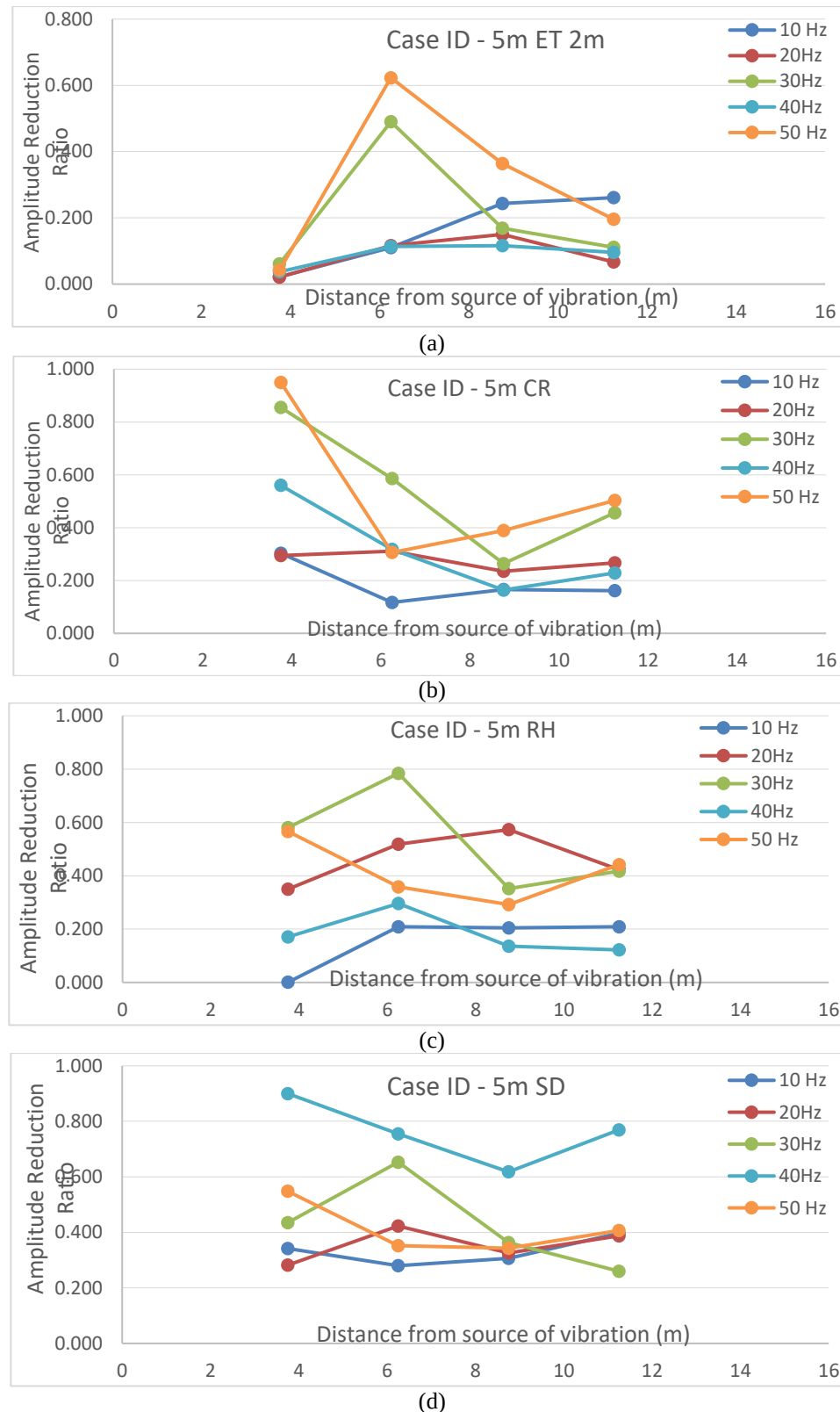
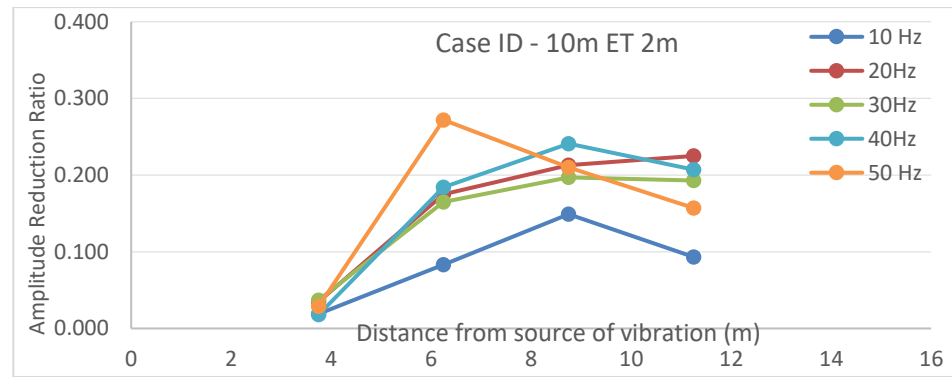
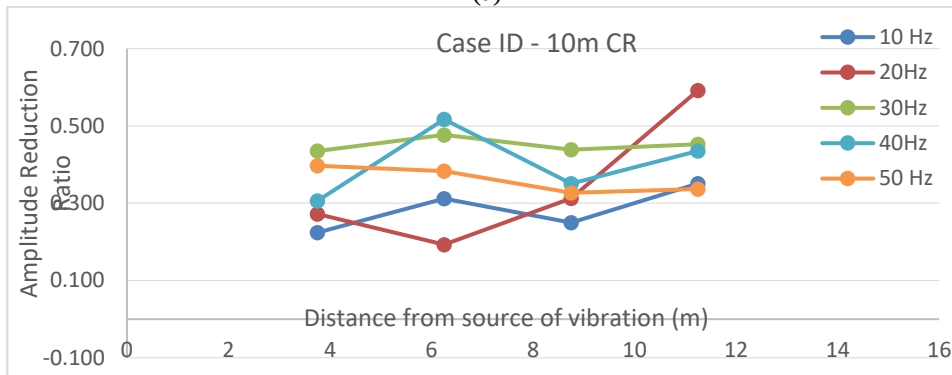


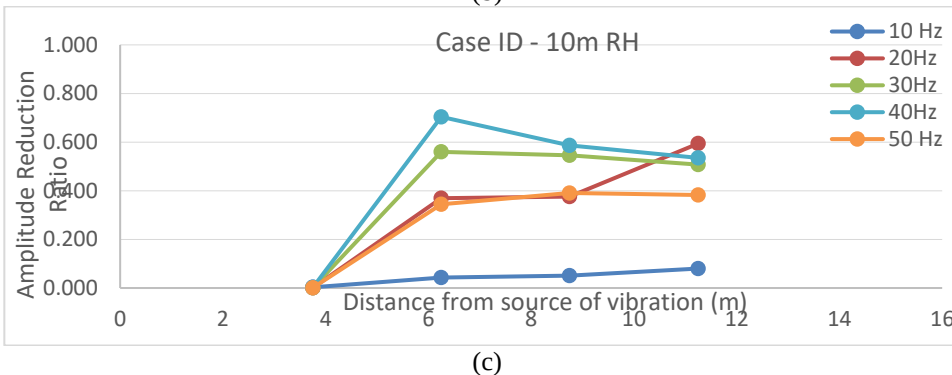
Figure 62: Amplitude reduction ratio for a trench at second location (x=5 m) (a) Empty trench-2m, (b) Crumbed rubber (c) Rice Husk (d) Saw Dust



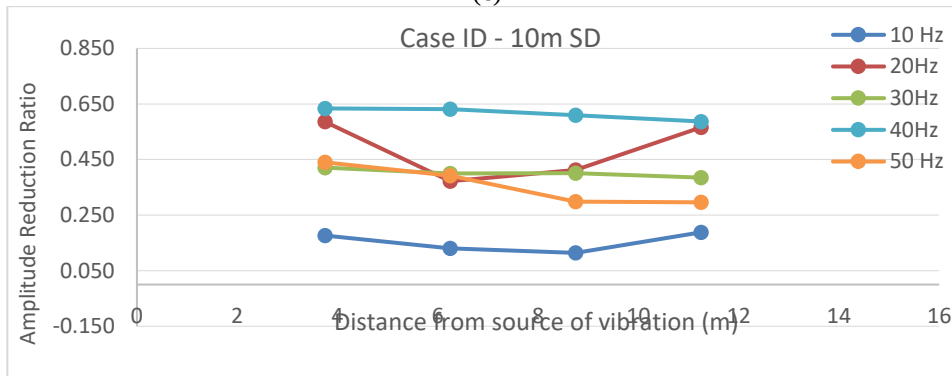
(a)



(b)



(c)



(d)

Figure 63: Amplitude reduction ratio for a trench at third location ($x=10$ m) (a) Empty trench-2m, (b) Crumbed rubber (c) Rice Husk (d) Saw Dust



4.4.3 Validation with Numerical study results:

Numerical models in Plaxis-3D were developed for each type of trench wave barrier and subjected to the test conditions as was in field. The results obtained were then compared with the field results. FE model results follow the same trend of the experimental results but with slightly higher values at some points and lower values at others. This may be attributed to considering horizontal homogeneous soil layers in FE model, which may be or may not be the case in the field. Another source of discrepancy between the experimental and FE model results is that the soil components contained stone or boulder components at some of the locations on ground at depth. Nonetheless, it can be concluded that the FE model can adequately represent the vibration scattering problem for the case of open and in-filled trench barrier. Thus, the model can be reliably used to extrapolate the results and conduct an extensive parametric study to better understand the crumbed rubber, rice husk and saw dust trench barriers.

4.4.4 Comparison with published data:

The ground motions were monitored along a center line perpendicular to the trench as shown in Figure 30, which has been used to calculate the amplitude reduction ratio, respectively. That means the vibration amplitudes are decreased (i.e. barrier effectiveness) by 82.86%, 61.10%, 67.23% and 57.00% for the open, Crumbed rubber, Rice husk and Saw dust filled trench barriers, respectively. On the other hand, published literature revealed that all the experimental studies were performed using small scale models while the experiments conducted in this thesis involves a large (full) scale setup in which the soil layering effects is expected to influence the results. Therefore, no strict and direct comparisons can be made between the present and previously published results. As per the result of Haput (1981), the Amplitude reduction ratio (A_r) comes to be in range of 0.285 to 0.375 whereas, according to Ahmad and Al-Hussaini (1991), the Empirical formula-based study, the results were in the range of 0.202 to 0.305. The results of present field investigation are on higher side of the published results. That is probably because of the true



nature of full-scale experiment in which a real wave propagation problem can be simulated taking into consideration a real soil conditions in terms of soil non-homogeneity and layering as well as the applied frequencies are the same as what soil will experience in practice. Besides, the difference in defining A_r could be another source having some discrepancy even though its influence will be minor. However, the results follow the same general trend which is as the trench normalized depth increased, a better screening efficiency is achieved. In terms of optimum normalized depth, the recommended optimum normalized depth in the study agrees with the minimum normalized depth recommended by Woods [34], $D=0.6$ for the case of active isolation to achieve a remarkable level of screening. Moreover, the material used for trench wave barrier in this study are of low stiffness and prone to more damping of energy during wave propagation.

4.5 COMPARSON OF RESULTS:

Some results documented in previous literatures on softer barrier isolation are compared with the results obtained. It can be seen that the charts provide results qualitatively comparable to the published values. The figure shows that there is a variation of about 20-23% in the results of experimental and numerical study. The difference may be due to practical aspect of the ground the practices implemented during experimental study. Overall, both the result some similar conformity and validating both the studies.

The comparison of results obtained through the present experimental study and the results already published in previous researches is tabulated in Table-14

Table 15: Comparison of the present experimental results with published results

Barrier dimensionless depth	Amplitude Reduction Ratio			
$D=d/l_R$	Haput (1981)	Empirical formula, Ahmad and Al-Hussaini (1991)	Alzawi (2011)	Present research
	Ar (Average)	Ar	Ar (Average)	Ar (Average)
0.57	0.375	0.305	0.169	0.414
0.71	0.323	0.241	0.163	0.411
0.84	0.285	0.202	0.155	-

* Present study subjected to 40 & 50 Hz only

4.6 SUMMARY AND CONCLUSION:

A field scale experimental test program was carried out to investigate the protective effectiveness of open and in-filled trenches as wave barriers to scatter the steady state vibration. In order to simulate the machine foundations vibration, an electro-mechanical oscillator was used. The wave barriers protective effectiveness was evaluated based on the achieved reduction in soil particle velocities through a method in which the amplitude reduction factor for active and passive isolation has been found. Also, parametric study by changing one of the parameters at a time, the response has been collected. Based on the obtained results and their analysis, the following conclusions can be made:

1. The field results show that the in-filled trench barrier can be considered as a practical alternative for wave scattering and the observed protective effectiveness was up to 82%.
2. The wave barriers protective effectiveness is influenced by the barriers normalized depth and the barrier's proximity to the source of disturbance. The barriers are found to be generally more effective when $D \geq 0.60$ (i.e. an optimum barrier normalized depth) for both open and in-filled trench wave barriers.
3. The results show that a deeper trench is required as the ratio x/d increases to achieve the same

improvement in the system's effectiveness. As the ratio x/d increased, the open trench barrier effectiveness decreased while no significant change was observed in the case of in-filled geofoam trench barrier effectiveness.

4. The experimental observations made in this study are valid for the soil profile considered in this study.

4.6.1 Progress of Project work at different stages:

The progress of project work in different stages starting from laying out trench to data acquisition is presented here as shown in Figure from Figure 64. to Figure 82.



Figure 64: Drone view of site location in CSIR-CRRI



Figure 65: Fixing layout of trench over the ground



Figure 66: Layout of trench and excavation in progress



Figure 67: Installation of Geophones and excavating pit for Oscillator



Figure 68: Discussion with CRR and DTU officials at site



Figure 69: Visit of CRRI officials at site



Figure 70: Removing Oscillator for next location



Figure 71: Drone view of in-filled trench under investigation



Figure 72: View of Electro-Mechanical Oscillator & Testing of its Footing



Figure 73: Installed Geophones on the centre line of the profile



Figure 74: Data acquisition during the experiment



Figure 75: Visit by divisional scientist on experimental site



Figure 76: Removing and shifting of Oscillator from one location to another



Figure 77: Empty trench and in-filled trench with material Crumbed rubber



Figure 78: Excavated pit for Oscillator and Oscillator set up with tripod system



Figure 79: Filling of trench with in-filled material and compaction in progress



Figure 80: Filling of trench with in-filled material and compaction in progress



Figure 81: In-filled rectangular trench with materials Rice Husk and Saw dust



Figure 82: Full set up for Electro-Mechanical Oscillator during run



Figure 83: Data acquisition during the experiment



CHAPTER-5

Numerical Investigation and Parametric Study



5.1. INTRODUCTION

Ground vibration induced by human activity such as industrial activities, high speed traffic, piling and blasting in construction or deconstruction operation, generally reaches the troublesome limit for human and occasionally attain the harmful limit. In the densely populated urban regions and buildings housing sensitive equipment, ground vibration has to be strictly controlled. Up to now, many vibration reduction methods have been proposed, one of which is the installation of wave barrier between the dynamic sources and the structure to be protected. Over the past decades, the vibration isolation effectiveness of wave barrier has been extensively studied. However, to the best of the writer's knowledge, there is little study about the mutual influence of the parameters of soil-barrier system on the barrier screening efficiency and the optimization design for wave barrier is rare as well. On the other hand, the influence of ground vibration generated by explosions on the nearby existing tunnel has attracted more and more attention due to the recent damage or even failure of tunnels. As of now, there are few mitigation measures comprehensively proposed by researchers and engineers for the tunnel vibration reduction during explosions. To overcome those drawbacks, this dissertation focuses on the investigation of the influence of various parameters of soil-barrier system on the barrier isolation efficiency. Key parameters are identified. More importantly, a developed optimization design method is developed, aiming to find out the desirable barrier that is able to minimize the ground vibration in protected site. Besides, the dynamic behaviour of existing tunnel under nearby explosions is examined. Parameters that significantly affect the response of tunnel are pointed out. Furthermore, two practical mitigation measures: the installation of a protective layer along the tunnel lining and time-delayed explosions (rather than instantaneous explosions), are presented with details. The research in this dissertation is able to provide a good reference for the optimization design of wave barrier in reducing ground vibration in protected site and for the design of practical mitigation measures to protect existing tunnel from nearby explosions.



Vibrations produced by factors except than seismic one, such as high-speed traffic, construction activities, deconstruction operation, vibrating machine footing, blasting, etc., cause nuisance and are not safe for human life in terms of health hazards. To mitigate the effects of such vibrations, screeners are used by means of providing in-filled trench wave barriers. The performance of in-filled trench barriers is significantly affected by properties of in-filled materials, its dimensions, Poisson's ratio, stiffness and density of the filling materials, distance between source of vibration and trenches, etc. The performance of in-filled materials will enhance if economy and sustainability features is added to desired properties of these materials. The performance of in-filled trench barriers demands support and validation after numerical or experimental study. This subjected study focuses on two major works (i) the numerical investigation on the isolation performance of wave barrier in reducing ground vibration generated by external load using in-filled materials as CR, RH and SD (ii) parametric study i.e. effect of geometrical parameters, properties of in-filled materials and location of source of vibration, etc. This paper deals with numerical study and then validation in which a 3D finite element study on vibration screening in PLAXIS-3D for steady-state surface vibrations by means of in-filled trench wave barriers in an elastic, isotropic, and homogeneous half-space. The in-filled materials used in trench barriers are Crumbed tyre rubber (CR), Rice husk (RH) and Saw dust (SD). Influence of geometric dimensions of trench wave barriers, shear wave velocity and source to barrier distances have been numerically studied for investigating the performance of in-filled materials on diminution of vertical and horizontal components of displacements in surficial soil layers. The study considered a non-dimensional approach where the geometric parameters are normalized in terms of wave length of Rayleigh waves of vibration in half-space. Shear wave velocity of in-filled materials is expressed as a ratio of that of in-situ soil. Trench wave barriers with shear wave velocity ratio less than unity are considered significantly effective. Effects of the parameters participating in vibration screening are elaborately discussed. Recommendations are framed regarding the optimal selection of geometrics of trench



wave barriers and for in-filled materials. Non-dimensional charts are developed which would provide a sound basis for designing such barriers in engineering application. The design charts are validated with some published results and found in close agreement.

Apart from seismic action, the sources for producing ground vibrations are high speed traffic, construction activities and deconstruction operation, vibrating machines, blasting, underground nuclear explosion, etc. Exaggerated ground vibrations are required to be properly screened off, otherwise, it may result in nuisance to the dwellers, fatigue of structural and non-structural components of the structure affected and malfunctioning of high-precision instruments. In mitigating vibration effect, vibration screening measures is an important development in vibration isolation. The measure consists of providing in-filled trench barriers in the path of propagation of surface waves from source to the affected structure. The effect is in form of abundant reduction in the amplitude of incident waves propagated in the way. Commonly used different types of barriers deployed for mitigating the wave amplitude are open and in-filled trench barriers, gas cushion, solid, hollow or sheet piles etc. Depending on the proximity of providing the barrier with respect to source of vibration and structure to be protected, there are two types of isolation; Active and Passive isolation. When the proximity of the trench barrier is near to the source of vibration is called as active isolation and when the proximity of the trench barrier is near to the structure to be protected is called as passive isolation. The energy produced by a surface source is distributed away which is a coupled form of waves consisting of all three types of waves i.e. Primary, Secondary and Rayleigh waves. While producing the vibration by vertical oscillation, Miller and Pursey [61] had found out the shares of energy between these waves in elastic half space. Rayleigh waves carry two third (almost equal to 67%) of total vibration energy and propagate in half space near to the ground surface zone. Being the prime reason, in vibration screening measures, wave amplitude reduction of Rayleigh waves is of prime focus. In concern with surface waves, Rayleigh waves have the feature of having maximum amplitude comparing with all other waves. It is the



reason why surface waves are disastrous among all waves. Also, wave attenuation of Rayleigh waves with respect to the distances from the source of vibration is slower than all other waves. The contribution of researchers in development of techniques for vibration isolation is dealt herewith as much as possible. According to Woods [62], measurement for amplitude reduction factor on straight trenches with various depths and lengths has been observed. Experimental study for evaluating the performance of in-filled materials has been already carried out [63]. To validate the results of an experiment, a numerical investigation is the requirement for validating the outcome. In the context of above, a numerical study for validating the experimental work is present here. Moreover, a parametric study affecting the performance of these in-filled materials and wave trench barrier is also dealt with.

5.1.1 Review of research

The efficiency of passive isolation is lesser than that of active isolation as observed by Beskos et al. [64]. The results were placed in form of amplitude reduction factor (A_r) contour diagram which showed that amplitude reduction is highest just behind the trench. The diversion of the surface waves at the trench end develops a zone of increased amplitude. Alzawi, Naggar [67] developed numerical models to further investigate the effectiveness of geofom trenches as wave barriers. 2D & 3D numerical models were developed in time domain using FEM software PLAXIS 3D. The parametric study is conducted by varying the key parameters such as barrier geometric dimension, location and soil properties. The barrier depth and location were varied independently as well as the soil dynamic properties. It was concluded that the soil density, Poisson's ratio and material damping are less significant. A deeper trench is required to achieve effectiveness as proximity of disturbance increases. Effectiveness of barrier improves in stiffer soil (with high V_s values). Belinassi et. al. [68] developed a numerical method based on the frequency domain direct BEM to solve vibration isolation problems for a homogeneous, liner elastic and isotropic medium. This methodology can be used to perform studies by varying the trench depth, length and width. It is also possible



to analyze the effect of distance between source and trench to obtain effective amplitude reduction or the scenario of multiple trenches. Javier, Sesma [69] studied the wave barrier problems for underground explosions. It includes theoretically study about the foundation isolation from vibrations using solid piles as wave barriers. It was proposed two models, one with piles of infinite length and second pile with finite length with different waves. In this study, effect of pile diameter, separation and length were considered and conclusion has been made relevant to guidelines for design. Baker [70] compared the experimental findings with the available numerical results in the literature has been obtained using the boundary element method (BEM) and the empirical design equations developed by Al-Hussaini (1992), but that was limited to the already derived equations.

Sivakumar Babu et. al. [71] carried out 2D numerical analysis using finite difference tool FLAC 5.0 was performed to suggest effective vibration isolation systems. In the analysis, the numerical model is first calibrated with respect to material properties, damping value, and boundary conditions to obtain the output comparable to the field test results. The calibrated model was further used to perform a parametric study, a decision on the isolation system was determined. The study demonstrates the use of vibration test results in the calibration of a numerical model and discusses the evaluation of effective vibration isolation systems using numerical simulations of various proposals. Kattis et. al. [72] solved the numerical problem of vibration isolation by using a row of piles in a 3D context by an advanced frequency domain boundary element method (BEM). An advanced-frequency domain BEM code has been developed for the dynamic analysis of complex 3-D elastic structural systems. The BEM analysis of a row of piles as wave barriers in vibration isolation problems is analogous to that of trenches with the only difference being the size of the problem which is always much larger for piles than for trenches. The general wave screening behaviour of piles is similar to that of trenches with the latter being always more effective than piles as wave barriers. Pile spacing, Length, depth and width of a row of piles influence its vibration isolation effectiveness in a

manner analogous to trenches. Gazetas [73] investigated numerically the vibrational behaviour of heterogeneous deposits with increasing wave velocities. Analytical numerical methods have been presented to study the dynamic behaviour of such deposits due to vertical-shear or Rayleigh waves. Studies show that as the heterogeneity increases, the attenuation with depth increases sharply. The decay with depth of Rayleigh-wave induced vibration has been found to be dependent on shear wave velocity, rate of heterogeneity and also on frequency.

5.2 WORK METHODOLOGY

The numerical investigation has carried out to calibrate and validate the experimental results obtained after operating the vibratory source at exciting frequencies in different condition of backfilling and in open trench. In numerical study also, the properties of in-filled materials are utilized in developing conditions of back filling as realistic. The problem is viewed in this study from a 3D perspective [83, 84]. Numerical investigation comprises of various sub components such as numerical modelling, assumptions in study, etc. Barrier geometric features are normalized against the Rayleigh wavelength in half-space to avoid dependency on the excitation frequency and half-space parameters. The simplified procedure for analyzing the model through Plaxis 3D is given in steps as follows:

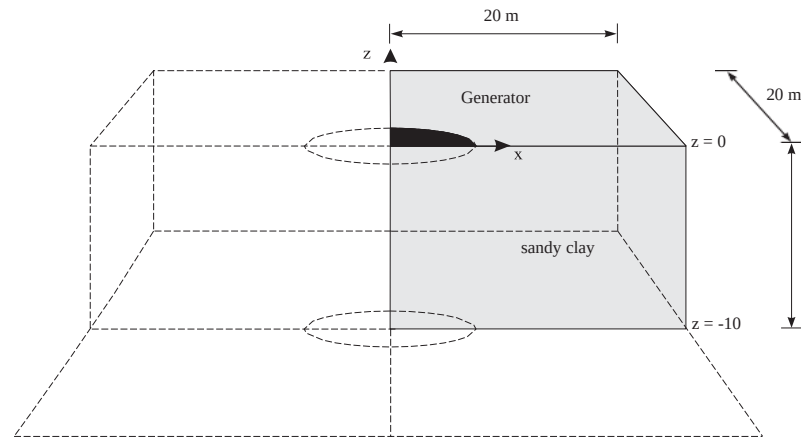
- (i) Assigning soil properties to elastic half space
- (ii) Creation of test site geometry
- (iii) Defining dynamic boundary conditions
- (iv) Defining dynamic loads by means of load multipliers
- (v) Defining material damping by means of Rayleigh damping
- (vi) Performing dynamic calculations

5.2.1 Numerical Modelling and Discussion

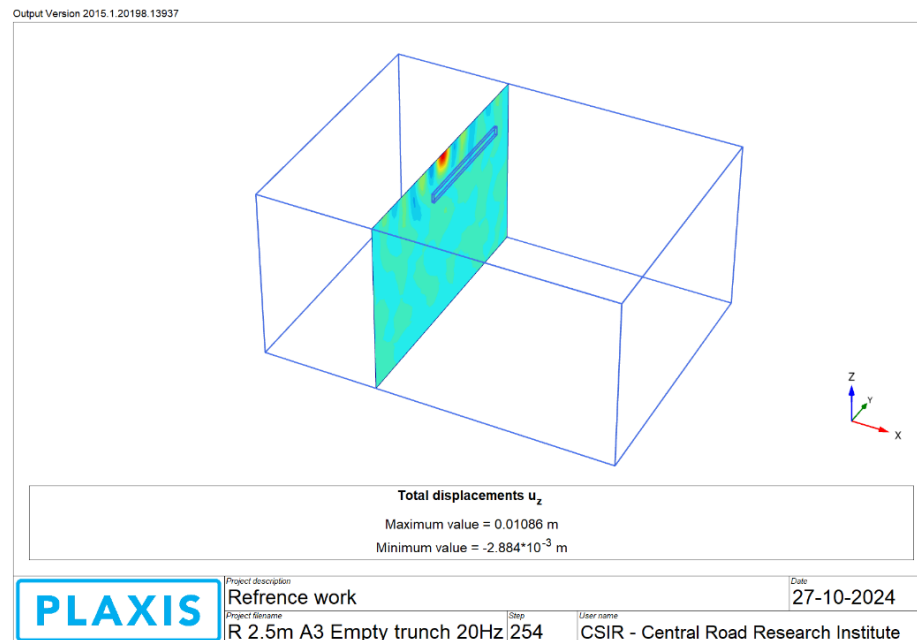
Finite element method (FEM) of modelling has become an important tool for predicting behavioural response to vibration problem. The finite element (FE) modelling approach provides a more precise tool that is capable of incorporating various aspects like soil continuity, dynamic load application, etc. Since FEM analyses require large number of computational resources, the geometric dimensions of the models are often kept to a minimum to reduce calculation time. PLAXIS 3D software has been used in the present research work and the model tests have been simulated in FEM based PLAXIS 3D. These boundary conditions were simulated by applying the standard fixities to the geometry as provided in software. In this study, the influence of a vibration source on its surrounding is studied. To reduce the calculation time, only one quarter of the overall geometry is modelled, using symmetric boundary conditions along the lines of symmetry. The physical damping due to the viscous effect is taken into consideration via Rayleigh damping.

5.2.2 Geometry and elastic half space parameters in the study

The model has been assumed as a case of dynamic analysis of a generator on an elastic foundation. The vibrating source is a generator founded on a 0.75 m thick RCC footing of 0.50 x 0.50 m size as shown in Figure 84. Oscillations caused by the generator are transmitted through the footing into the subsoil. These oscillations are simulated as a uniform harmonic loading, with a frequency of 10, 20, 30, 40 and 50 Hz with an amplitude of 10 kN/m². In addition to the weight of the footing, the weight of the generator is modelled as a uniformly distributed load of 8 kN/m². The model boundaries should be sufficiently far from the region of interest, to avoid disturbances due to possible reflections.



(a)



(b)

Figure 84: Source of vibration founded on an elastic subsoil

Although special measures (absorbent boundaries) are adopted in order to avoid spurious reflections, there is always a small influence and it is still a good habit to put boundaries far away. In a dynamic analysis, model boundaries are generally taken further away than in a static analysis. The size of the area to be under investigation is kept as $x = 40$ m and $y = 20$ m, the geometry model is shown in Figure 84.

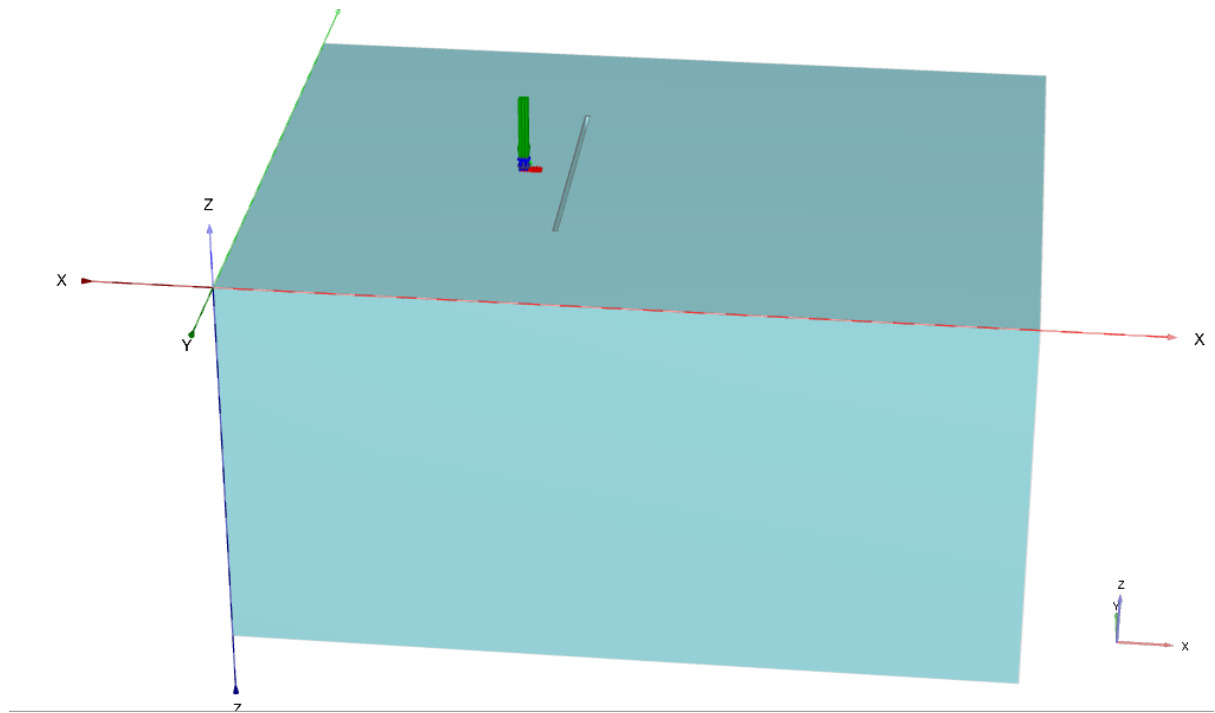


Figure 85: Geometry of the model in Plaxis-3D for active isolation at $X1 = 2.5\text{m}$

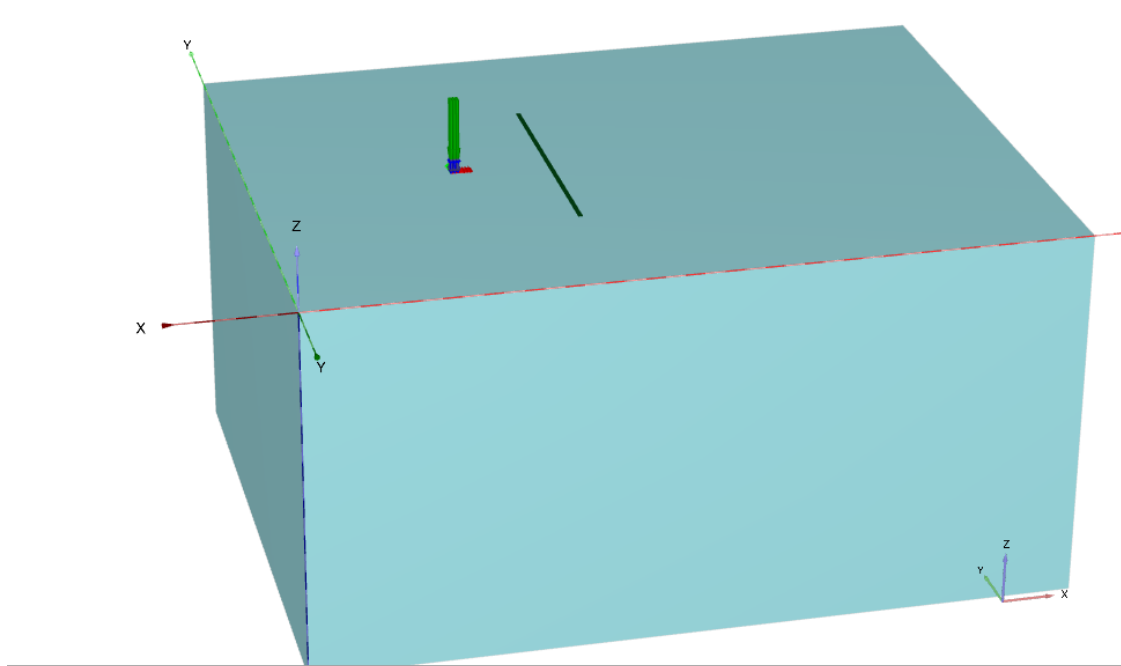


Figure 86: Geometry of the model in Plaxis-3D for active isolation at $X2 = 5\text{m}$

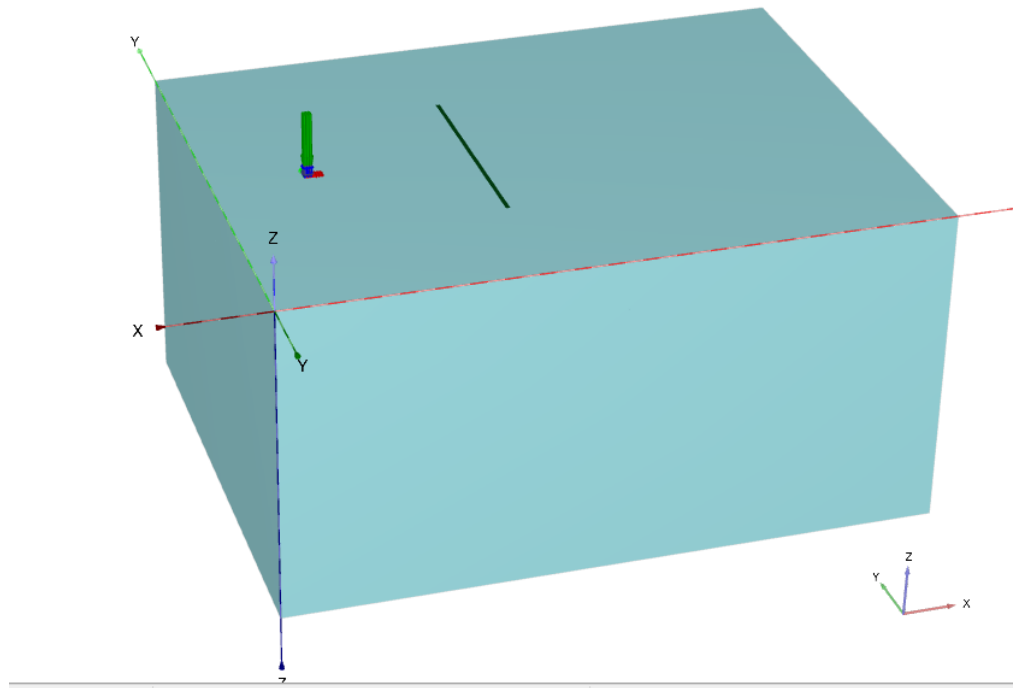


Figure 87: Geometry of the model in Plaxis-3D for active isolation at $X3 = 10\text{m}$

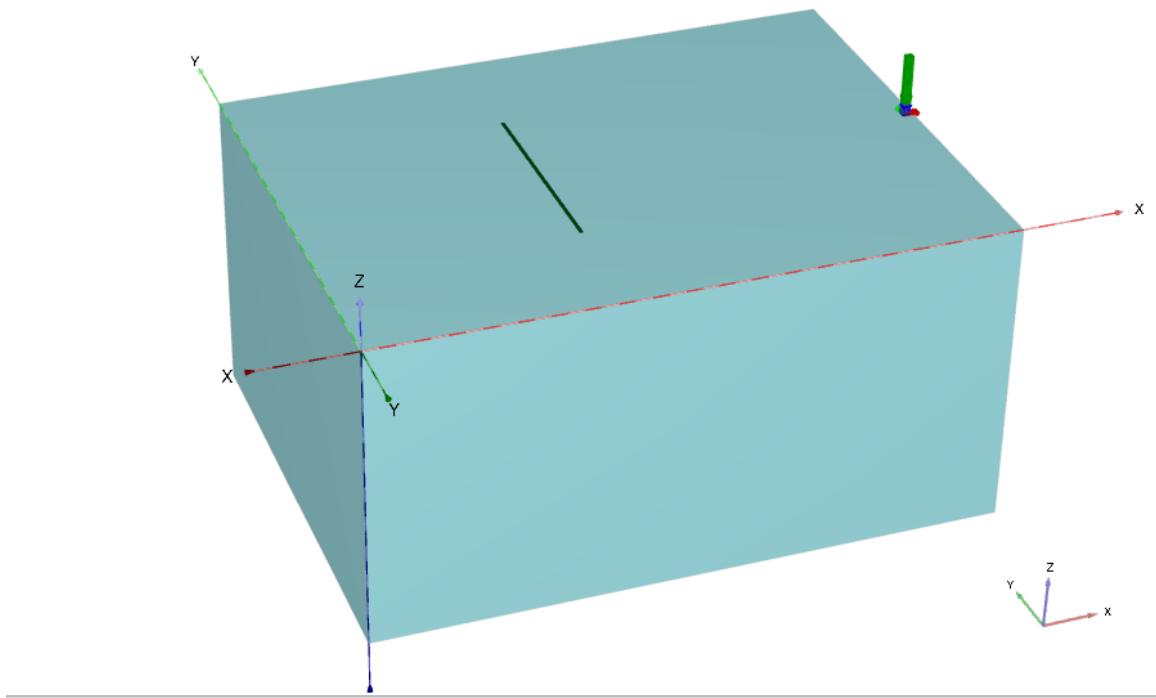


Figure 88: Geometry of the model in Plaxis-3D for Passive isolation $X4 = 23.75\text{m}$

The subsoil consists of one layer with a depth of 10m. The ground level is defined at $z = 10\text{m}$. The material data set and half space elastic parameters are assigned according to Table 15 and assigned it to the soil layer and geometrical properties of model as depicted in Figure 85 to 88. The water conditions are not considered in this study.

Table 16: Material properties for the soil layers:

S. No.	Parameter	Value
1.	Material model	Linear, elastic
2.	Element	10 Nodded
3.	Material model	Mohr-Coulomb
4.	Drainage type	Drained
5.	Unsaturated Unit weight	16.00kN/m^3
6.	Saturated Unit weight	16.15kN/m^3
7.	Young's modulus (E)	$33.00 \times 10^3 \text{ kN/m}^2$
8.	Poisson's ratio (ν)	0.30 (soil)
9.	Interface strength	Rigid
10.	Damping ratio (ξ)	7.50
11.	Element	10 Nodded
12.	Shear wave velocity of soil (V_s)	88.22 m/sec

The already published paper [21] can be referred for material parameter assumptions and properties. A sinusoidal varying vertical downward load of magnitude unity ($P_0 = 1 \text{ kN}$) and frequency of excitation 10 Hz and amplitude of 10 N/mm^2 is assumed to act uniformly over an imaginary footing of width, $B = 0.50 \text{ m}$. Footing mass is ignored not taken into calculations as the effect of footing mass on isolation effectiveness of a barrier is found insignificant [69]. The half-space parameters and excitation frequency, the shear wave velocity (V_s), Rayleigh wave velocity (V_R), and Rayleigh wavelength ($L_R = V_R/f$) of half-space are as per Table 16. The density, Poisson's ratio, material damping and elastic modulus of backfill materials are as per the Table 16.

Table 17: Properties of Back filled materials:

S. No.	Name of backfill material	Density (g/cm ³)	Poisson's ratio	Damping %	Elastic modulus kN/m ²
1.	Crumbed Rubber (CR)	0.37	0.45	22.00	10.53 x 10 ²
2.	Rice Husk (RH)	0.33	0.40	20.00	3.64 x 10 ²
3.	Saw Dust (SD)	0.23	0.37	12.40	3.71 x 10 ²

5.2.3 Normalized dimension study

Barrier geometric features are normalized against the Rayleigh wavelength in half-space to avoid dependency on the excitation frequency and half-space parameters. The geometric parameters, i.e. trench barrier distance from source (l), its depth (d), and width (w) are expressed in terms of Rayleigh wavelength as: $l = L \cdot L_R$, $d = D \cdot L_R$, and $w = W \cdot L_R$ as depicted in Figure 5.4. Here, 'l', 'd', and 'w' are dimensionless quantities and respectively denote distance of the barrier from source, depth, width respectively and ratio (V_b / V_s) is, therefore, used to investigate the effect of backfill material characteristics. Material damping of backfill is applied as per available test results. The shear wave velocity is a function of elastic modulus, density, and Poisson's ratio, implying that variations of any of these parameters would bring about a change in shear wave velocity. Backfill shear wave velocity is varied by altering its elastic modulus, keeping other parameters same. The sample of parametric properties in numerical study is shown in Figure 89. The schematic view of the problem studied: Active and passive vibration isolation by rectangular trench system and geometrical parameters is shown in Figure 90.

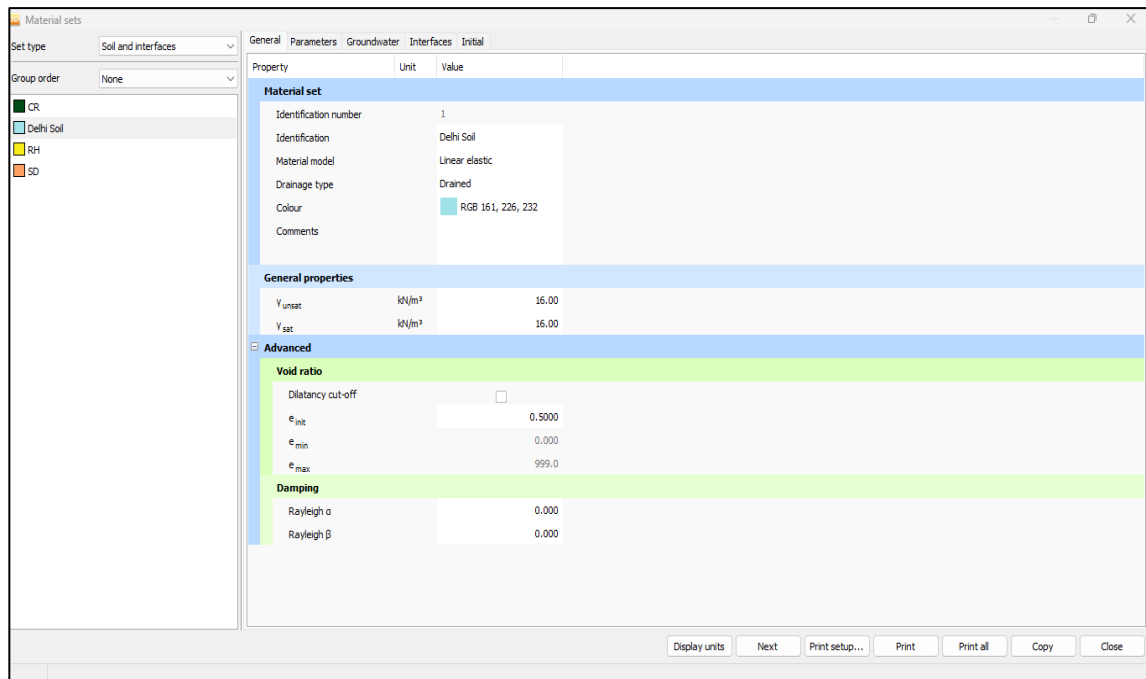


Figure 89: View of material properties used in FEM model study

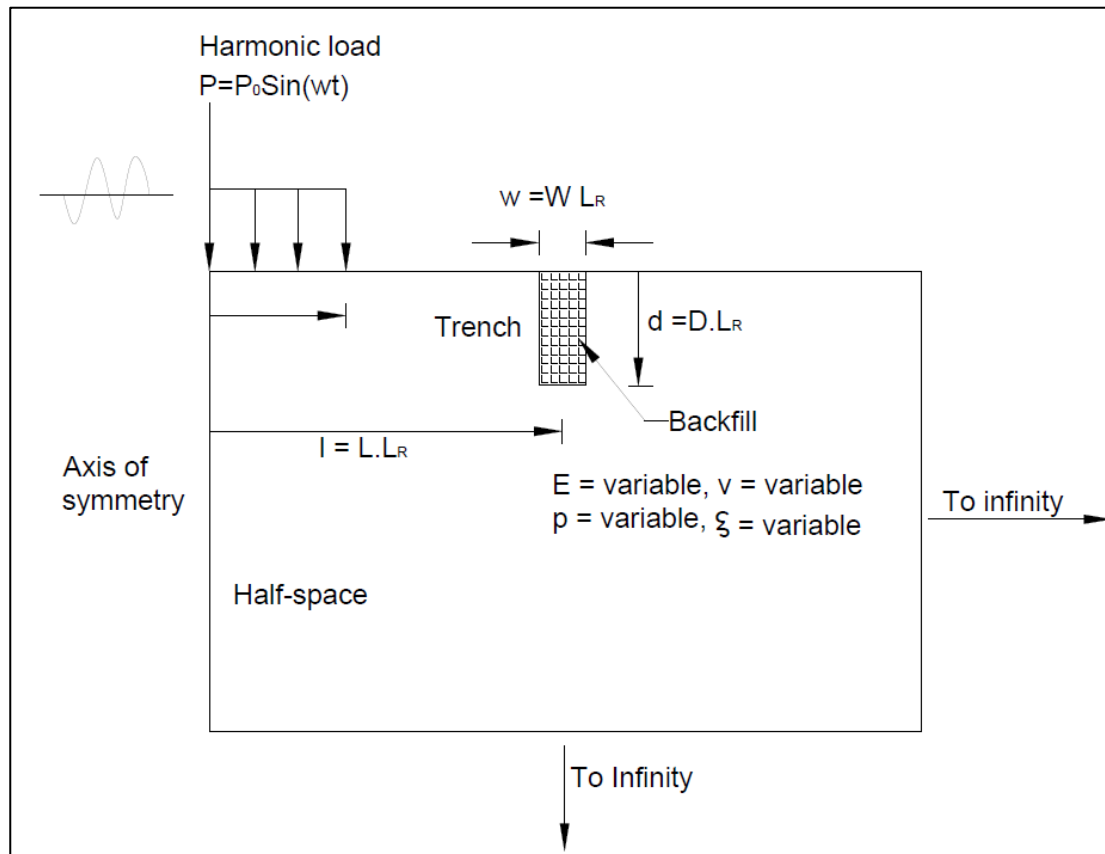


Figure 90: Schematic view of the problem studied: Active and passive vibration isolation by rectangular trench system and geometrical parameters



5.2.4 Finite element model and Validation:

The study is performed in PLAXIS 3D with finite element models of dimension 40m x 20m discretized with ten noded triangular mesh elements. A zone extending to a distance of $10L_R$ from source is indicated to be sufficient for wave barrier analyses. Against a Rayleigh wavelength varying with the frequency, the crucial zone extends to 40 m from source. The reason behind adopting somewhat higher model length is to avoid any likelihood of interference problem which could arise due to wave reflection at boundaries. The adequacy of model dimension is affirmed by convergence studies by subjecting an undisturbed half-space (assigning the assumed soil parameters and boundary conditions) to a steady-state excitation of stated magnitude and frequency. Repeated trials are made on models of different dimensions and based on the convergence of the plots between peak particle displacements and distance from source, a dimension of 40 m x 20 m is finally adopted. The model boundaries are assigned to standard fixities that imposes horizontal fixities ($u_x = 0$) to the symmetry edge and right-hand boundary and total fixities ($u_x = u_y = 0$) to the bottom boundary. The bottom and right-hand model boundaries are subjected to special absorbent boundary conditions available in PLAXIS to allow for absorption of dynamic stresses. Absorbent boundaries are created with Lysmer and Kuhlemeyer [84] dampers and on the basis of previous study, the wave relaxation coefficients assigned to these boundaries for reasonable absorption of compression and shear waves are taken as, $C_1 = 10$ and $C_2 = 0.25$. The convergence studies also justify that the wave relaxation coefficients assigned to the absorbent boundaries allow for sufficient wave absorption.

Linear elastic material model is used for modelling soil and backfill clusters considering the material type as drained. Material damping is assigned to half-space and backfill by introducing Rayleigh mass and stiffness matrix coefficients (α and β). The mesh division is done using medium elements with local refinements along the surface and in backfill cluster. Use of local refinement tool enables further subdivision of mesh elements ensuring higher degree of precision. A steady-state excitation of magnitude 1

kN/m and frequency 10 Hz is applied over one-half of the assumed footing width as axi-symmetric models are used. A time interval of 0.5s. is chosen for the dynamic analyses and computations are done in 1000 steps in total, keeping the time-step of integration (δt) as 0.0005s. Chosen time interval is sufficient to permit the complete transit of dynamic disturbance in the zone of investigation. Peak surface displacement amplitudes are estimated from displacement-time histories at pre-selected nodes in intervals of $0.5L_R$ beyond the barrier. A typical schematic view of problem and finite element model showing generated mesh, dimensions and boundary conditions etc. is presented in Figure 91 and Figure 92 respectively.

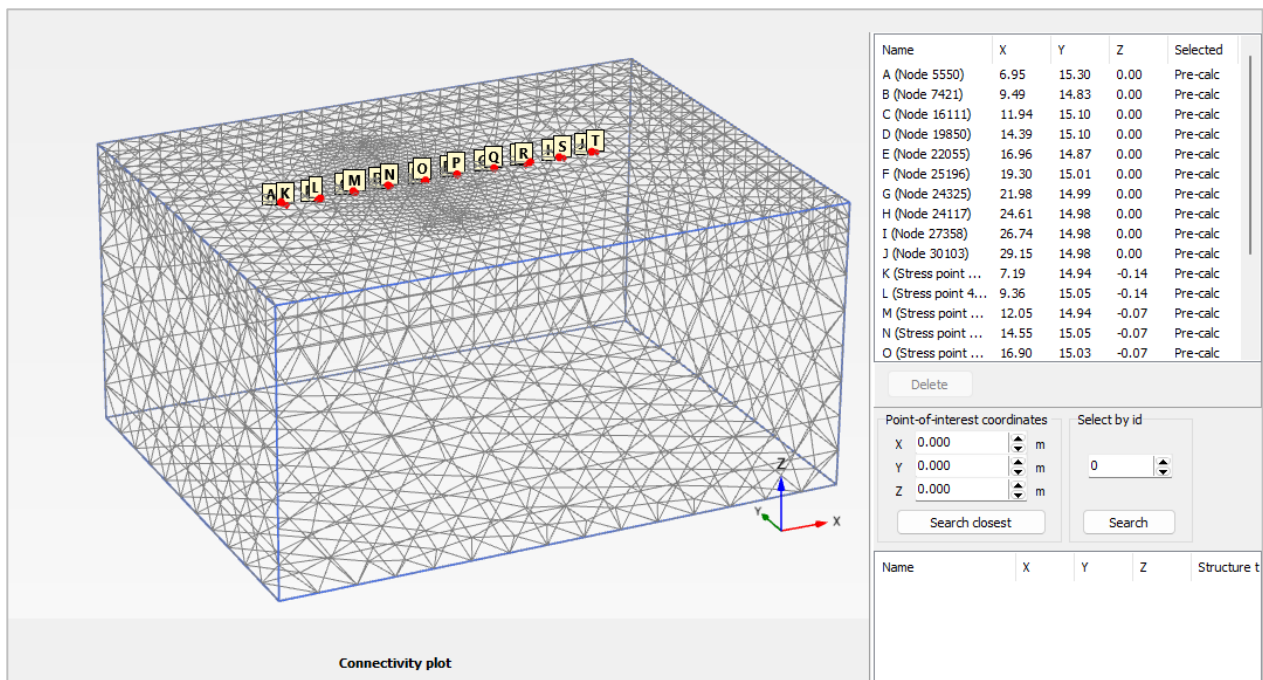


Figure 91: View of Deformed mesh with selected nodes and stress points for observation

This modelling scheme is validated with reference to an isolation example by an open trench of dimension, Depth = 2 m, Width = 0.25 m, and Length = 14 m. The dynamic load was applied for each case of an open trench, trench filled with Crumbed rubber, Rice husk and Saw Dust with five nos of different frequencies and four nos of locations. The vertical dynamic load was applied with frequency of 10, 20, 30, 40 and 50 Hz. the source of vibration was located in four different configurations with reference to centre line of trench

i.e. for 2.5 m, 5.0 m, 10 m on one side and 23.75 m on other side. Amplitude reduction factors at different distances from source are found to be in excellent agreement with experimental work as presented in Chapter 4. Readers may refer to author's previous works as presented in Chapter 3 for material parameters and validation.

5.2.5 Effectiveness of vibration isolation

The effectiveness of isolation of trench wave barrier is assessed in terms of amplitude reduction factor (A_{rf}) which is defined as the ratio of surface displacements amplitudes after barrier to the surface displacements amplitudes before barrier. The overall degree of isolation over a zone of study is expressed in terms of average amplitude reduction factor (A_m) as A_{rf} values are not uniform throughout the zone. A_m is defined as the weighted average of the A_R values measured at different distances from source (x) over the zone of interest. Lesser value of A_m indicates a better screening effect.

$$Ar = \frac{\text{Displacement amplitude of ground surface after barrier}}{\text{Displacement amplitude of ground surface before barrier}}$$

$$Ar = \frac{(Ar)_{After}}{(Ar)_{Before}} \quad (3.1)$$

To evaluate the system effectiveness (screening effectiveness) of the wave barrier system, the averaged amplitude reduction ratio (A_r) over a distance of interest $x_{measured}$ behind the wave barrier can be calculated using the following equation:

$$Ar = \frac{1}{x} \int Ar \, dx \quad (3.2)$$

Thus, the system effectiveness is calculated using Equation 3-4 as follows:

$$Eff = (1 - Ar) \times 100 \quad (3.3)$$

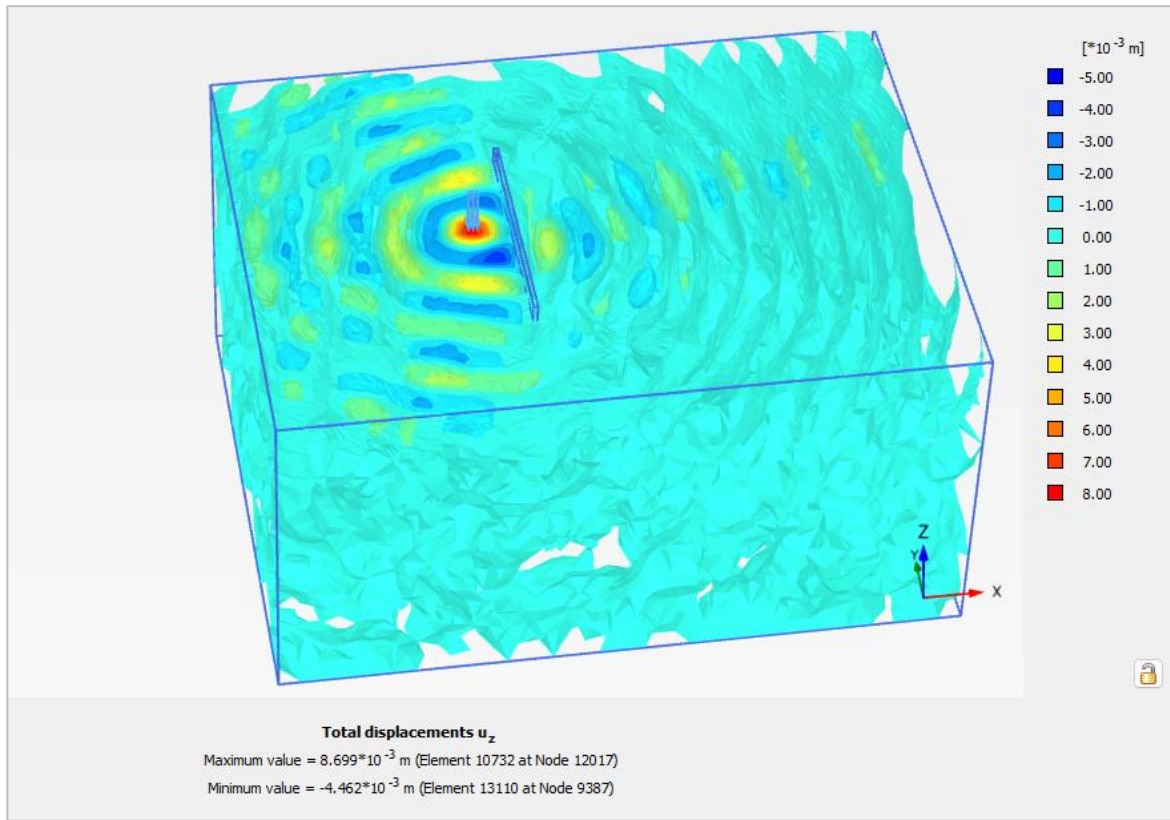


Figure 92: Colour contouring for deformation in in-filled trench with Crumbed rubber

5.2 Effect of Parameters

In order to perform a dimensionless parametric study, the geometric features are expressed in terms of Rayleigh wavelength and backfill material parameters in terms of backfill shear wave velocity ratios. In the subsequent sections, notation U_x is used to denote the horizontal vibration components, while A_x refers to the average amplitude reduction factors of the respective component. Other notations have their usual meanings as previously explained. As already stated, the geometric features and backfill shear wave velocity ratio are the parameters that govern the isolation effectiveness of in-filled trench. Effects of these parameters are discussed in the following sub-sections. However, softer wave barriers characterized by shear wave velocity ratios less than unity are considered as they are found significantly effective than stiffer barriers.



5.3.1 Effect of various properties on Attenuation of wave motion

Screening performance of in-filled materials in trench barrier depends on the property i.e. attenuation of waves. Wave attenuation is affected by number of factors such as stiffness, particle size, specific gravity, saturation and dynamic properties such as damping ratio, shear modulus and shear wave velocity. The case stated in Figure 90 is investigate here with different factors affecting performance in screening. Unless specified, the properties of soil and back filled materials are as per the Table 16. Though, there is less availability of resources revealing much about the dependence of the factors on wave attenuation, the influence of these factors on the attenuation of wave is dealt herewith.

Initially, the effect of overall extent of the area to be projected on the average amplitude reduction ratios is observed. Figure 95 to Figure 102 gives the concept of the normalized ground displacement amplitudes which is normalized with respect to ground displacement. The difference between the curves and the reduced effect in curve shows significant reduction in amplitude achieved at subsequent observation points. For a particular size of open and in-filled trench. In terms of normalized depth D and normalized width W , the frequency was varied from 10 to 50 Hz. For the case of passive isolation, the incident wave motion principally consists of Rayleigh wave energy. Placing an open or in-filled trench means creating a finite geometric or material discontinuity for the wave field in the otherwise undisturbed half-space. Based on available literature (Richart et al. 1970; de Bremaecker 1958; Haupt 1977, 1978; Fuyuki and Matsumoto 1980), a brief qualitative description of the complex wave process is presented here. Figure 93 shows the Rayleigh wave incident on an in-filled (or open) trench. After incidence on the trench, it gives rise to:

- (1) Reflected Rayleigh wave (R-wave)
- (2) Body (P and S) waves that radiate outward from the trench and
- (3) Transmitted R-wave

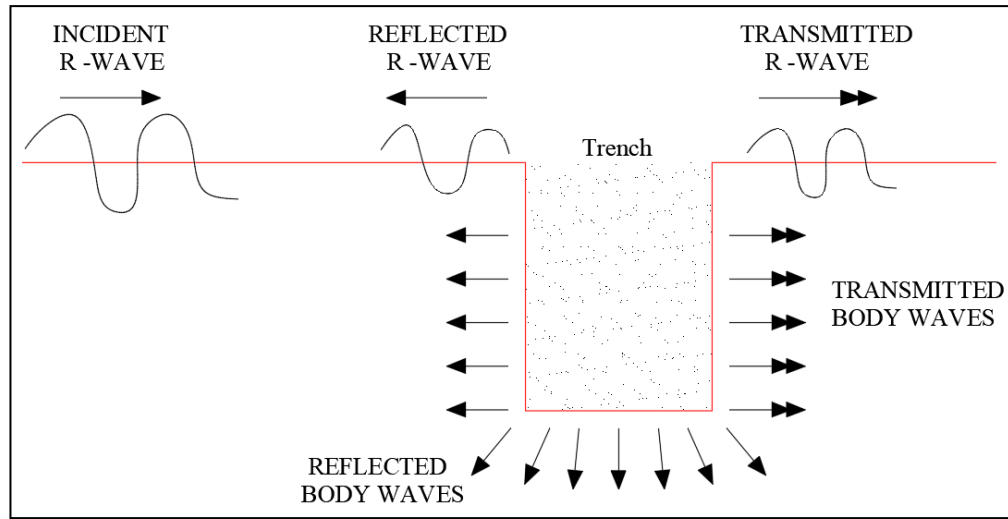


Figure 93: Generation of waves caused by incident Rayleigh Wave on Trench

The body waves may be subdivided into two groups; reflected body waves that radiate downward and toward the source and transmitted body waves that propagate away from the source. It is the energy contained within the transmitted R-wave and the transmitted body waves (double-headed arrows in Figure 93) that causes the ground vibration beyond the trench. The phenomenon of conversion of R- wave energy to other wave forms (P and S) due to the presence of a scattered (wave barrier) is known as mode conversion. Beyond the trench, as the distance between trench and transmitted body waves increases, the body waves are partially transformed to R-waves. The functional difference between the two types of trenches is primarily due to the ability of an in-filled trench to effect passage (transmission) of incident waves into the trench material and then to the zone of screening, which is not possible for open trenches. This results in completely different amounts of wave reflection and mode conversion. It is these two processes that govern vibration isolation. The deformation caused by the vibrating load is depicted in form of colour contours in Figure 92 and view of one of the deformed mesh due to vibrational load at $X_1 = 2.5\text{m}$ is presented in Figure 94. The average amplitude reduction factor (A_r) in case of no trench and trench wave barrier with in-filled materials under different exciting frequencies has calculated separately and tabulated in Table 17 to Table 20.

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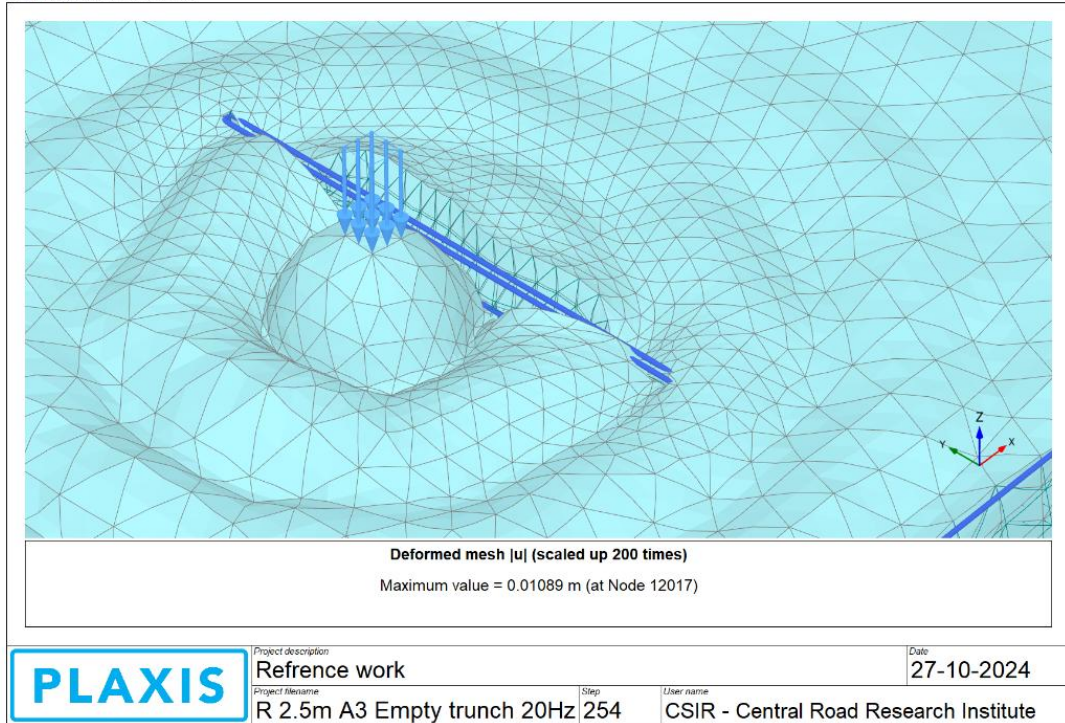
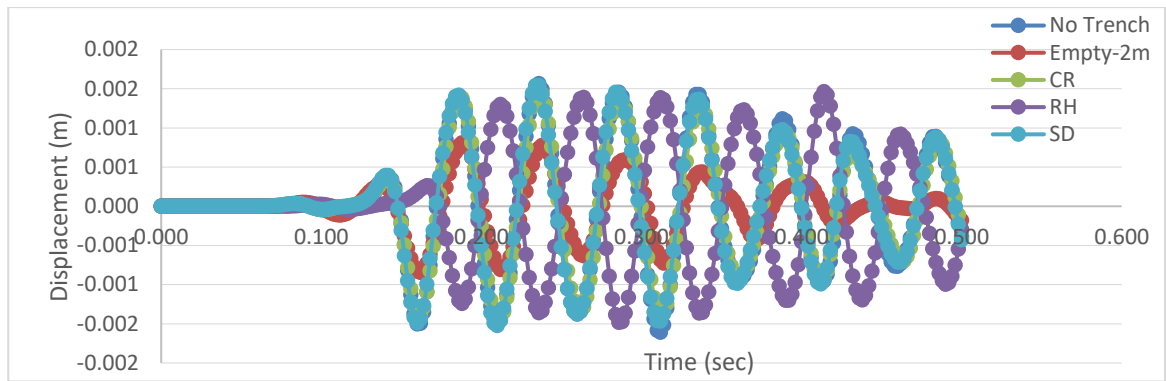
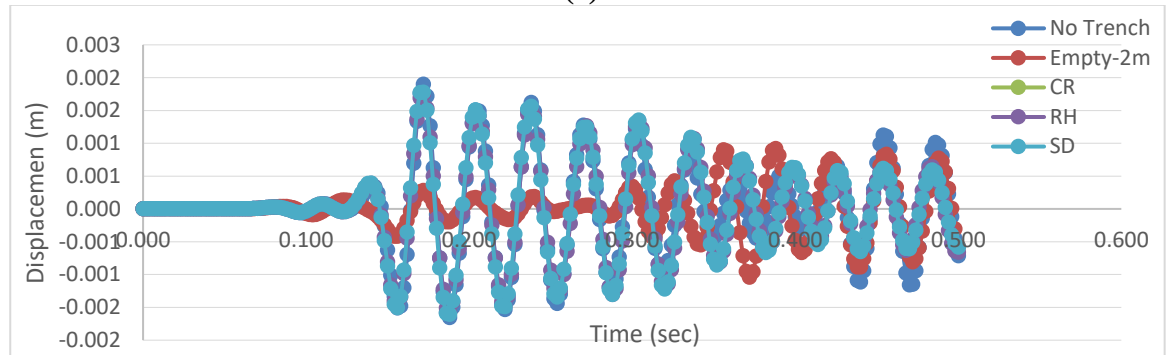


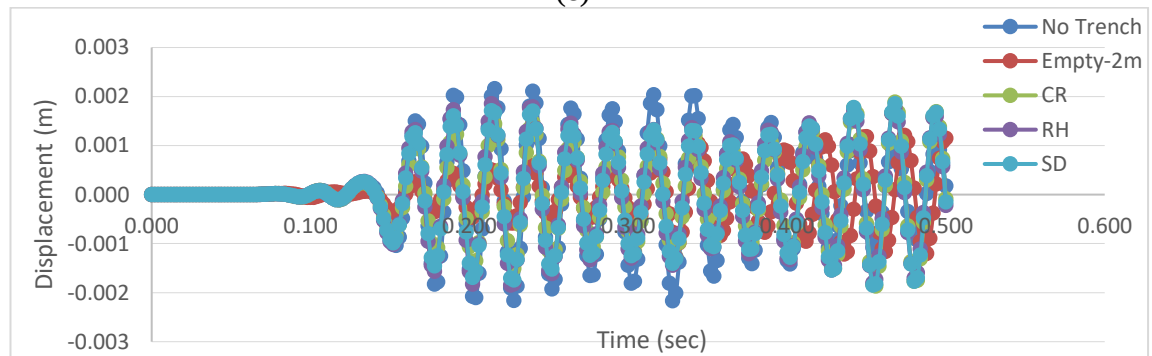
Figure 94: Deformed mesh due to vibrational load $X1 = 2.5\text{m}$



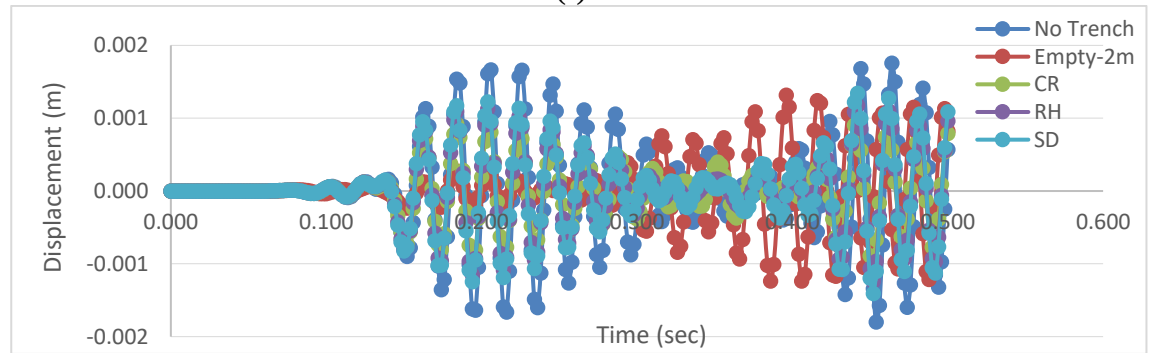
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(e)

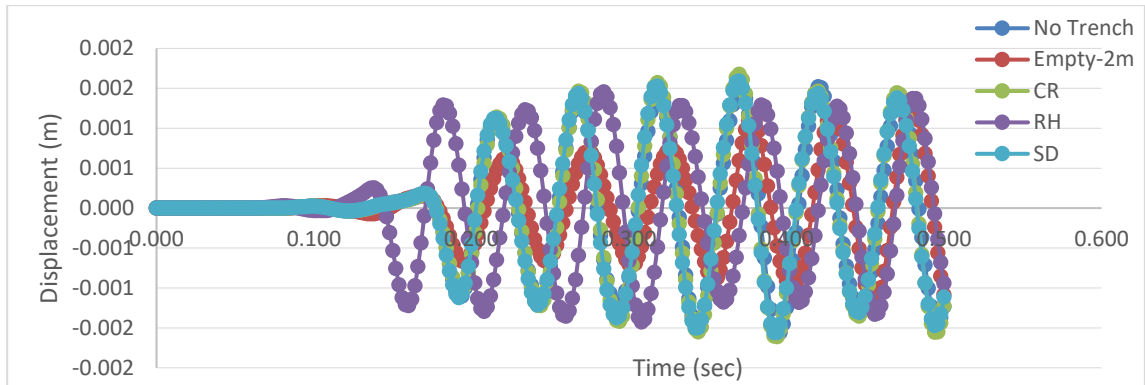


(f)

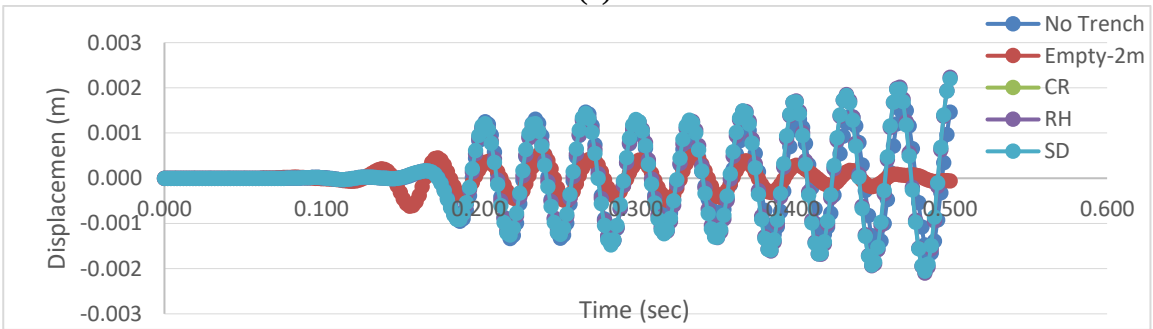


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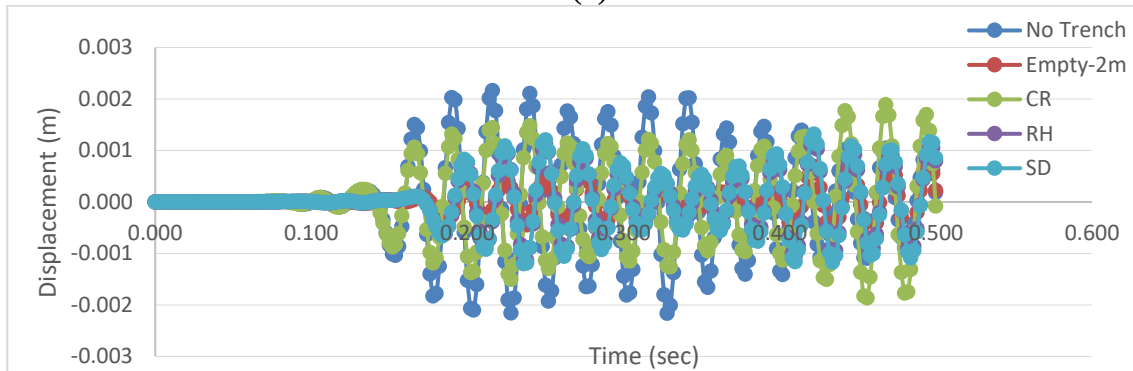
Figure 95: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to frequency of (a) 20 Hz (b) 30 Hz (c) 40 Hz & (d) 50 Hz at the source vibrator location 2.5 m from centre of trench



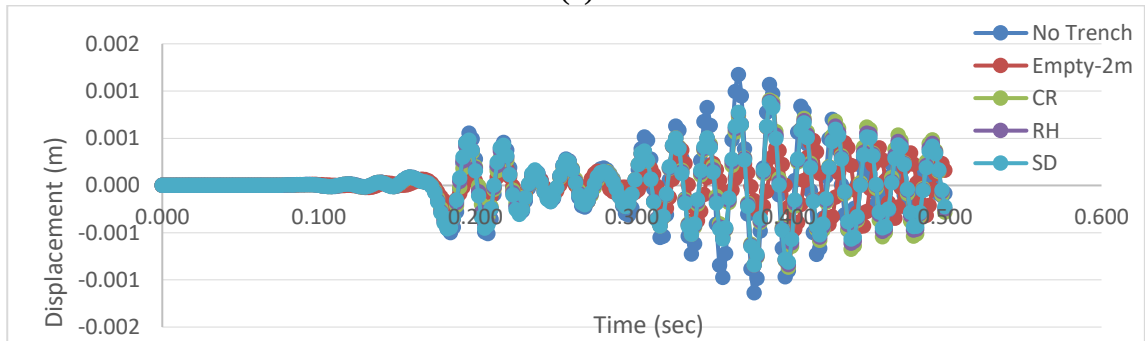
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(d)

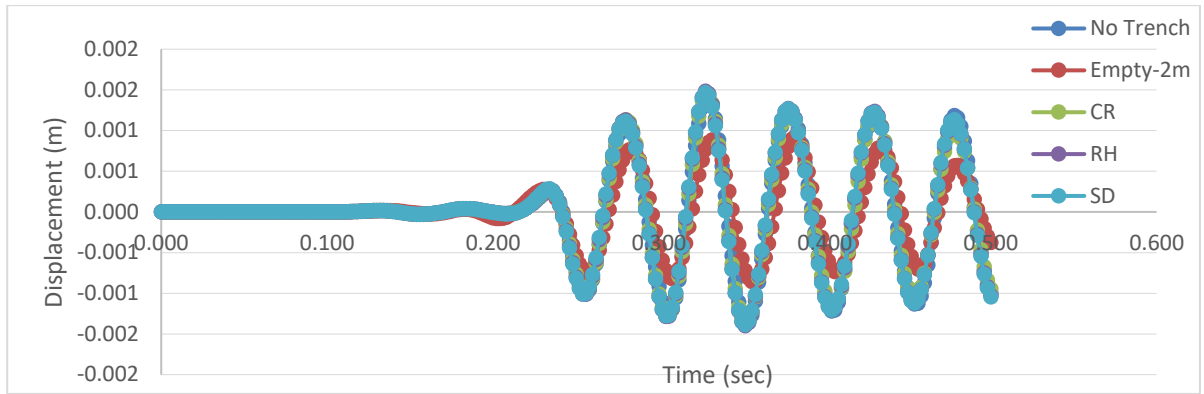


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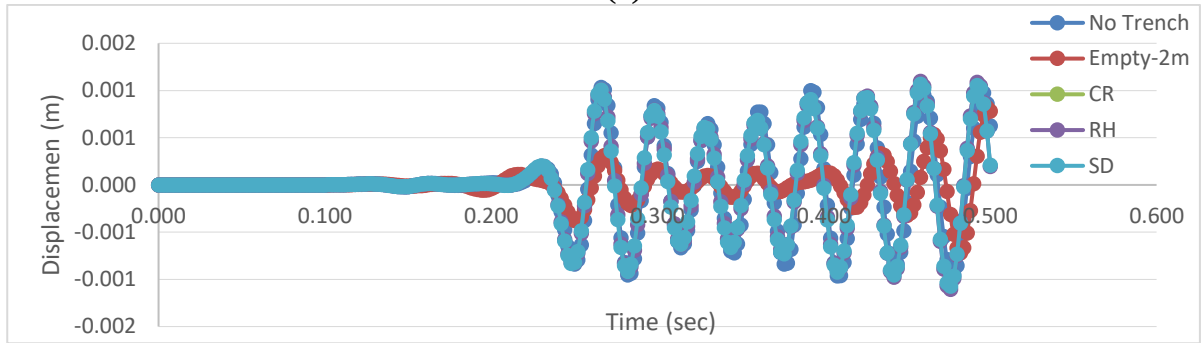


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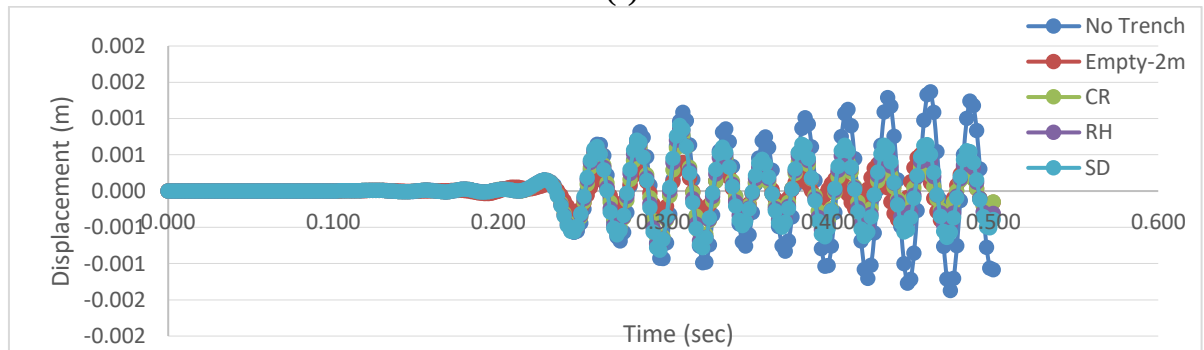
Figure 96: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to exciting frequency of (a) 20Hz (b) 30Hz (c) 40Hz & (d) 50Hz at the source vibrator location 5 m from centre of trench



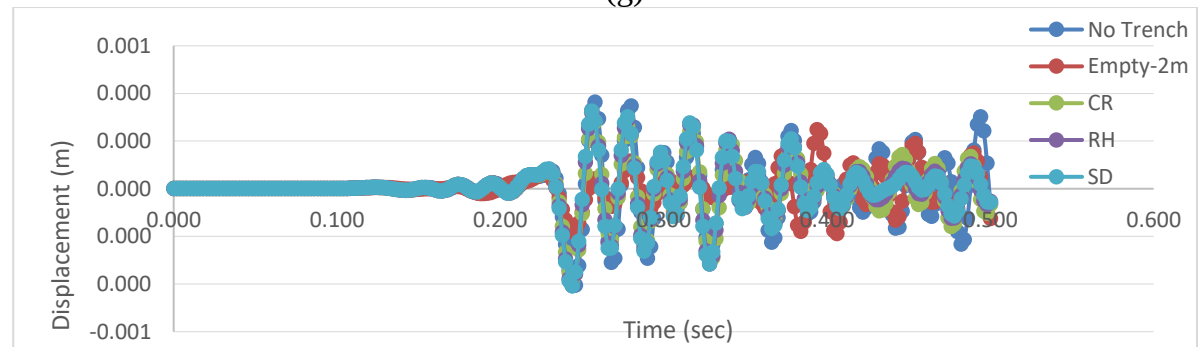
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(f)

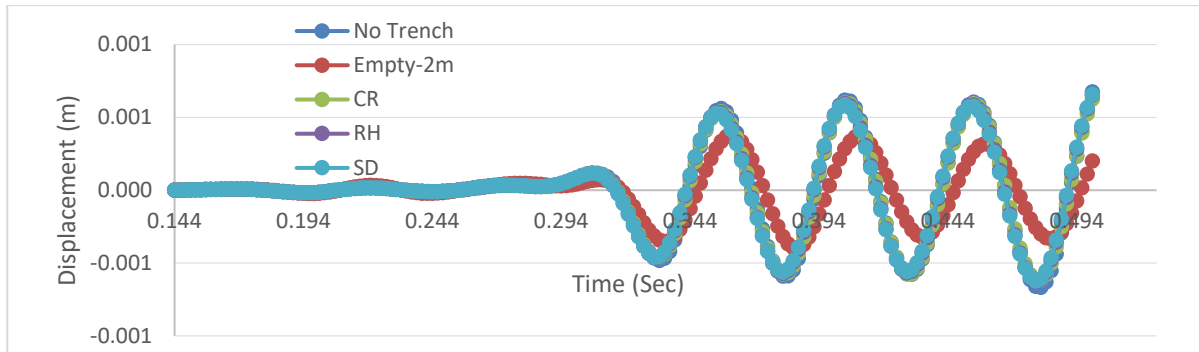


(g)

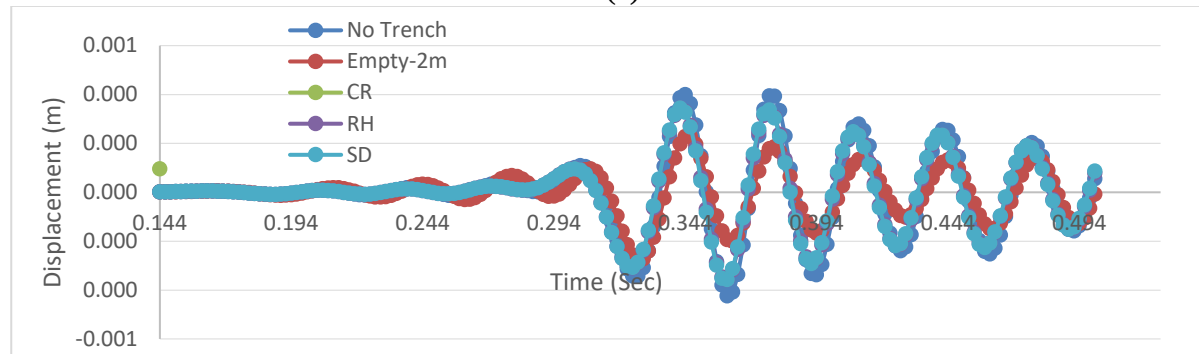


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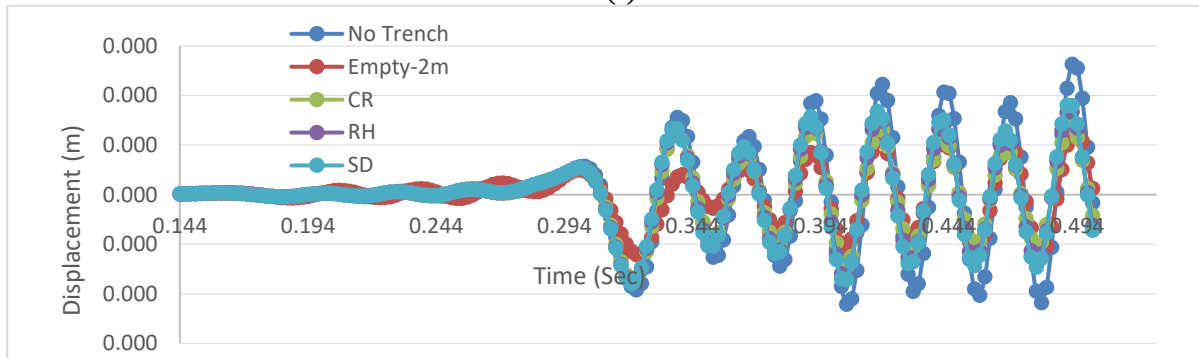
Figure 97: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to exciting frequency of (a) 20 Hz (b) 30 Hz (c) 40 Hz & (d) 50Hz at the source vibrator location 10 m from center of trench



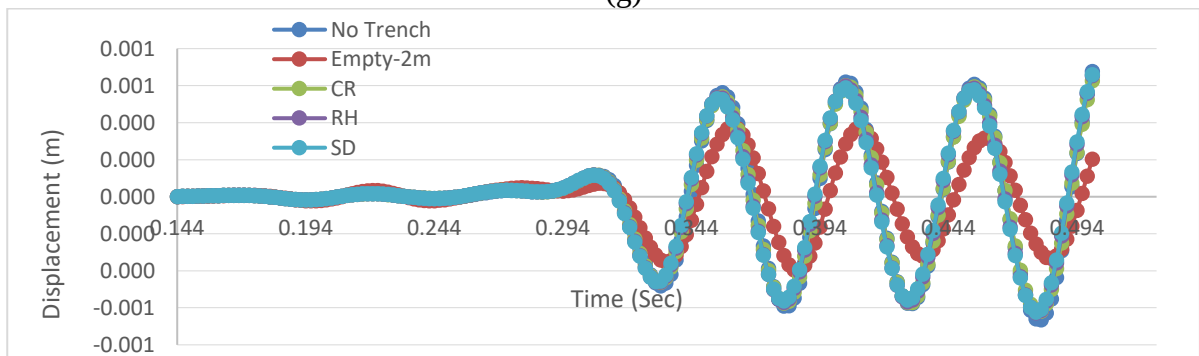
(e)



(f)

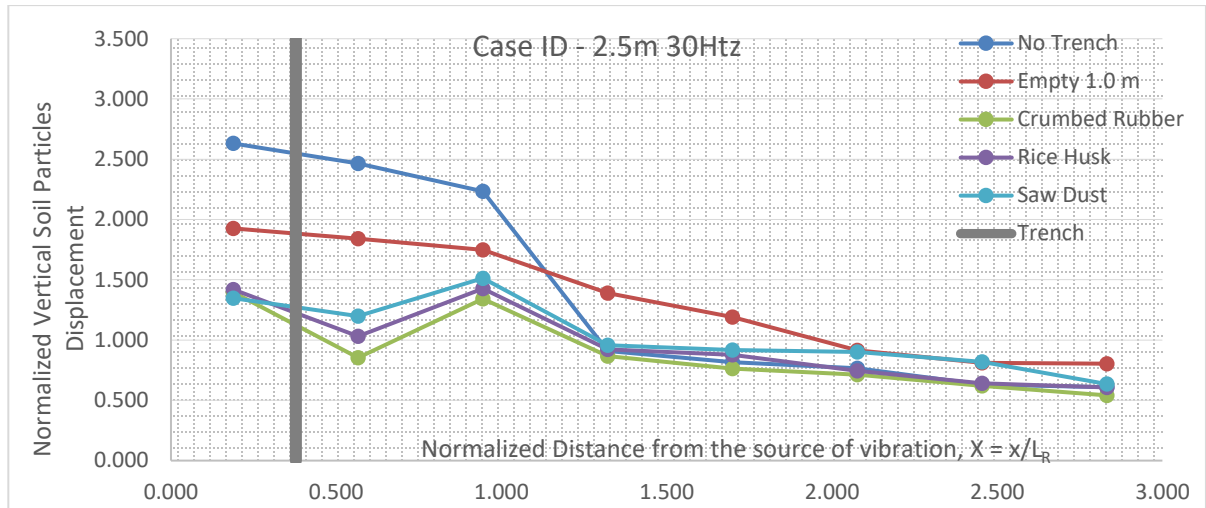


(g)

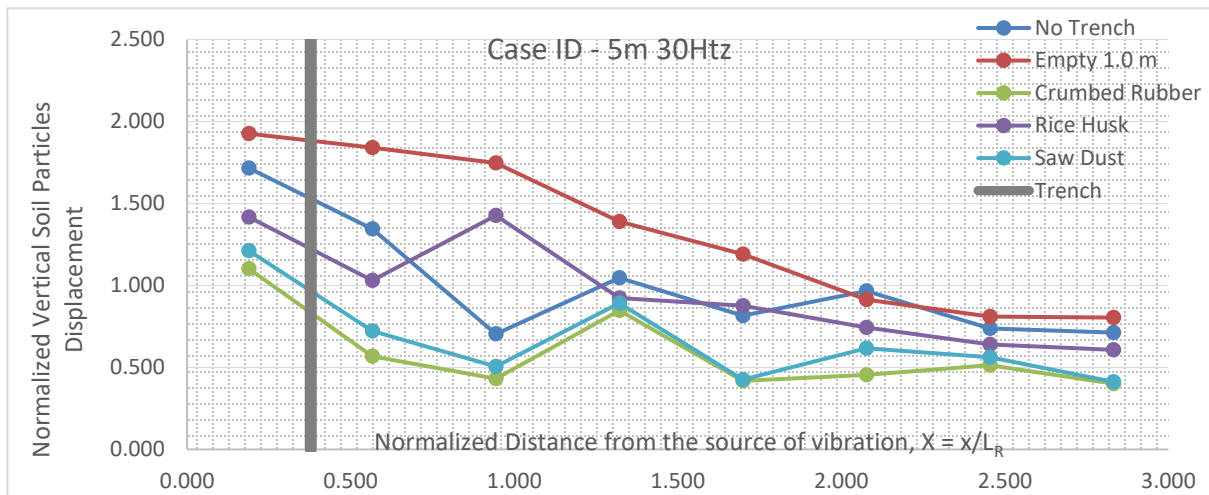


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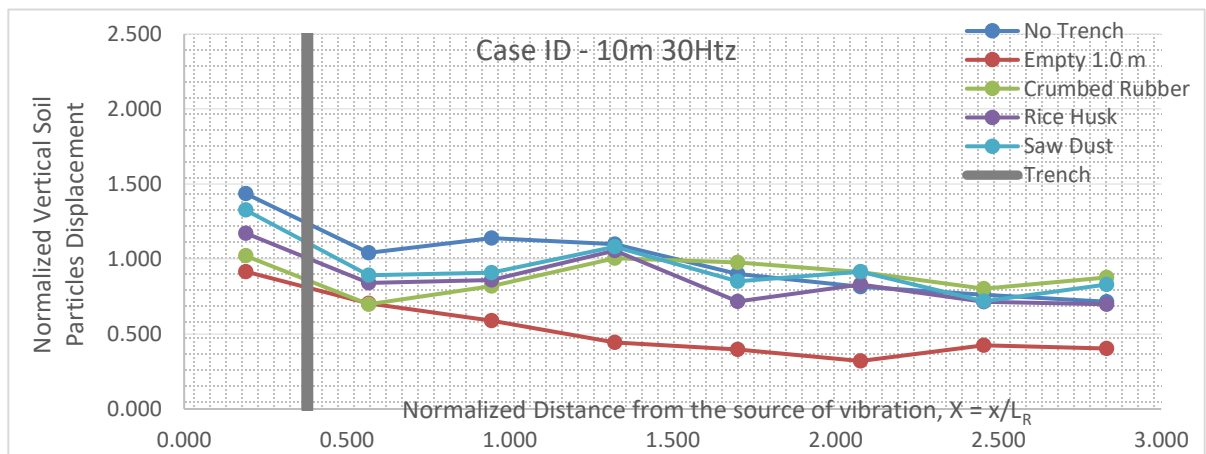
Figure 98: Comparison of the spectral amplitude vs time histories at observation point G-10 for passive isolation measures due to exciting frequency of (a) 20 Hz (b) 30 Hz (c) 40 Hz & (d) 50Hz at the source vibrator location 23.75 m from centre of trench



(a)

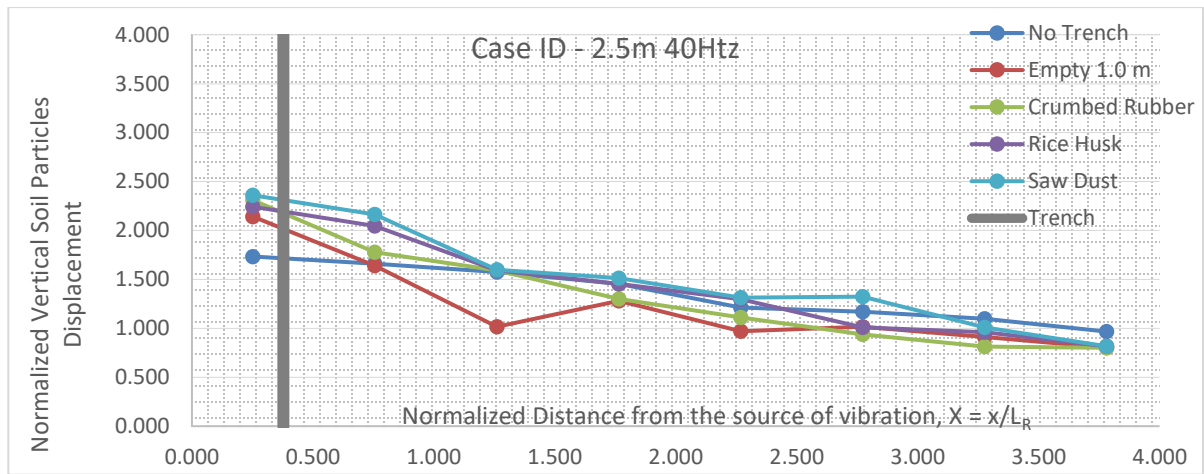


(b)

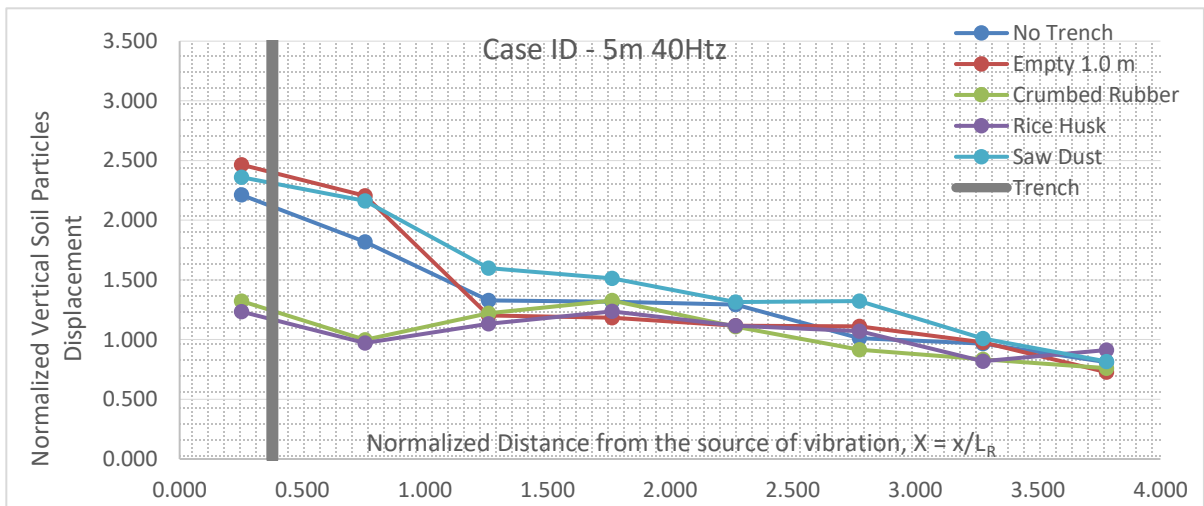


(c)

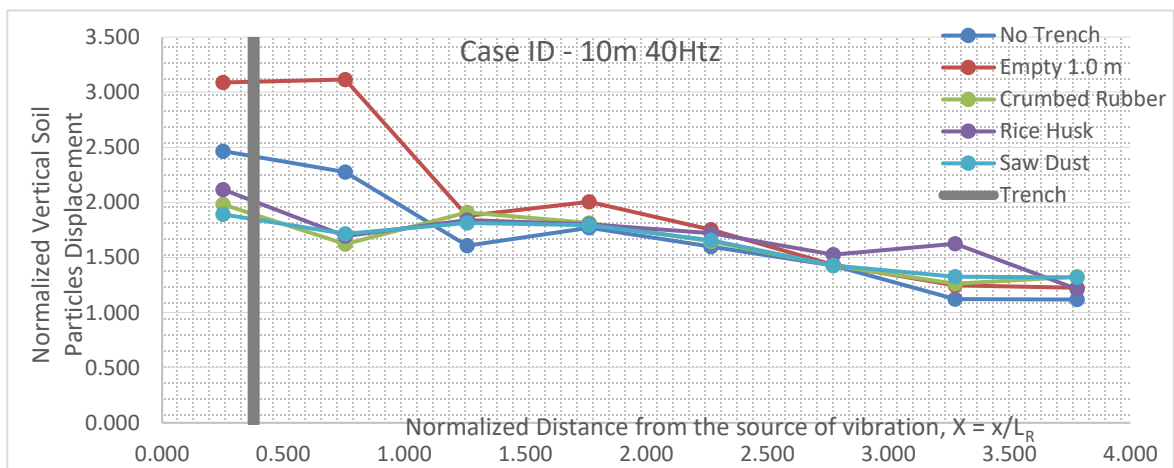
Figure 99: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 30\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from centre of trench in active isolation



(a)

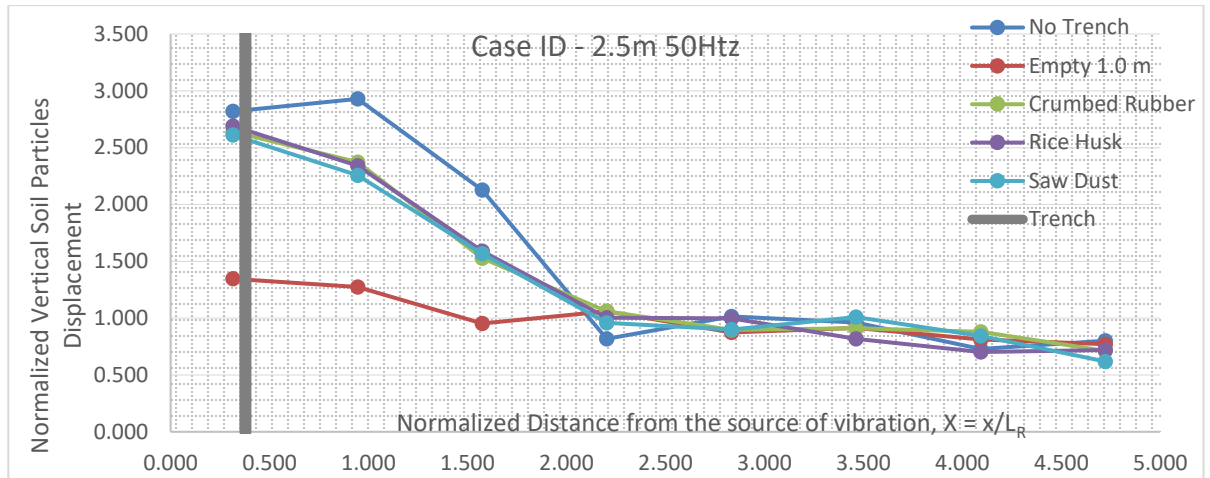


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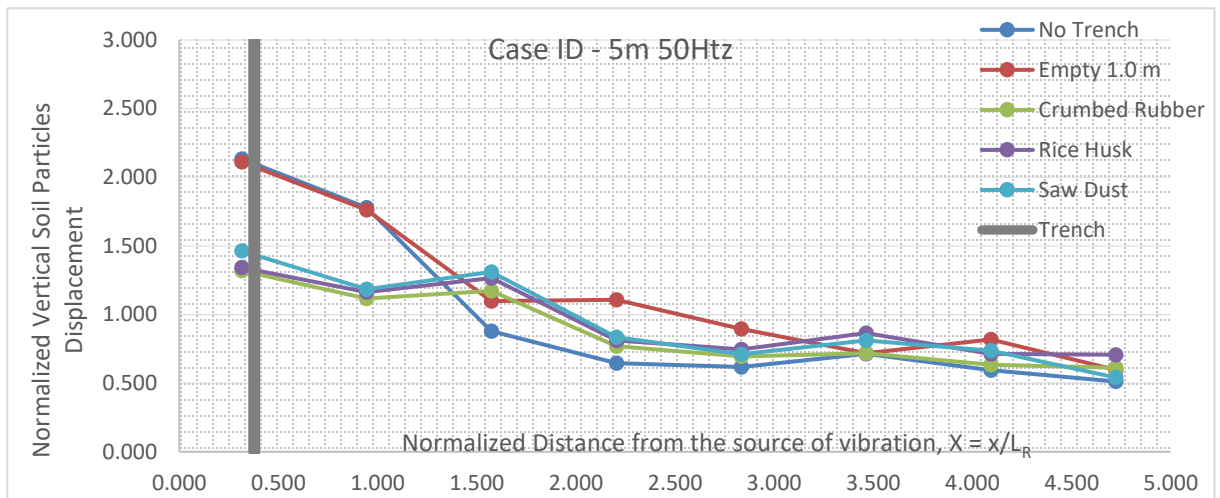


(c)

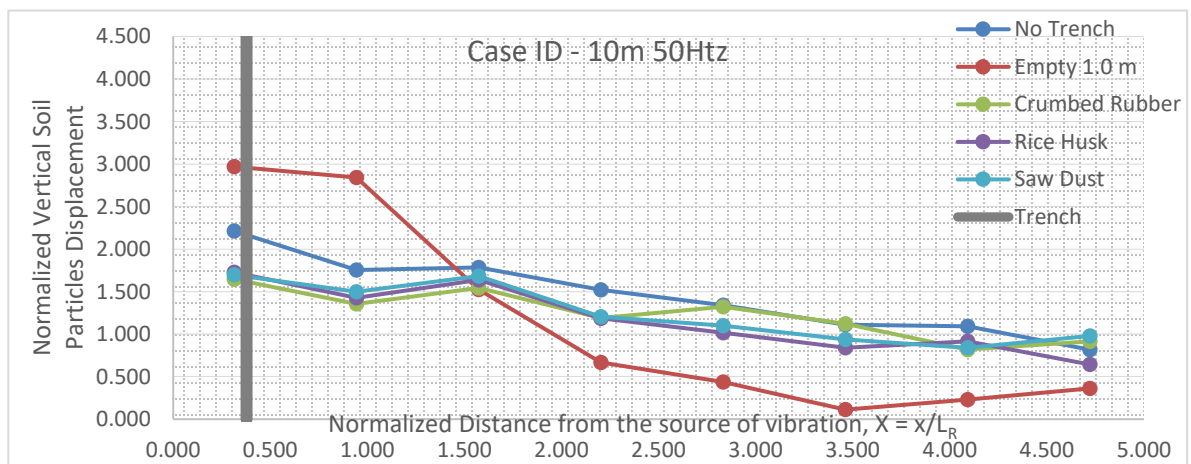
Figure 100: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 40\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from centre of trench in active isolation



(a)

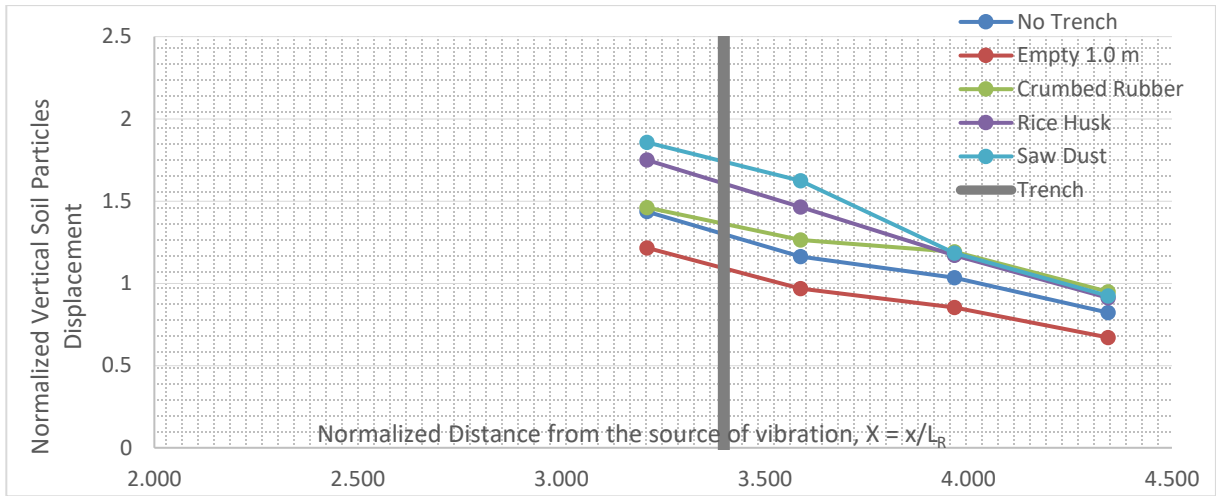


(b)

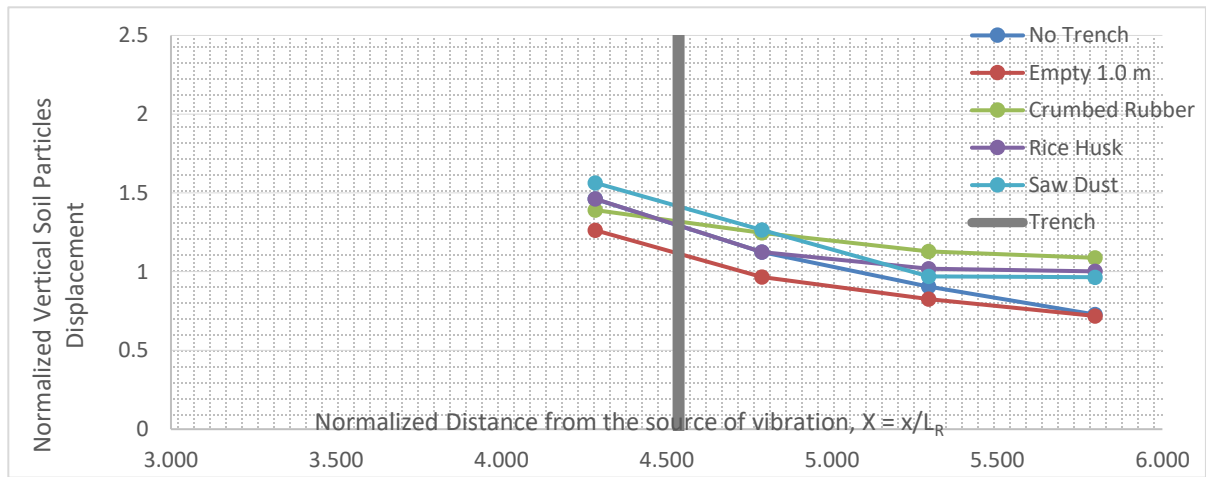


(c)

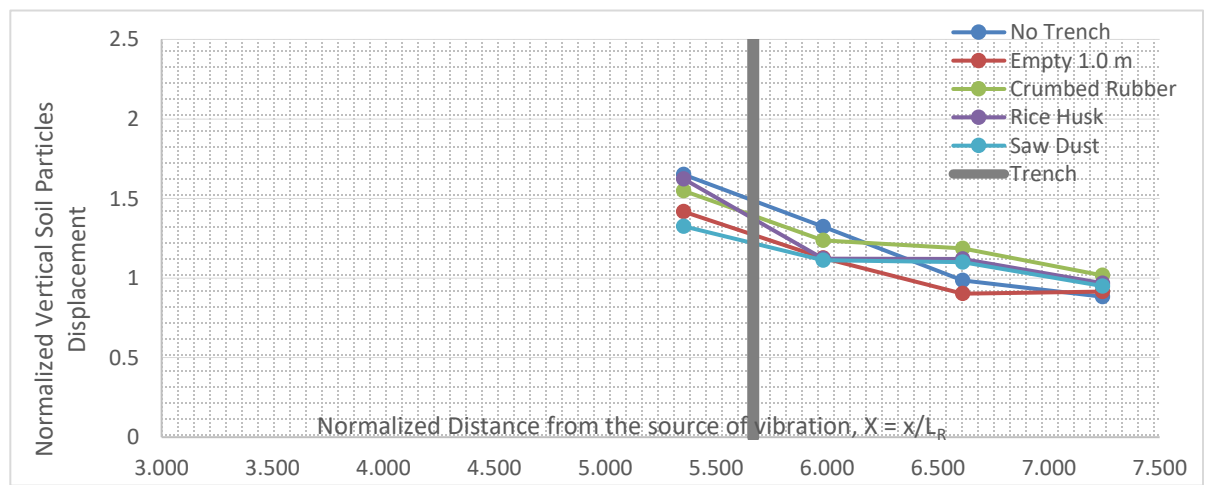
Figure 101: Normalized ground motion (G10 to G3) due to exciting frequency of (a) $f = 50\text{Hz}$ when source of vibration at (a) 2.5 m (b) 5.0 m and (c) 10 m from centre of trench in active isolation



(a)



(b)



(c)

Figure 102: Normalized ground motion (G9 to G12) due to exciting frequency of (a) $f = 30\text{Hz}$ (b) 40Hz and (c) 50 Hz when source of vibration at 23.75 m from center of trench in passive isolation



Table 18: Amplitude reduction ratio (A_R) in presence of wave barriers when $X_1=2.5m$

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIoT2.5/20	20Hz	0.714	0.286	0.522	0.518	0.510
AIoT2.5/30	30Hz	0.362	0.380	0.673	0.485	0.475
AIoT2.5/40	40Hz	0.552	0.360	0.491	0.558	0.490
AIoT2.5/50	50 Hz	0.326	0.335	0.324	0.456	0.360
2 CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AICR2.5/20	20Hz	0.629	0.711	0.375	0.510	0.556
AICR2.5/30	30Hz	0.286	0.496	0.760	0.520	0.516
AICR2.5/40	40Hz	0.754	0.582	0.597	0.675	0.652
AICR2.5/50	50 Hz	0.424	0.375	0.676	0.523	0.500
3. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIRH2.5/20	20Hz	0.768	0.777	0.465	0.435	0.611
AIRH2.5/30	30Hz	0.385	0.587	0.415	0.620	0.502
AIRH2.5/40	40Hz	0.651	0.566	0.498	0.451	0.542
AIRH2.5/50	50 Hz	0.535	0.501	0.517	0.670	0.556
4. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD2.5/20	20Hz	0.544	0.521	0.614	0.614	0.573
AISD2.5/30	30Hz	0.455	0.634	0.588	0.417	0.524
AISD2.5/40	40Hz	0.465	0.480	0.310	0.591	0.462
AISD2.5/50	50 Hz	0.589	0.563	0.312	0.354	0.455



Table 19: Amplitude reduction ratio (A_r) in presence of wave barrier when $X_2=5$ m

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIOT5/20	20Hz	0.469	0.411	0.473	0.389	0.436
AIOT5/30	30Hz	0.499	0.646	0.469	0.347	0.490
AIOT5/40	40Hz	0.563	0.516	0.565	0.586	0.558
AIOT5/50	50 Hz	0.329	0.507	0.375	0.406	0.404
2. CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AICR5/20	20Hz	0.515	0.382	0.391	0.660	0.487
AICR5/30	30Hz	0.572	0.616	0.316	0.519	0.506
AICR5/40	40Hz	0.402	0.673	0.538	0.673	0.572
AICR5/50	50 Hz	0.483	0.463	0.491	0.649	0.522
3. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIRH5/20	20Hz	0.478	0.495	0.299	0.548	0.455
AIRH5/30	30Hz	0.682	0.930	0.552	0.377	0.635
AIRH5/40	40Hz	0.481	0.453	0.438	0.451	0.456
AIRH5/50	50 Hz	0.495	0.458	0.210	0.656	0.455
4. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD5/20	20Hz	0.384	0.490	0.516	0.514	0.476
AISD5/30	30Hz	0.728	0.712	0.574	0.417	0.608
AISD5/40	40Hz	0.513	0.692	0.617	0.591	0.603
AISD5/50	50 Hz	0.496	0.510	0.513	0.645	0.541



Table 20: Amplitude reduction ratio (A_R) in presence of wave barrier when $X_3=10m$

1. OPEN TRENCH:						
Case ID	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIOT10/20	20Hz	0.399	0.336	0.631	0.656	0.506
AIOT10/30	30Hz	0.537	0.409	0.320	0.593	0.465
AIOT10/40	40Hz	0.552	0.429	0.416	0.367	0.441
AIOT10/50	50 Hz	0.319	0.582	0.298	0.681	0.470
2. CRUMBED RUBBER:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AICR10/20	20Hz	0.451	0.379	0.514	0.501	0.461
AICR10/30	30Hz	0.748	0.511	0.237	0.317	0.453
AICR10/40	40Hz	0.513	0.668	0.576	0.562	0.580
AICR10/50	50 Hz	0.517	0.680	0.615	0.486	0.575
3. RICE HUSK:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AIRH10/20	20Hz	0.219	0.415	0.577	0.649	0.465
AIRH10/30	30Hz	0.551	0.492	0.671	0.399	0.528
AIRH10/40	40Hz	0.449	0.720	0.640	0.629	0.610
AIRH10/50	50 Hz	0.712	0.645	0.618	0.574	0.637
4. SAW DUST:						
	Frequency	Point G-9	Point G-8	Point G-7	Point G-6	Average A_R
AISD10/20	20Hz	0.477	0.519	0.368	0.486	0.463
AISD10/30	30Hz	0.579	0.566	0.597	0.546	0.572
AISD10/40	40Hz	0.511	0.744	0.659	0.660	0.644
AISD10/50	50 Hz	0.766	0.545	0.574	0.434	0.580



Table 21: Amplitude reduction ratio (A_R) in presence of wave barrier when $X_1=23.75$ m

1. OPEN TRENCH:					
Case ID	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIOT2.5/20	20Hz	0.559	0.598	0.669	0.609
PIOT2.5/30	30Hz	0.570	0.465	0.470	0.502
PIOT2.5/40	40Hz	0.497	0.459	0.491	0.482
PIOT2.5/50	50 Hz	0.501	0.519	0.459	0.493
2. CRUMBED RUBBER:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PICR2.5/20	20Hz	0.372	0.290	0.482	0.381
PICR2.5/30	30Hz	0.641	0.578	0.551	0.590
PICR2.5/40	40Hz	0.529	0.660	0.791	0.660
PICR2.5/50	50 Hz	0.762	0.877	0.531	0.723
3. RICE HUSK:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PIRH2.5/20	20Hz	0.454	0.382	0.697	0.511
PIRH2.5/30	30Hz	0.513	0.511	0.493	0.506
PIRH2.5/40	40Hz	0.636	0.716	0.717	0.690
PIRH2.5/50	50 Hz	0.413	0.787	0.459	0.553
4. SAW DUST:					
	Frequency	Point G-10	Point G-11	Point G-12	Average A_R
PISD2.5/20	20Hz	0.671	0.574	0.660	0.635
PISD2.5/30	30Hz	0.862	0.568	0.596	0.675
PISD2.5/40	40Hz	0.684	0.734	0.506	0.641
PISD2.5/50	50 Hz	0.596	0.561	0.499	0.552

5.4 RESULTS AND DISCUSSION

Isolation response of rectangular in-filled trenches in an elastic, isotropic, and homogeneous half-space is numerically studied in this work in a 3D context. Softer barrier is considered in this study as such barriers are found to provide significantly better screening effect than stiffer barriers. The key results and crucial observations of this study are summarized as follows:

1. It can be conceived that an open trench is a special case of an in-filled trench of $V_b / V_s \approx 0$. Vibration attenuation is caused only when the backfill is either softer or stiffer than the surrounding half-space. In order to achieve a good degree of isolation, the shear wave velocity ratio, V_b / V_s of backfill should be around 0.3 or preferably less. It can also be concluded that in-filled trenches can isolate the vertical vibration component more effectively than the horizontal.
2. The effect of barrier location on its screening effectiveness depends on the barrier depth and width and also on the component of vibration under consideration.
3. Increase in barrier depth not necessarily decreases amplitude to much extent. To obtain optimum screening effect in vertical vibration case, a particular trench depth must be accompanied by a specific width and vice-versa. There exists a certain value of D/W at which a softer barrier yields optimum efficiency irrespective of the cases whether active or passive.
4. Based on the numerical study, amplitude dissipation rates of the vibration and in turns, Table 21 summarize the average protective effectiveness (Eff_A) of the open trench and three types of in-filled trench wave barriers.
5. The results obtained from 3D finite element models are in excellent agreement. Thus, 3D finite element model can be used with confidence, in modeling the field experimental tests as well as in conducting a parametric study.
6. Wave attenuation curves obtained numerically utilizing the 3D finite element model follow the same

trend of the experimental measurements and they are in good agreement, but with slightly higher values at some points and lower values at others.

7. The results obtained from the finite element models are comparable to those obtained experimentally with a difference of about 10.65%, 17.86% and 25.20% for open and in-filled trench barriers with in-filled material as Crumbed rubber, Rice husk and Saw dust respectively. The discrepancy can be attributed to the soil non-homogeny as well as imperfect bonding between the soil and the in-filled wall.
8. The developed finite element models can be used to extrapolate the results and conduct a parametric study on the in-filled trench barrier performance with different dimensions and in different soil profiles.

Table 22: Protective Efficiency of Barriers (%age) based on numerical study:

Trench Type	1st Location	2nd Location	3rd Location	Average
Open Trench	44.41%	47.85%	48.28%	46.84%
Crumbed Rubber	54.11%	52.81%	52.96%	53.29%
Rice Husk	44.74%	49.98%	44.00%	46.24%
Saw Dust	49.68%	44.30%	43.55%	45.84%

5.5 COMPARSON OF RESULTS OF EXPERIMENTAL AND NUMERICAL STUDY

Some results documented in previous literatures on softer barrier isolation are compared with the results obtained from the charts with reference to Figure 103 and presented in Table 21. It can be seen that the charts provide results qualitatively comparable to the published values. The figure shows that there is a variation of about 20-23% in the results of experimental and numerical study. The difference may be due to practical aspect of the ground the practices implemented during experimental study. Overall, both the result some similar conformity and validating both the studies.

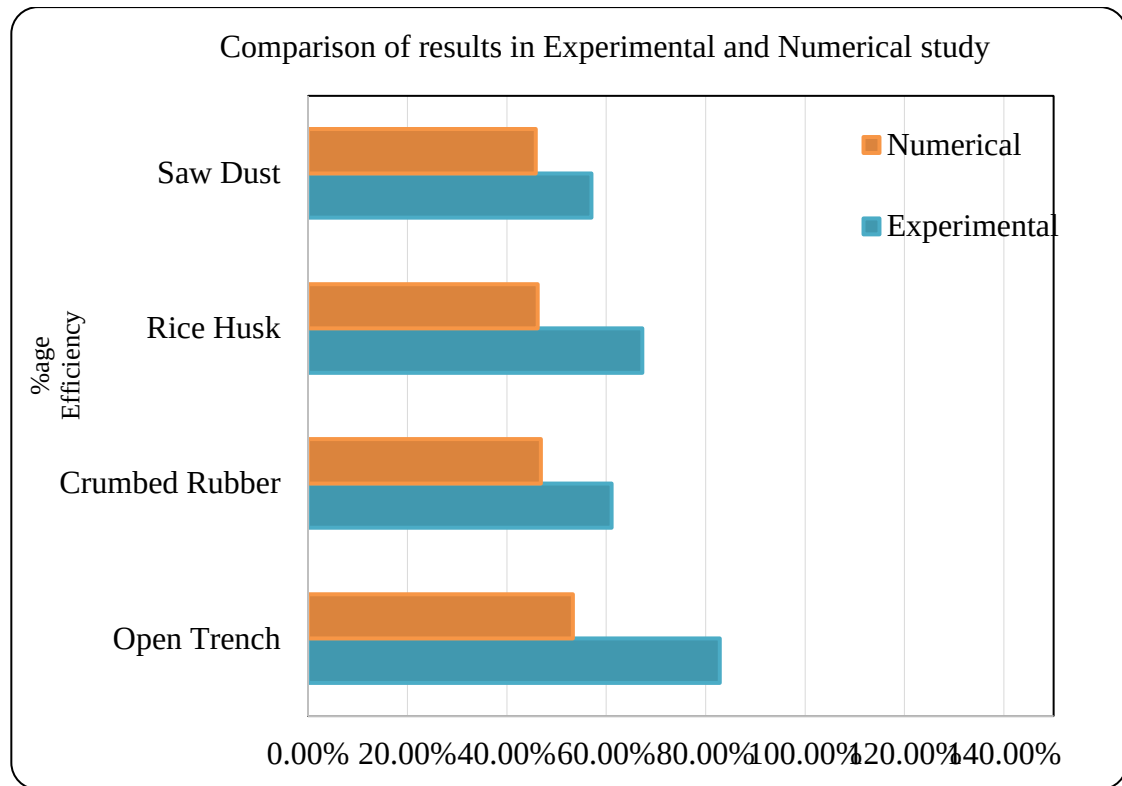


Figure 103: Comparison of results from experimental vs numerical investigation in determining the efficiency of in-filled materials

5.6 PARAMETRIC STUDY

The case described in Figure 89 is further subjected to parametric study by changing the values of key parameters used in above study which influences the performance of in-filled materials from major to minor extent. The dimensionless parametric study is performed where geometrical properties of the trench barrier are normalized against the Rayleigh wavelength of oscillation in elastic half space. This will eradicate dependency of the operating frequency and elastic half space parameters. The parameters were normalized as $L=l/L_R$, $D=d/L_R$ and $W=w/L_R$, where L , D and W are the dimensionless quantities represented in terms of Rayleigh wavelength and represents location of the source location, depth and width of trench normalized against Rayleigh wavelength. The basic assumptions and the geometrical properties required in modelling, assigned as detailed given in Table 15 and Table 16. The values of parameters assigned in parametric study to study the changes are summarized in Table 22 as below:

Table 23: Variable properties adopted in numerical modelling for parametric study:

S. No.	Properties	Value 1	Value 2	Value 3	Value 4
A	Open Trench:				
1	Poisson's ratio (ν)	0.300	0.400	0.480	-
2	Barrier Location (L)	2.500m	5.000m	10.000m	23.750m
3	Width (w)	0.250m	0.500m	0.800m	1.000m
4	Depth (d)	1.000m	2.000m	3.000m	4.000m
B	In-Filled Trench:				
1	Width (w)	0.250m	0.500m	0.800m	1.000m
2	Depth (d)	1.000m	2.000m	3.000m	4.000m
3	Stiffness (E)	25kN/m ²	20 kN/m ²	15kN/m ²	-
4	Barrier Location (L)	2.500m	5.000m	10.000m	23.750m
5	Shear wave velocity Ratio (V_b/V_s)	0.200	0.400	0.600	-
6	Poisson's ratio (ν)	0.300	0.400	0.480	-
7	Density ratio (ρ_s/ρ_b)	1.250	0.800	0.600	-
8	Damping ratio (ξ)	5%	10%	15%	-

In the succeeding sections, only vertical vibration components and average amplitude reduction factors of the respective component is taken into consideration. It has been found that as a whole, running of all the tests for all the cases of in-filled materials in trench wave barriers on all the operating frequencies is quite cumbersome and tedious. So, considering the permissible time, the case of Crumbed rubber is picked as in-filled material case with source of vibration located at 5m from centre of trench and the operating frequency applied is 30Hz. The case studies considered for parametric study are subjected for the above only. This case is specifically chosen for parametric study in view of quality of responses collected and overall efficiency of the in-filled materials.

In this section, extensive parametric investigation including the material properties of in-filled material in trench wave barriers, the dimensions, the location of source of vibration, the damping ratio, etc. has been studied to find the effect of these parameters on the screening efficiency of trench wave barriers. It is to be



kept in mind that when one of the parameters is studied, the other parameters remained unchanged.

5.6.1 OPEN TRENCH:

5.6.1.1 Effect of Trench Dimensions

Trench dimensions i.e. depth, width and cross-sectional area are having influence on screening efficiency. The trench depth has significant effect on screening efficiency as compared to the width of the trench and both the effects have been studied. The effect of barrier cross-sectional features is studied in terms of variations of amplitude reduction in case of trenches of varying depth ($d = 1.5\text{m}$, 2.5m and 3.5m) and width ($w = 0.25\text{m}$, 0.50m , 0.80m and 1.00m). This study considers specific barrier locations i.e. distance between Centre of trench and source of vibration which is $L=5.0\text{m}$ representing active case.

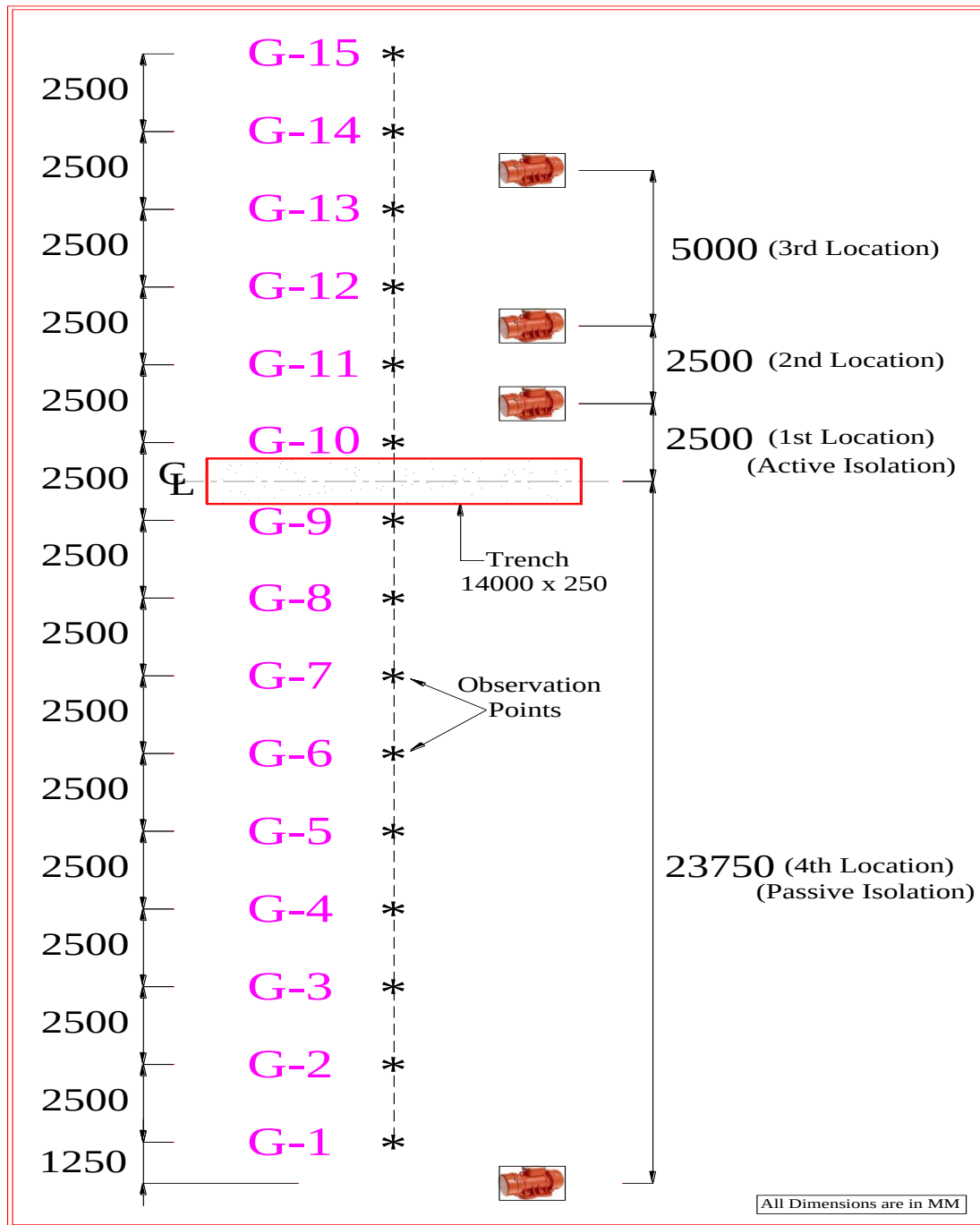


Figure 104: Layout and instrumentation detail showing locations of source of vibration and observation points

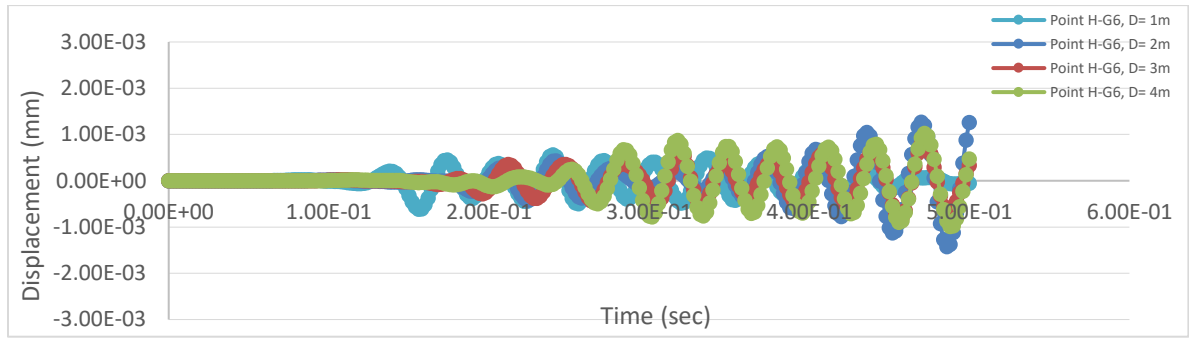
The instrumentation and layout of observation points in the parametric study are depicted in Figure 104. The installation detail of Geophones and the layout of positioning of source of vibration is also depicted.



The effect of normalized width on amplitude reduction is specific to cases. An increase in normalized width up to 0.5m causes a marginal decrease in amplitude. The trend is somewhat lower when width varies from 0.6 to 1m and can be considered as an upper limit of width beyond which a further increase in width adversely affects amplitude reduction of shallow trenches for active isolation cases in particular. For all other cases, an increase in width beyond 0.6 does not have any beneficial effect on amplitude reduction. In general, the effect of width has little significant in attenuating vertical vibrations and can be ignored in all practical cases.

5.6.1.1.1 Effect of Depth of Trench

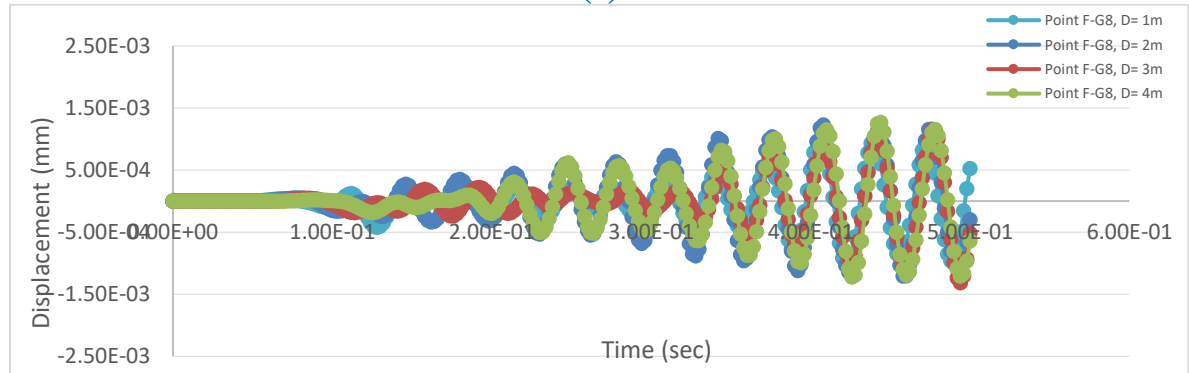
In case of open trench as shown in Figure 106, the optimum effectiveness is achieved at a shallower depth while for wider trenches the same is achieved at a higher depth. This implies that in order to attain optimum screening effectiveness, a specific depth must be accompanied by a specific width and vice-versa. The response at different observation points is as shown in Figure 105, for which the range of depth varies from 1m to 4.50m. By observing the width to the depth relation, it is found that with increasing depth, amplitude reduction ratio decreases until reach an optimum value. The width variation has shown a different phenomenon as expected. It is noted that at the lower value of width, higher depths are more effective rather than the shallow depth. As the width increases, the effectiveness becomes less significant. The phenomenon can be understood by the fact that thin trench barrier allows a significant portion of waves to transmit through it directly, causing poor effect on isolation. But for wider trench, it allows much more waves to travel along with periphery while propagating into the soil. It can be thus concluded that barriers with more depth contribute to reduce the amplitude too slender barriers are not effective. Limiting depth is also very helpful and further increasing the depth will have little improvement.



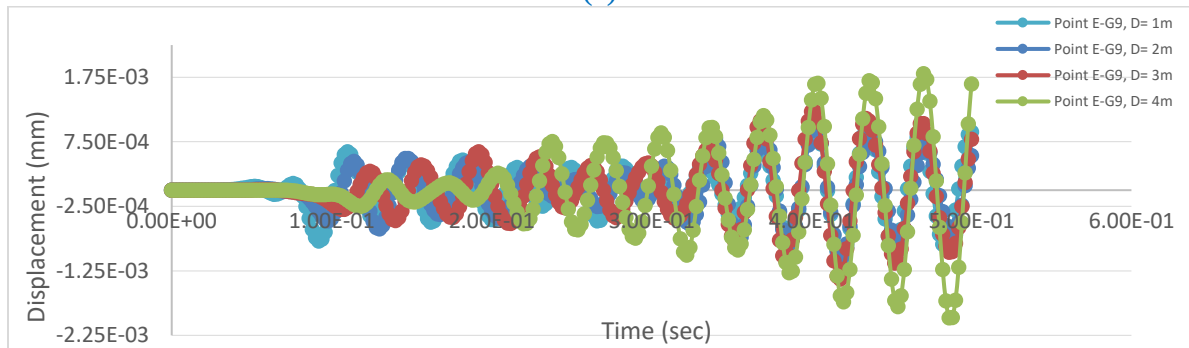
(a)



(b)



(c)



(d)

Figure 105: Effect of depth of empty trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench with Crumbed rubber as backfill material

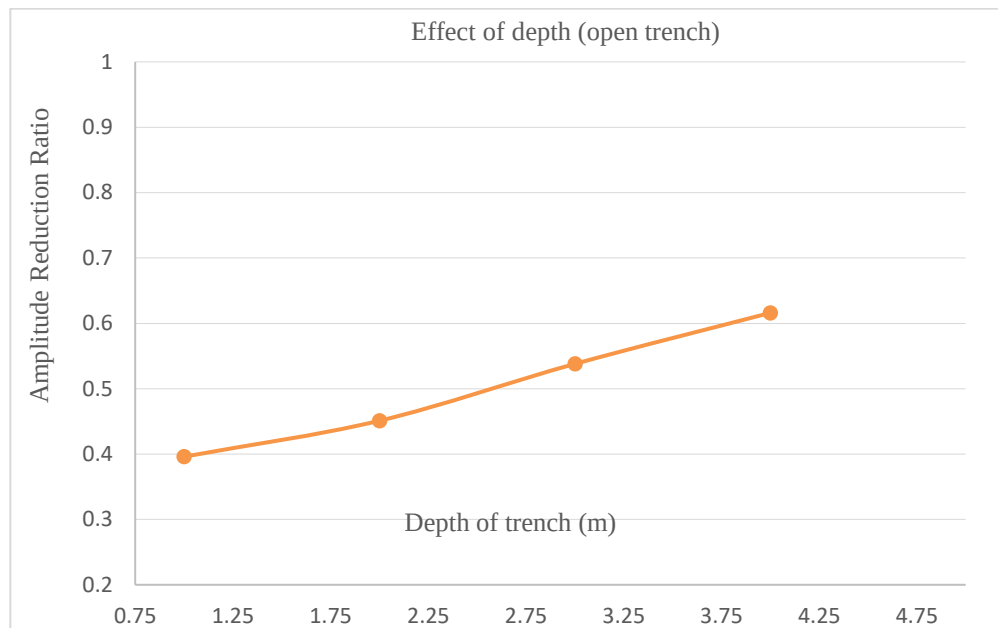


Figure 106: Effect of depth on Amplitude reduction ratio for open trench

5.6.1.1.2 Effect of Width of Trench

Figure 107 and 108 depicts the influence of the soil's Poisson's ratio (ν) on the performance of an open trench. The effect of width on amplitude reduction is studied and is found specific to some cases only. An increase in width up to 0.5m causes reduction in amplitude. The trend is somewhat lower when width varies from 0.6 to 1m and can be considered as an upper limit of width beyond which a further increase in width adversely affects amplitude reduction of shallow trenches for active isolation cases in particular. For all other cases, an increase in width beyond 0.6 does not have any beneficial effect on amplitude reduction. In general, the effect of width has little significant in attenuating vertical vibrations on higher width of trench and cannot be considered significant for all practical cases.

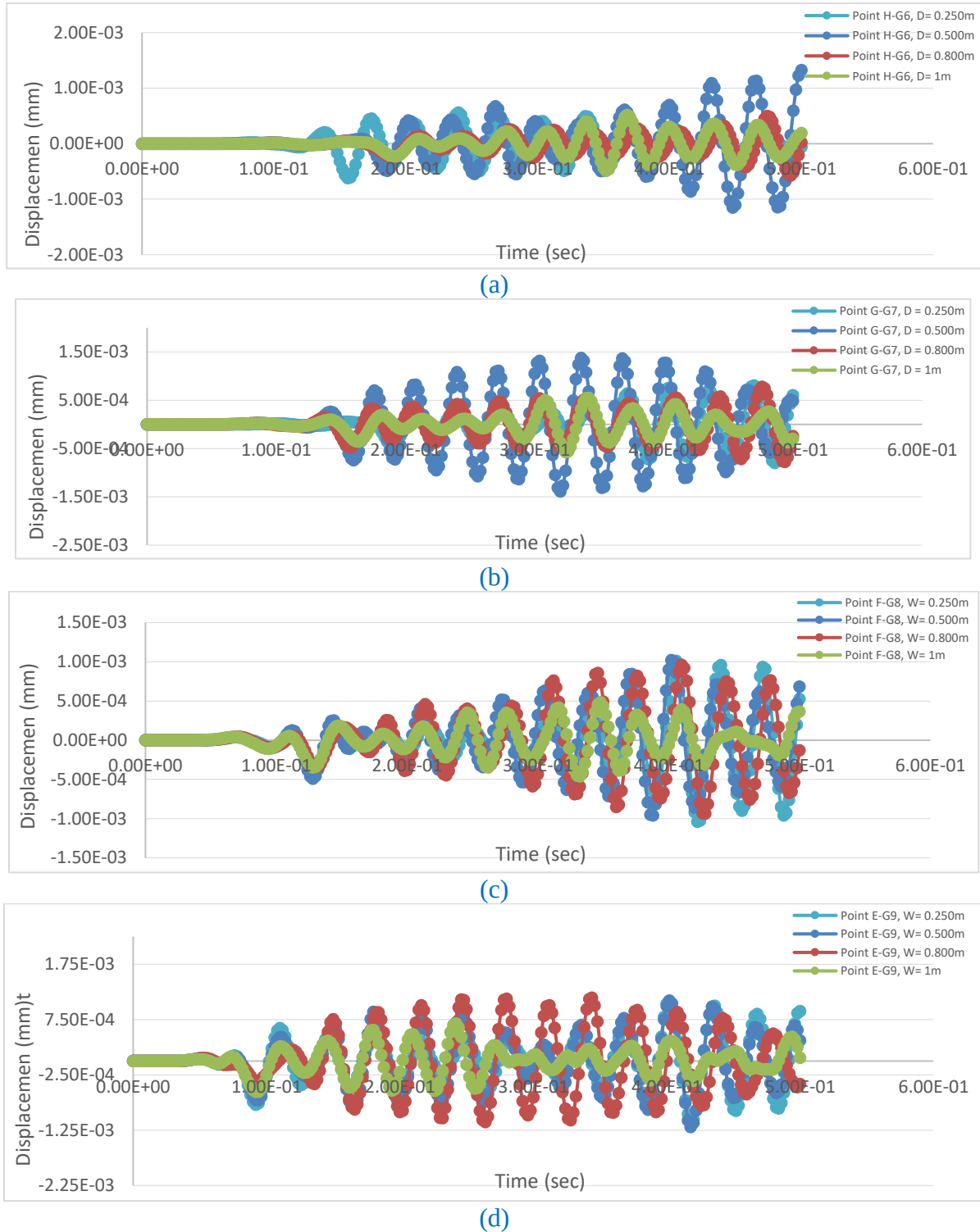


Figure 107: Effect of depth of empty trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench with Crumbed rubber as backfill material

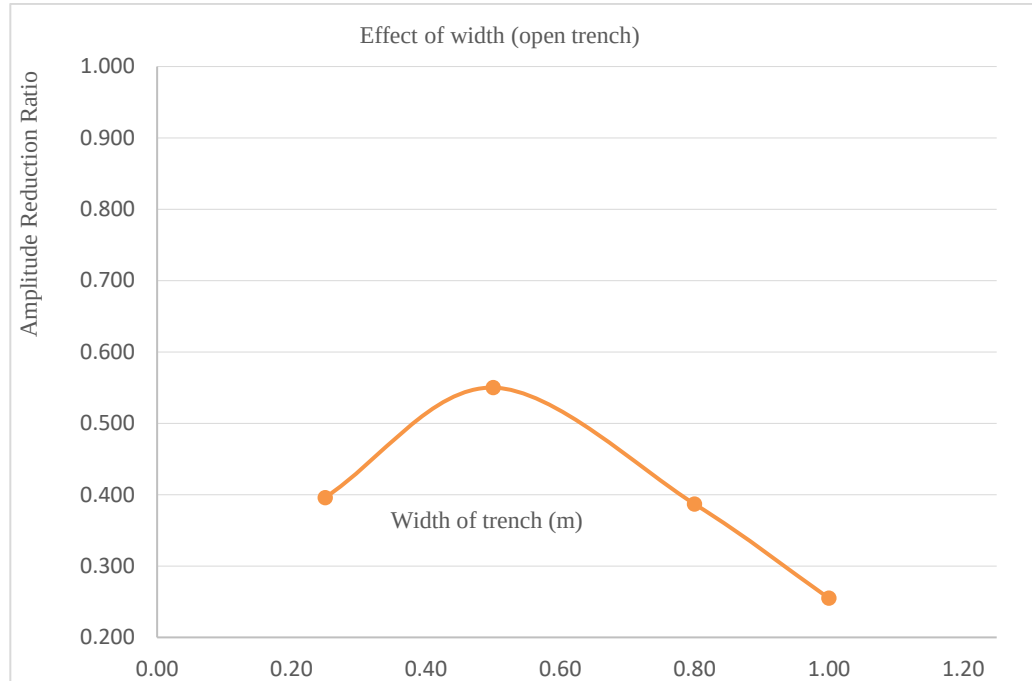
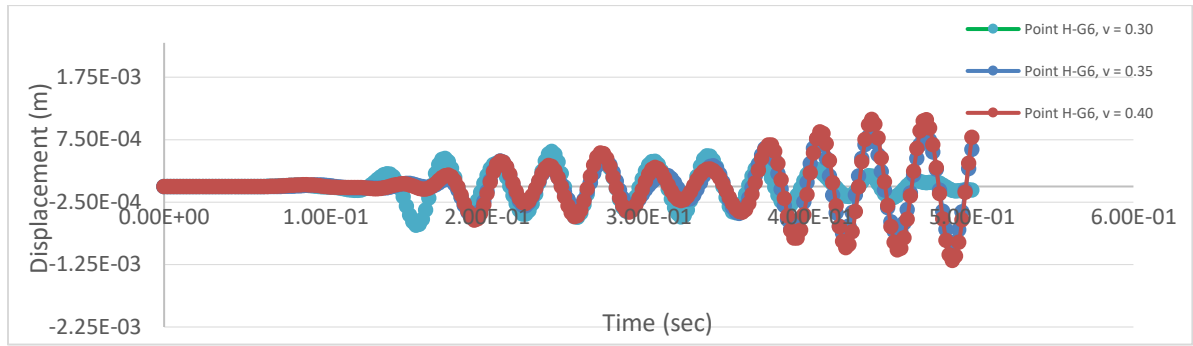


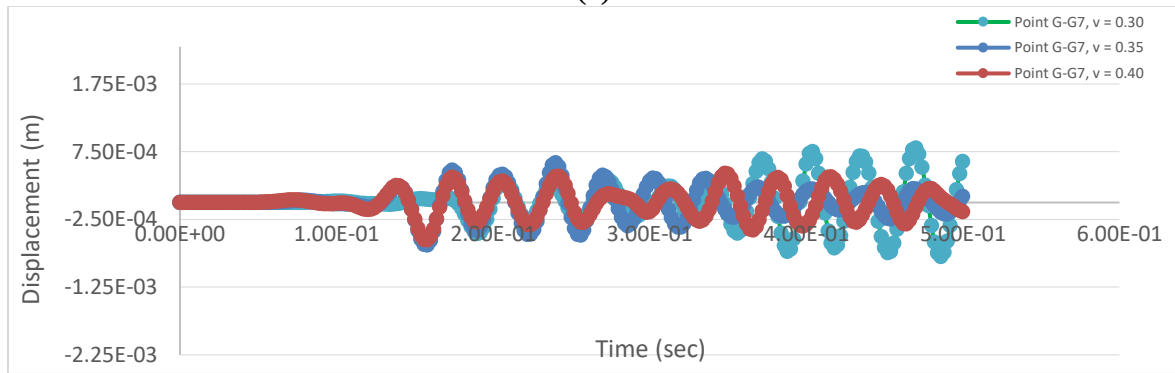
Figure 108: Effect of width on amplitude reduction ratio for open trench

5.6.1.2 Effect of Poisson's ratio of soil

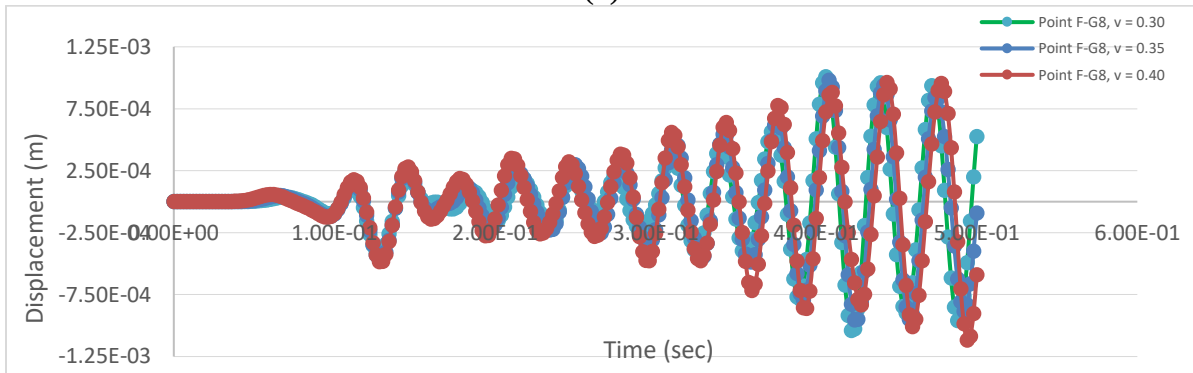
Figure 109 and 110 depicts the influence of the soil's Poisson's ratio (ν) on the performance of an open trench. The variations are limited to very low, but no significant conclusion may be derived from the responses observed. For Poisson's ratio $\nu_s = 0.30$, the normalized depth D may be extended as far as 2.0 for better efficiency of screening, while for $\nu_s = 0.40$, the normalized depth D may be 1.75 and for $\nu_s = 0.48$, a depth $D = 1.5$ appears to be the limiting value. For the three Poisson's ratios considered, the maximum variation in the amplitude reduction factor A_r is 6%. Thus, for the general range of the soil's Poisson's ratio of 0.30 to 0.48, the effect of ν , can be ignored.



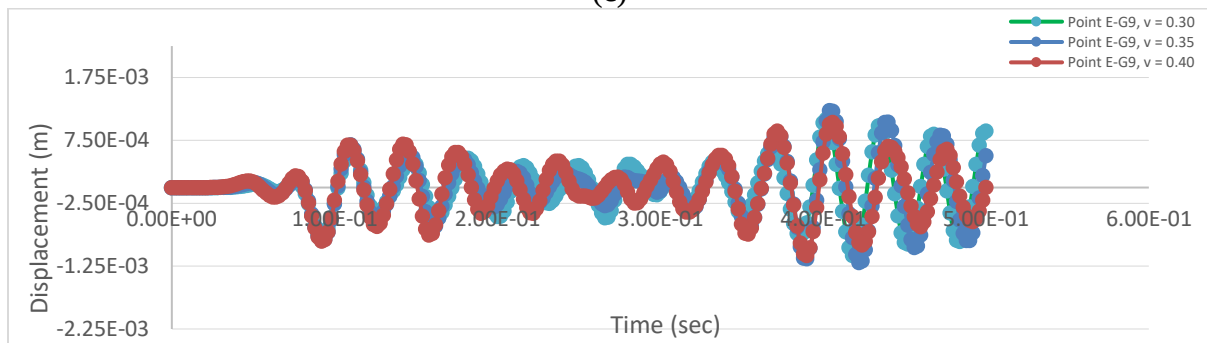
(a)



(b)



(c)



(d)

Figure 109: Effect of Poisson's ratio of soil on empty trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from centre of trench with Crumbed rubber as backfill material

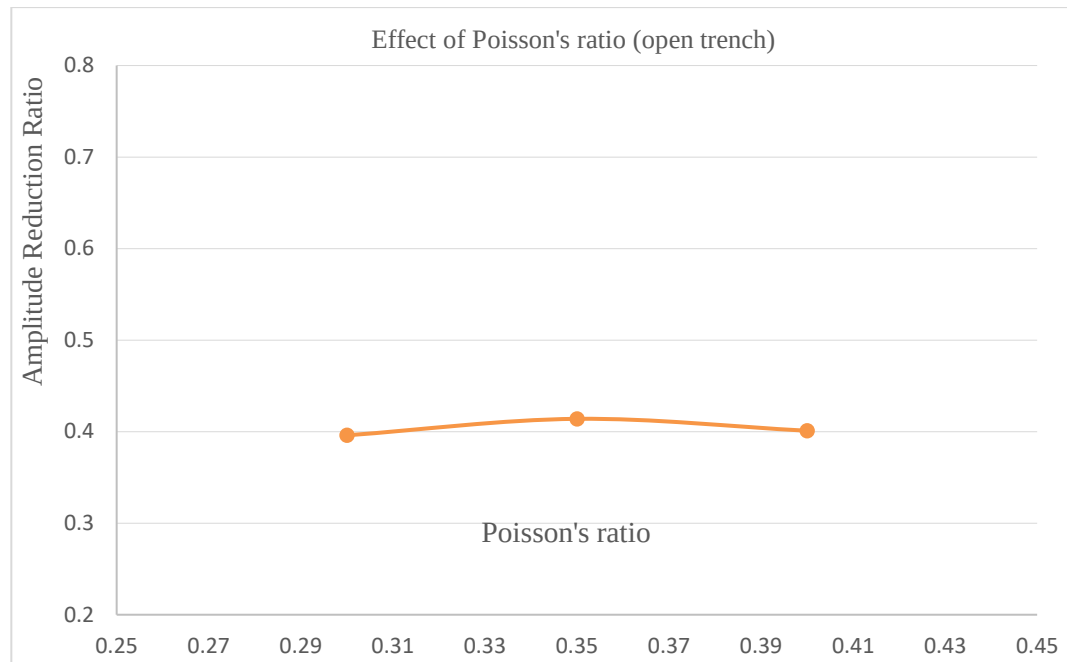


Figure 110: Effect of Poisson's ratio on amplitude reduction ratio for open trench

5.6.1.3 Effect of barrier location

The effect of location of source of vibration i.e. distance between trench and the vibration source is studied by amplitude reduction with reference to the responses as shown in Figure 111 and 112. The distance of the barrier from the source is varied in case of active isolation from $X = 2.50\text{m}$, 5.00m and 10.00m and $L = 23.75\text{m}$ in a passive case, where X is the distance between source of vibration and Centre line of trench barrier and average amplitude reduction factors are estimated at G6, G7, G8 & G9. The variation of amplitude reduction ratio against barrier location (L) is shown in Figure 111. Figure 112 overall indicates that there is no monotonic variation for amplitude reduction while considering the active case locations at 2.5m , 5m and 10m . But while observing the response when location at 23.75m , it is found that the amplitude reduction is somewhat increased but not significant. This increase at 23.75m distance may be erroneous due to its farness where some damping factors plays an important role in reduction of amplitude. It can be concluded that the location of source of vibration has no significant impact on amplitude reduction.

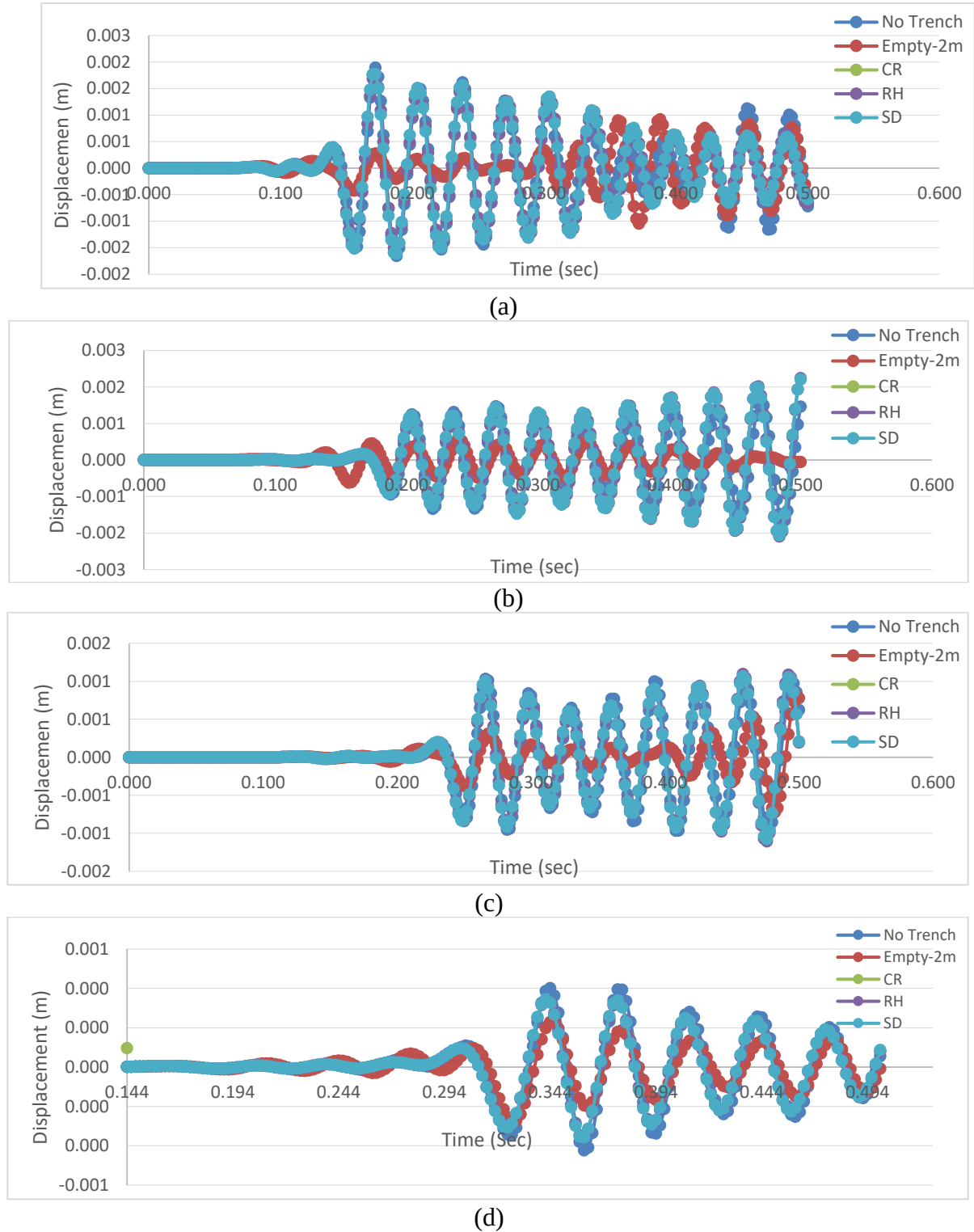


Figure 111: Comparison of the vertical displacement vs time histories at observation point G8 for active isolation measures due to frequency of 30 Hz with source of location at (a) 2.5m (b) 5m (c) 10m on one side & (d) 23.75m on other side from Centre of trench

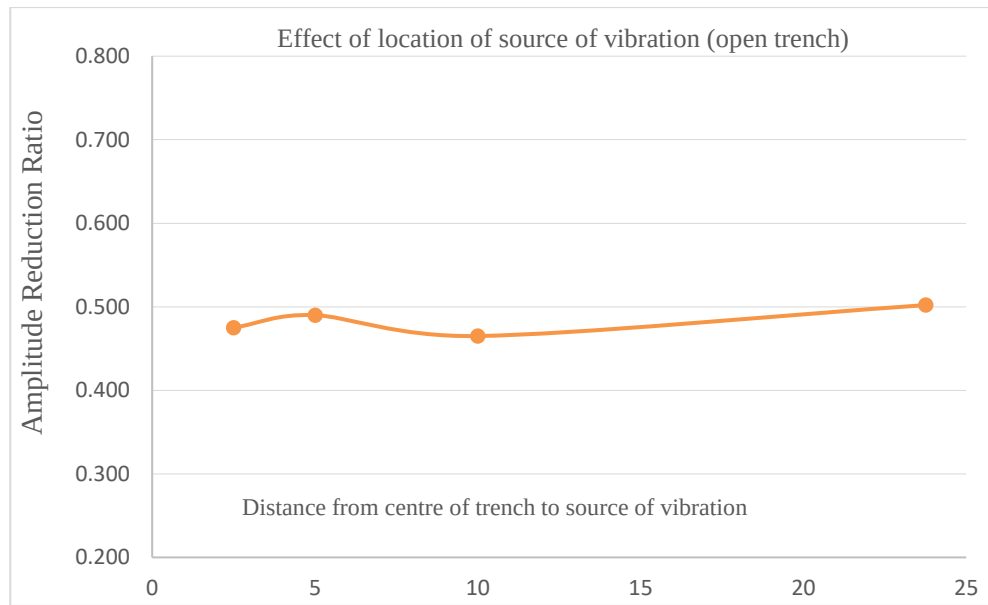


Figure 112: Effect of location of source of vibration on amplitude reduction ratio for open trench

5.6.2 IN-FILLED TRENCH

5.6.2.1 Effect of Trench Dimensions

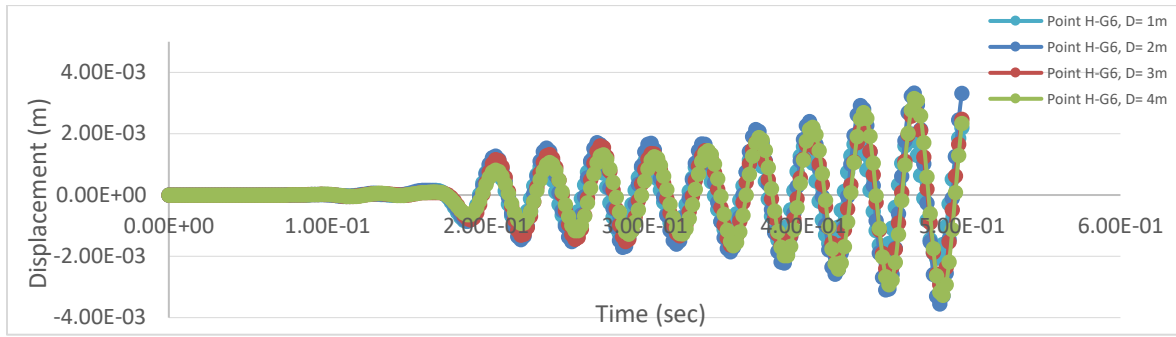
Depth and width of the trench i.e. trench dimensions and related cross-sectional area is having effect on performance of the barrier for vibration isolation. The depth of the trench has significant influence on screening efficiency. The width of the trench has lesser effect on the efficiency of the trench barrier and effects of both the parameters have been studied. The effect of in-filled trench barrier cross-sectional features with in-filled material as crumbed tyre rubber is studied in terms of variations of amplitude reduction. The trenches with varying depth and width ($d = 1\text{m}$, 2m and 3m & 4m) and width ($w = 0.25\text{m}$, 0.50m , 0.80m and 1.00m) has been considered for the investigation. This study considers specific barrier locations i.e. distance between centre of trench and source of vibration which is $X=5.0\text{m}$ representing active case.

5.6.2.1.1 Effect of trench depth

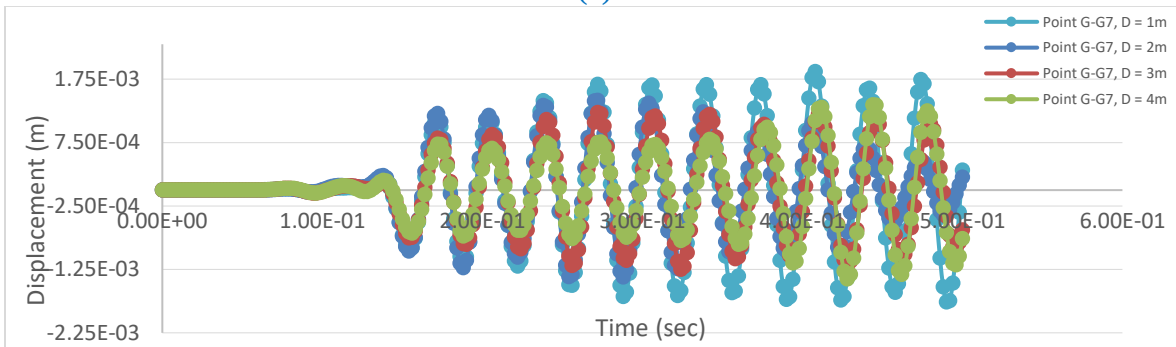
The responses in terms of amplitude reduction ratio for in-filled trench barrier with in-filled material as crumbed tyre rubber is as shown in Figure 113 and Figure 114, the effectiveness is observed at lesser depth



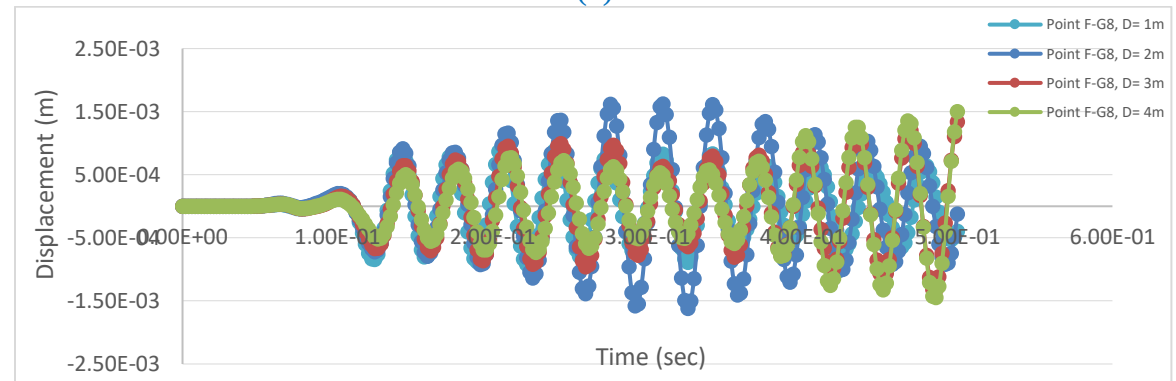
while for wider trenches the same is achieved at a higher depth. It shows that in order to find out optimum screening effectiveness, a specific depth must be associated by a specific width and vice-versa. The vertical amplitudes at observation points G6, G7, G8 and G9 are as shown in Figure 113 and its inference is depicted in Figure 114. The range of depth has been varied from 1m to 4.00m. By in sighting the relation of width to depth relation, it is noted that with increasing depth, the amplitude reduction ratio decreases to an optimum value. The variation of width has shown a different aspect as was expected. It is found that at lesser width, higher depths are more effective as compared to shallow depth. With increase in width, the effectiveness decreases. This behaviour may be understood by the fact that narrow trench barrier permits a significant part of waves to transmit through it directly, causing low effectiveness. But for wider trench, it allows much more waves to travel along with boundaries during propagating into soil. Barriers with more depth contribute to higher efficiency.



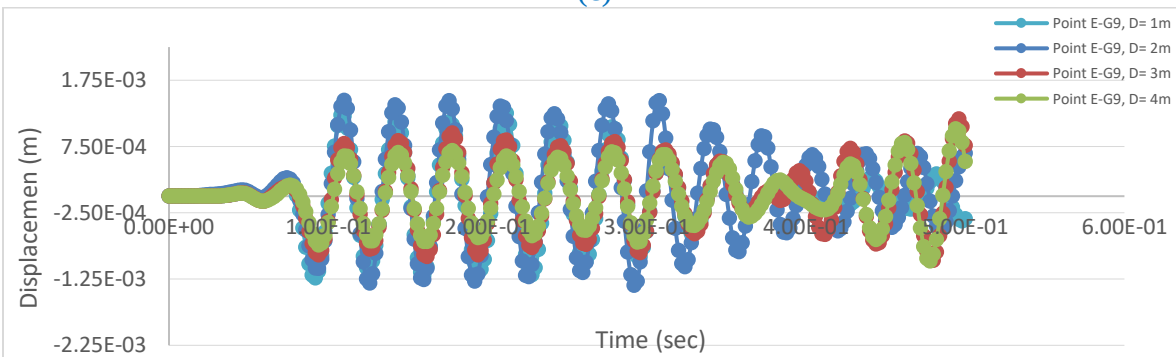
(a)



(b)



(c)



(d)

Figure 113: Responses for effect of depth of trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation due to frequency of 30 Hz at the source vibrator location 5 m from centre of trench with Crumbed rubber as backfill material

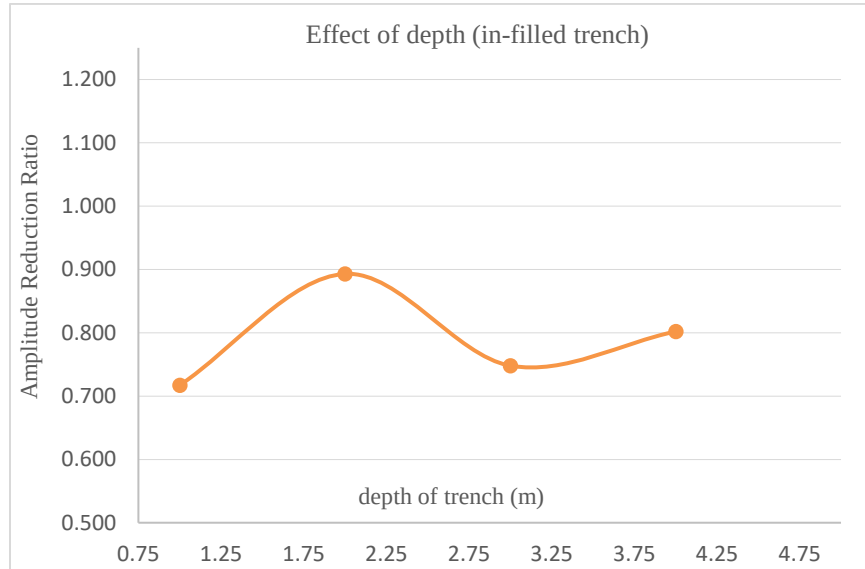
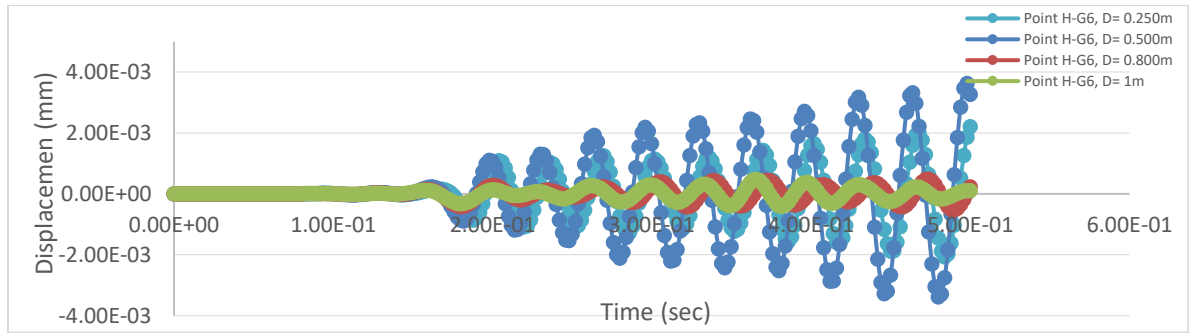


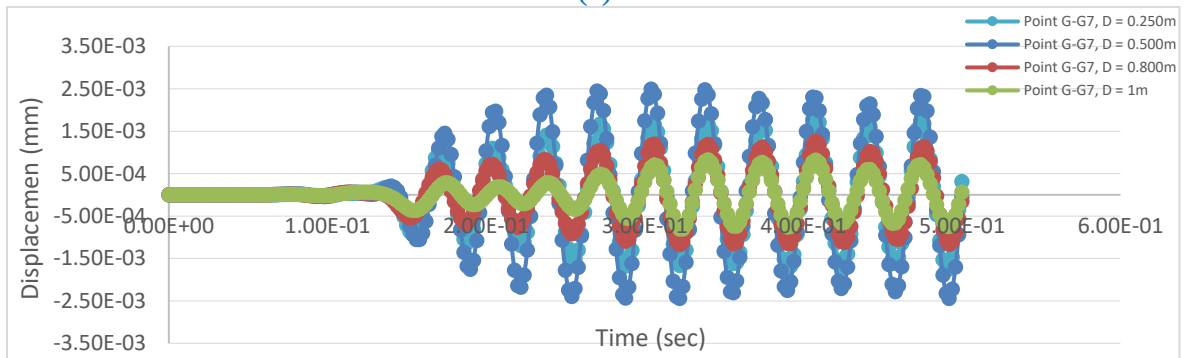
Figure 114: Effect of depth on amplitude reduction ratio for in-filled trench

5.6.2.1.2 Effect of trench width

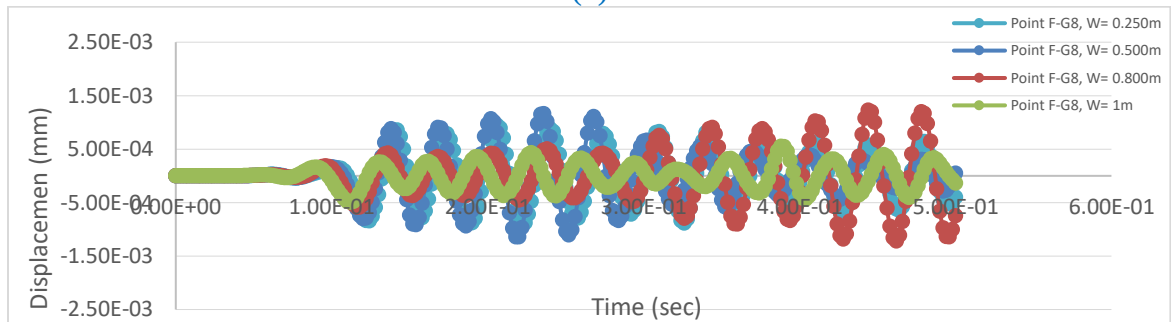
Figure 115 shows the responses in case of in-filled trench barrier, received at observation points G6, G7, G8 & G9 for determining active isolation performance when the frequency of the wave is at 30Hz and the source of vibration is kept at 5m from the centre of trench. Figure 116 depicts the influence of barrier width on the vibration isolation effectiveness. The effect of width on amplitude reduction is studied for in-filled trench barrier with in-filled material as crumbed tyre rubber and is found specific to some cases only. An increase in width up to 0.65m causes reduction in amplitude significantly. The trend is somewhat lower when width varies from 0.70m to 1m and can be considered as an upper limit of width beyond which a further increase in width adversely affects amplitude reduction of shallow trenches for active isolation cases in particular. For all other cases, an increase in width beyond 0.65m does not have any beneficial effect on amplitude reduction. In general, the effect of width has little significant in attenuating vertical vibrations on higher width of trench and cannot be considered significant for all practical cases.



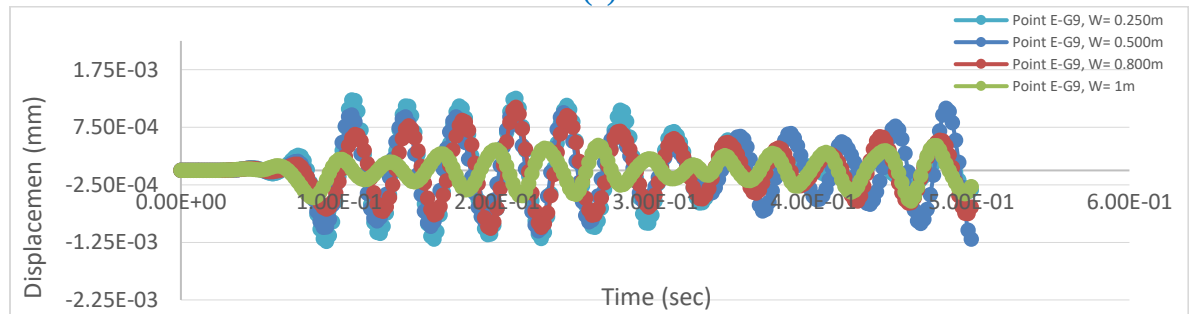
(a)



(b)



(c)



(d)

Figure 115: Responses for effect of depth of trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation due to frequency of 30 Hz at the source vibrator location 5 m from centre of trench with Crumbed rubber as backfill material

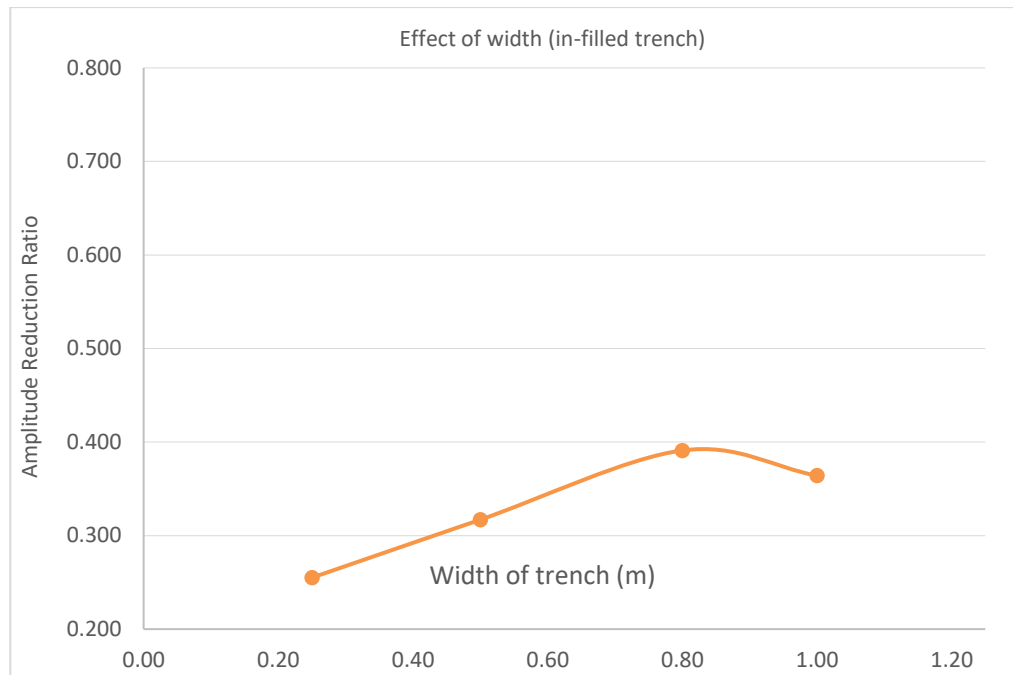
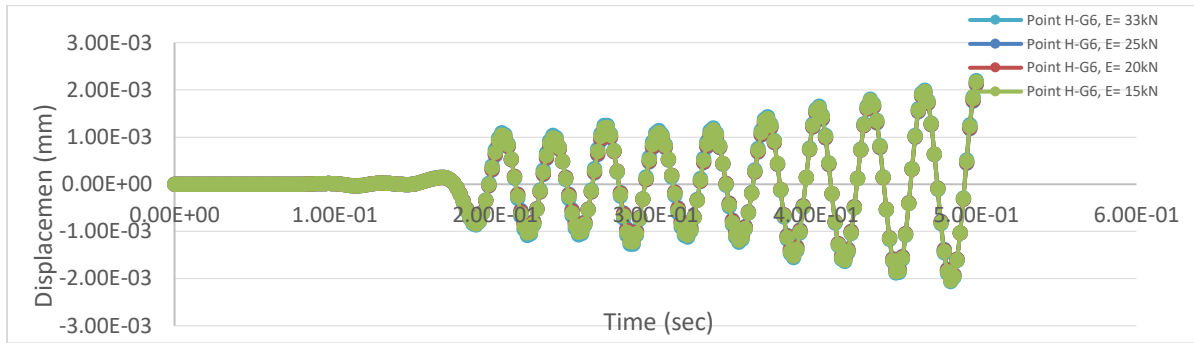


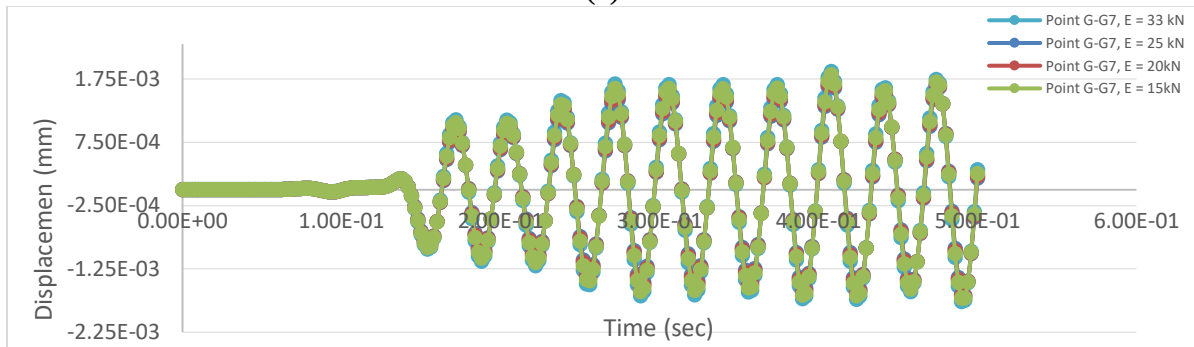
Figure 116: Effect of width on amplitude reduction ratio for in-filled trench

5.6.2.2 Effect of Stiffness (Young's modulus) of in-filled materials

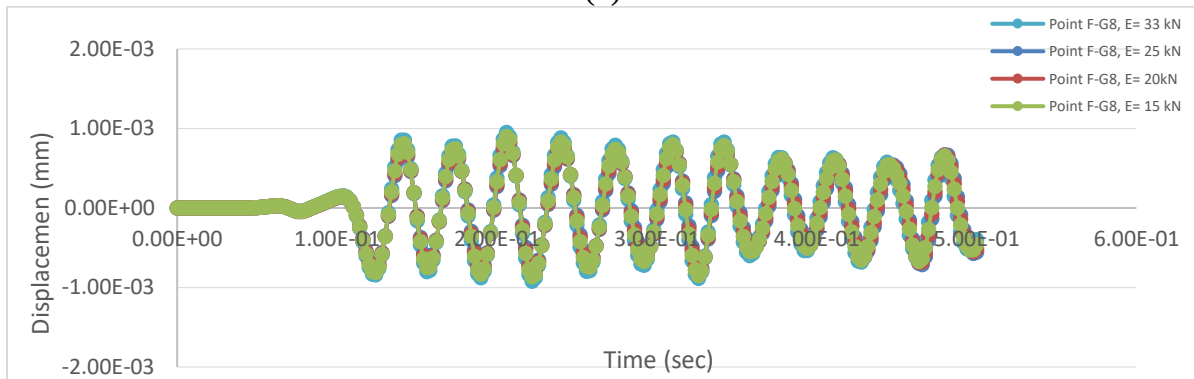
Figure 117 shows the responses in case of in-filled trench barrier, received at observation points G6, G7, G8 & G9 for determining active isolation performance when the frequency of the wave is at 30Hz and the source of vibration is kept at 5m from the centre of trench. Figure 118 depicts the influence of barrier Young's modulus on the vibration isolation effectiveness. The value of stiffness varied from 15 to 33 kN/m². It can be seen from the observation that when the value of stiffness is at lower value the reduction in amplitude is significant on higher side. It confirms with the conclusion that open trench barrier has the maximum isolation efficiency. Also, attenuation i.e. reduction in amplitude in stiffer material is lesser than the soft soils.



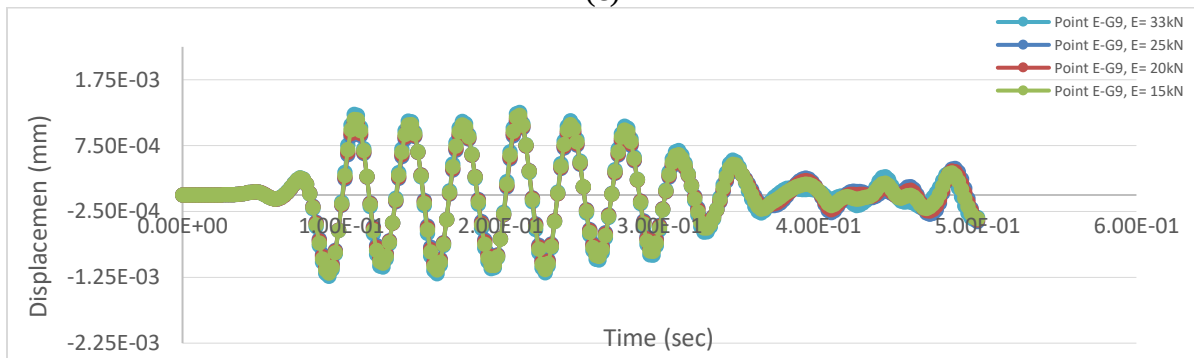
(a)



(b)



(c)



(d)

Figure 117: Responses for effect of Stiffness of in-filled materials in trench barrier at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench and crumbed tyre rubber as backfill material

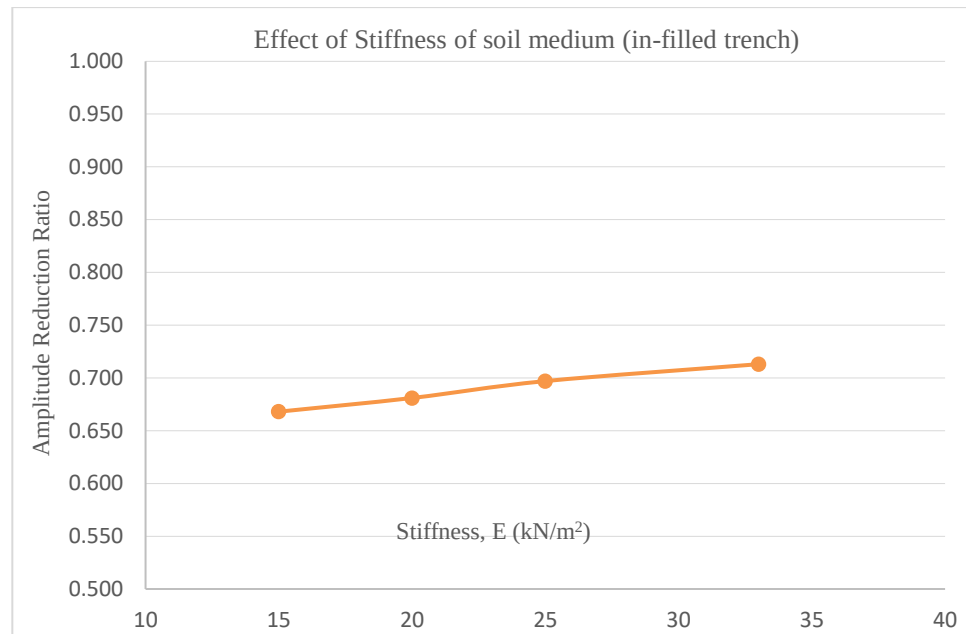


Figure 118: Effect of barrier Young's modulus on amplitude reduction ratio for in-filled trench

5.6.2.3 Effect of barrier location

To study the effect of barrier location on amplitude reduction, the distance of the barrier from the source is varied in case of active isolation from $L = 2.50$ m, 5.00 m and 10.00 m and $L = 23.75$ m in a passive case, where L is the distance between source of vibration and centre line of trench barrier and average amplitude reduction factors are estimated at G6, G7, G8 & G9. The variation of amplitude reduction ratio against barrier location (L) is shown in Figure 119. Figure 119 indicates that, there is no monotonic variation for vertical response while considering the location at 2.5 m, 5 m and 10 m. But while observing the response when location at 23.75 m, it is found that the amplitude reduction is somewhat increased. This increase at 23.75 m distance may be due to its farness where some other factors also play important role in amplitude reduction. It can be concluded that there is no significant impact of location of source of vibration on vertical amplitude reduction.

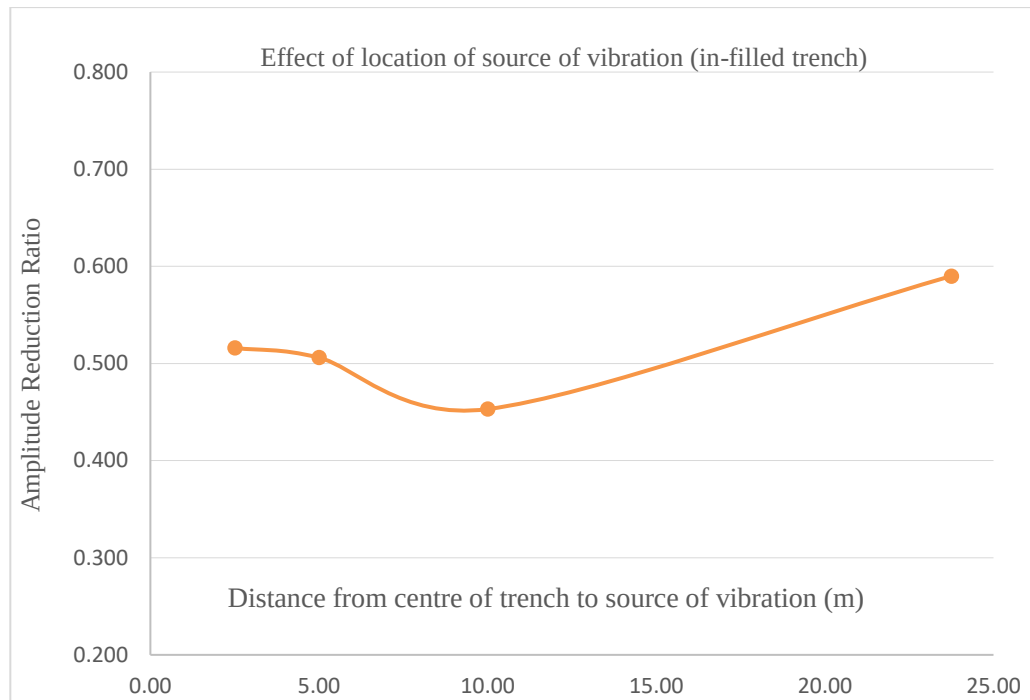


Figure 119: Effect of location of source vibration on amplitude reduction ratio for in-filled trench

5.6.2.4 Effect of shear wave velocity ratio (V_b/V_s)

The shear wave velocity is a function of stiffness of soil. As stiffness of soil increases, the shear wave velocity also increases. Though, it has been expressed in past researches that softer trench barriers are better isolators than stiffer ones. Few such cases are investigated justifying the choice of softer barriers in this study. Figure 120 shows the responses in case of in-filled trench barrier, received at observation points G6, G7, G8 & G9 for determining active isolation performance when the frequency of the wave is at 30Hz and the source of vibration is kept at 5m from the centre of trench. Figure 121 depicts the influence of shear wave velocity on the vibration isolation effectiveness.

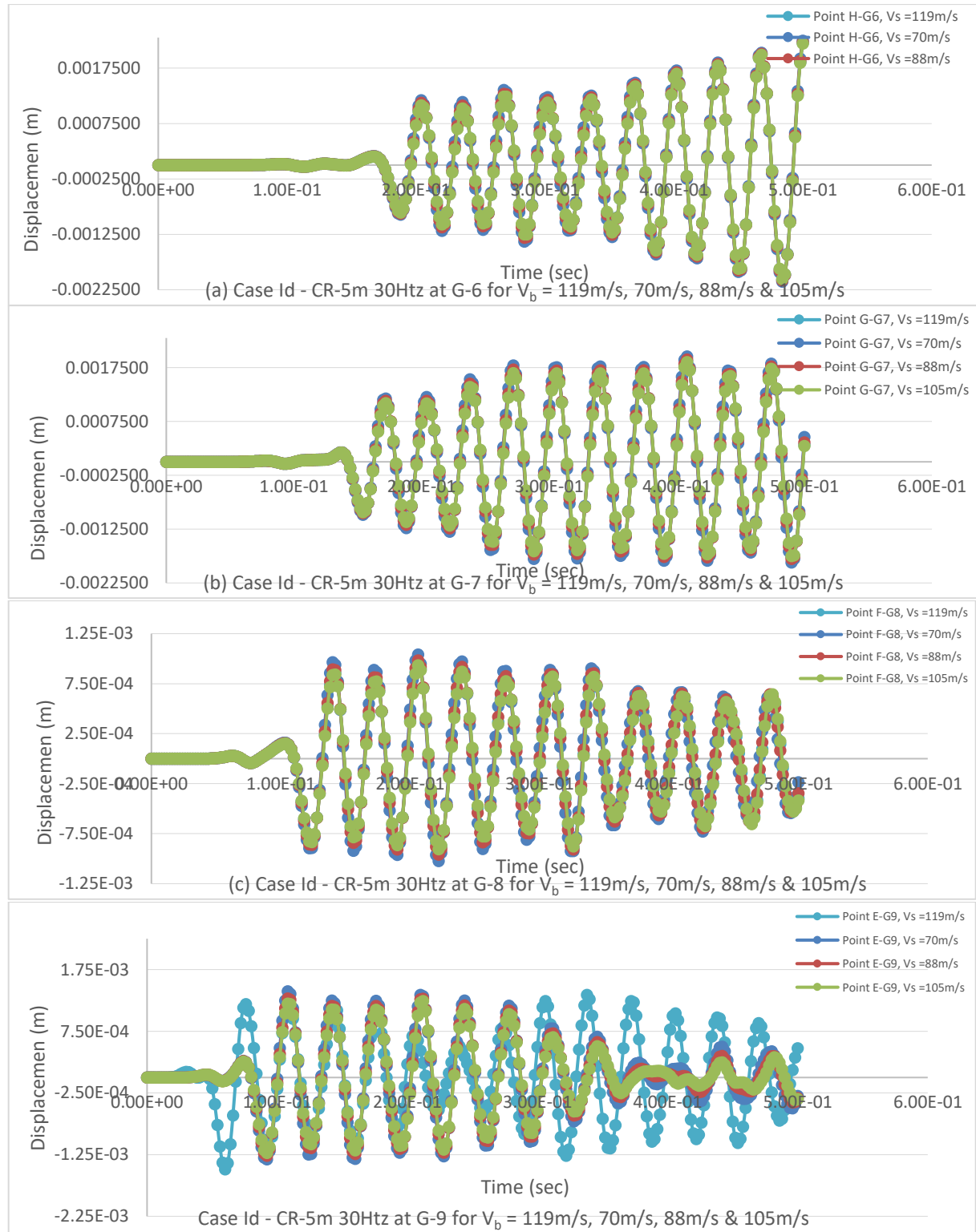


Figure 120: Effect of Shear wave velocity of backfill at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from centre of trench with Crumbed rubber as backfill material

The trenches are assumed to have a specific depth ($d = 1\text{m}$) and location ($X = 5\text{m}$) and width ($w = 0.25\text{m}$). The shear wave velocity ratio (V_b / V_s) is varied from 0.20 to 0.80 for softer barriers. The backfill shear wave velocity is varied by changing its stiffness keeping other parameters unchanged. Effect of V_b / V_s on amplitude reduction ratio are depicted in Figure 120 and Figure 121. It is evident that the backfill must differ and be softer than the half-space in terms of shear wave velocities to cause vibration attenuation. This implies that the backfill should have either preferably lower shear wave velocities than the in-situ soil. The amplitude reduction curves would reach unity irrespective of the trench configurations at $V_b / V_s = 1$, implying that the isolation scheme would behave as if there were no barrier if the shear wave velocity of backfill is identical to that of half-space. Another crucial observation is that in-filled trenches isolate vertical vibration component more effectively. Nevertheless, screening performances of softer barriers are found significantly higher than stiffer ones. Softer backfill characterized by shear wave velocity ratios less than unity are hence considered in the subsequent analyses. It is apparent that to achieve a good degree of isolation, V_b / V_s should be nearly 0.3 or preferably less.

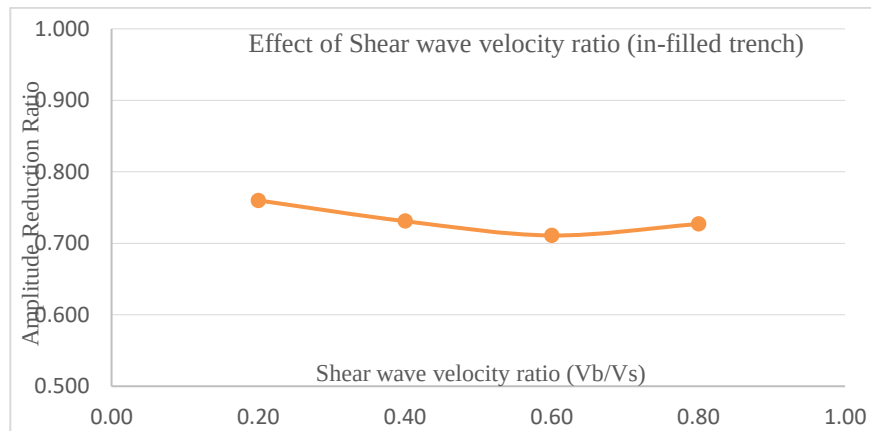


Figure 121: Effect of Shear wave velocity on amplitude reduction ratio for in-filled trench

5.6.2.5 Effect of soil's Poisson ratio:

Figure 122 shows the responses at observation points G6, G7, G8 and G9. Figure 123 represents the influence of barrier Poisson's ratio (ν_b) on the vibration isolation effectiveness. It is clear to see that vertical

amplitude reduction ratios almost keep constant with an increasing ν_b . It seems that the response of soil at observation points is not affected by the variation of barrier Poisson's ratio. Therefore, it is inferred that the barrier Poisson's ratio has negligible influence on its vibration isolation performance.

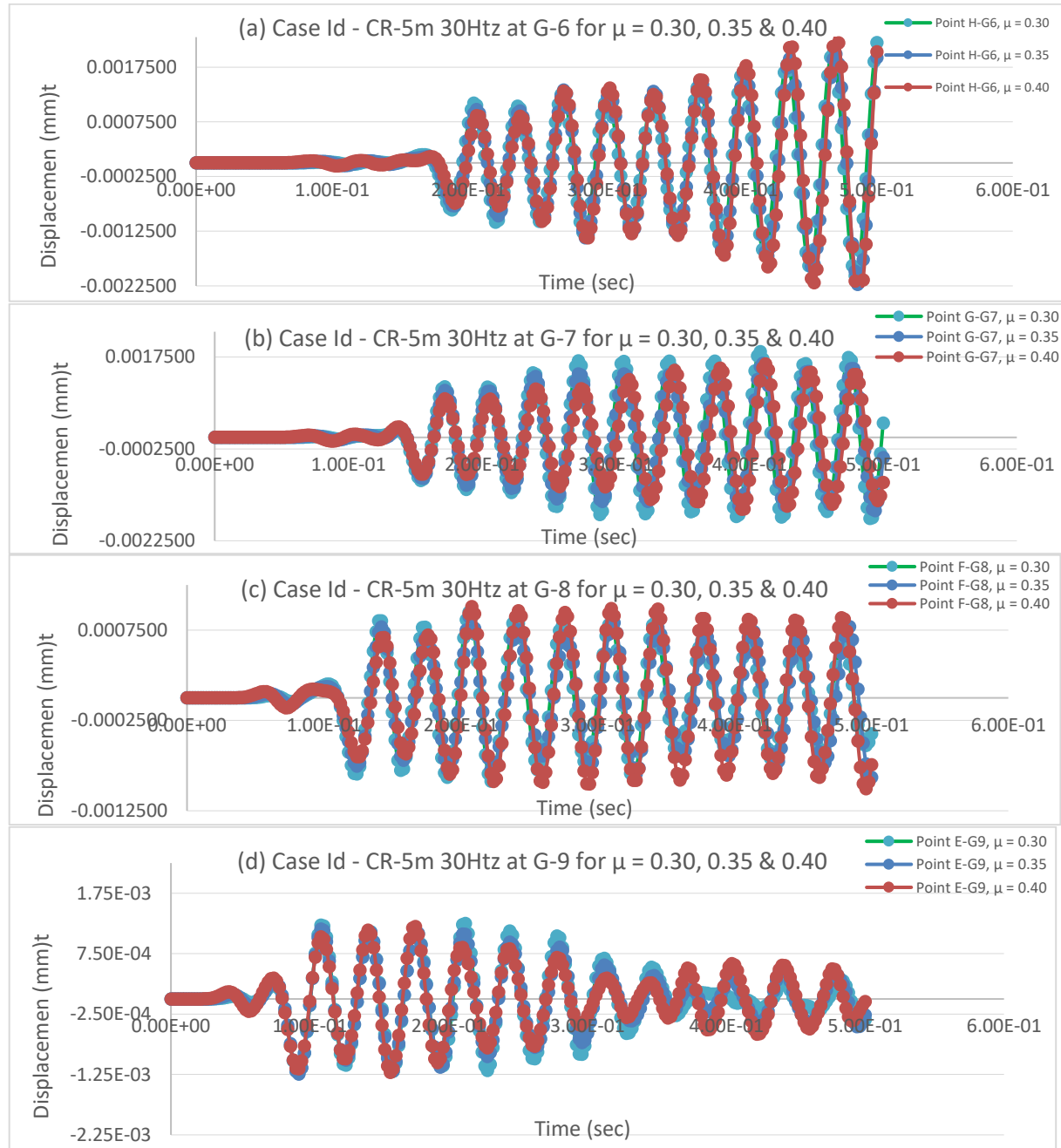


Figure 122: Effect of Poisson's Ratio of soil at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench with Crumbed rubber as backfill material

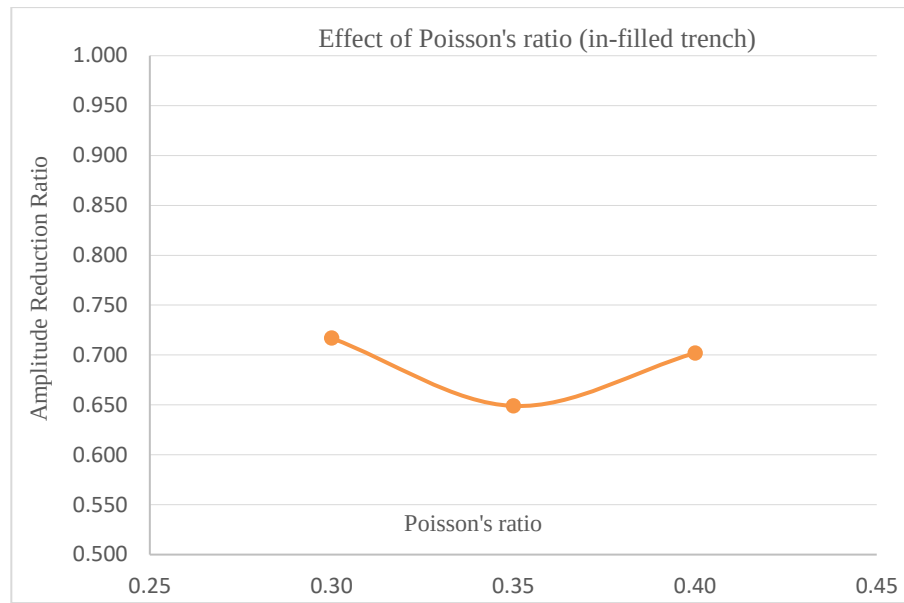
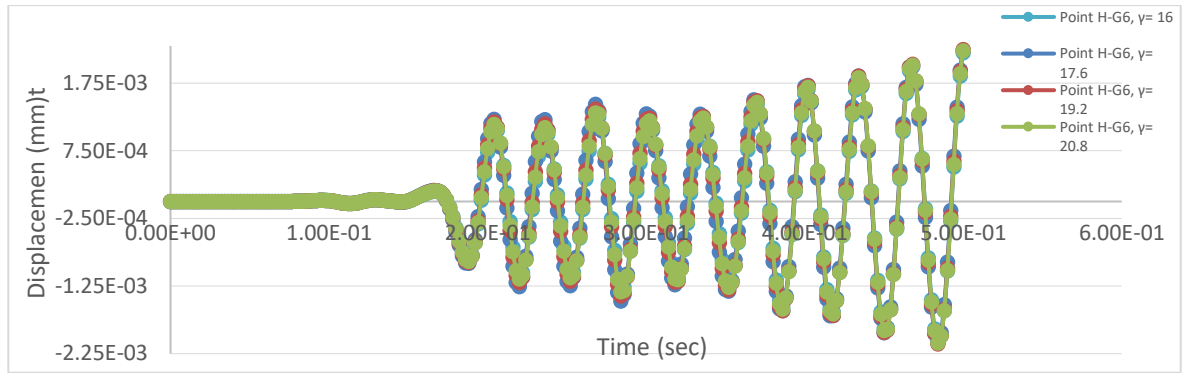


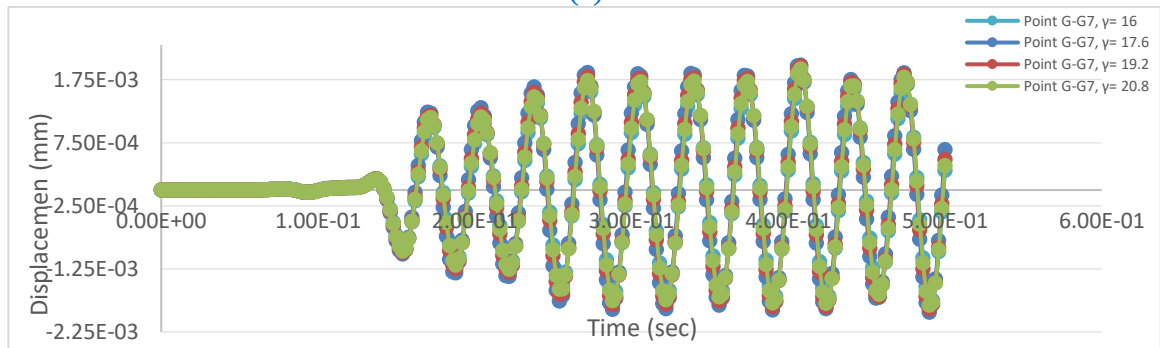
Figure 123: Effect of Poisson's ratio on amplitude reduction ratio for in-filled trench

5.6.2.6 Effect of density of soil:

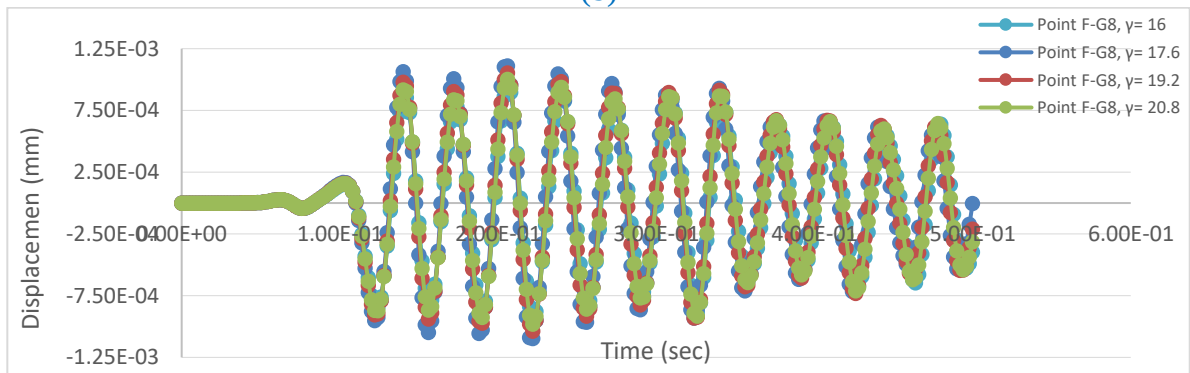
Figure 124 shows the responses for indicating effect of the ratio of density (ρ_b/ρ_s) on the vibration isolation effectiveness responses at G6, G7, G8 and G9 observation point. The density of barrier and soil are defined as ρ_b and ρ_s , respectively, and the ranges of density of soil from 16kg/m^3 to 20.80kg/m^3 . From Figure 125, it can be seen, in general, that the smaller the density of barrier is, the isolation effect the barrier produces is increased. On the other hand, barriers with large density tend to be efficient up to a limit in reducing vertical vibration. When ρ_s is increased as compared to ρ_b , the vertical velocity amplitude reduction ratio A_r reduces to some extent. The reasons quite possible for this difference is that the vertical motion of barrier tends to send wave energy deep into the soil. Thus, more energy that results in vertical vibration is consumed, leading to a better vertical vibration isolation effect. It is however noted that material with too large density will probably not be considered, for example, when ρ_b is multiple times of ρ_s , it indicates that the barrier density is too much and such barrier material with large density is difficult to achieve.



(a)



(b)



(c)

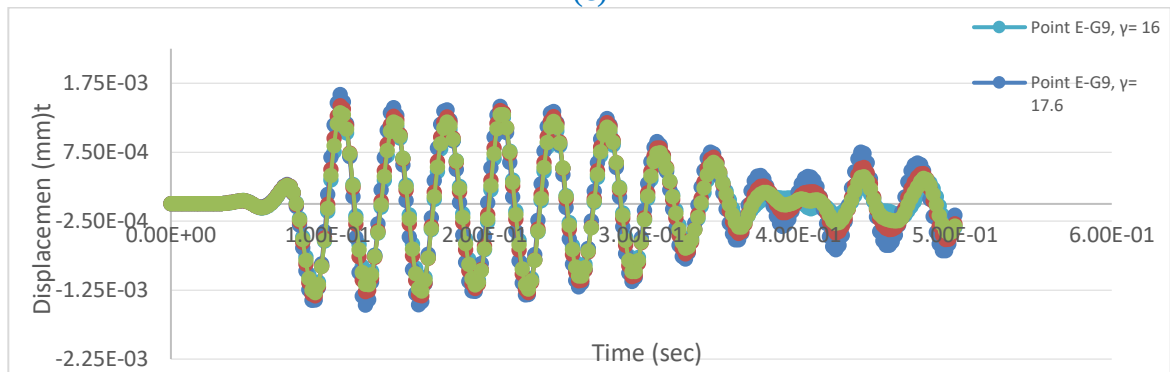


Figure 124: Effect of density of soil at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench with Crumbed rubber as backfill material

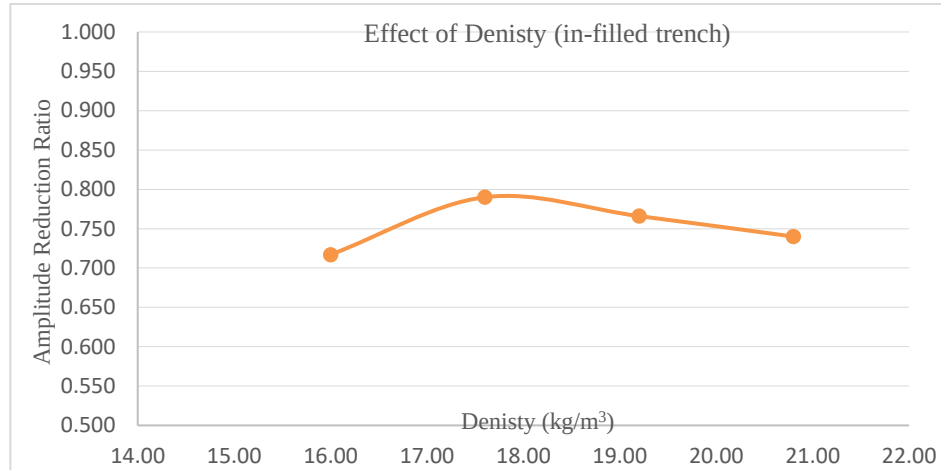


Figure 125: Effect of Density on amplitude reduction ratio for in-filled trench

5.6.2.7 Effect of barrier material damping:

Figure 126 shows the responses due to the effect of barrier damping ratio (β_b) on the vibration isolation effectiveness at observation points G6, G7, G8 and G9. Figure 127 indicates the effect of barrier damping ratio on the vertical amplitude ratio. The behaviour observed in figures, vertical responses change little as β_b increases. Thus, the influence of barrier damping ratio can also be ignored.



Figure 126: Effect of Material Damping of in-filled material at observation point (a) G6 (b) G7 (c) G8 and (d) G9 for active isolation measures due to frequency of 30 Hz at the source vibrator location 5 m from Centre of trench with in-filled Crumbed rubber

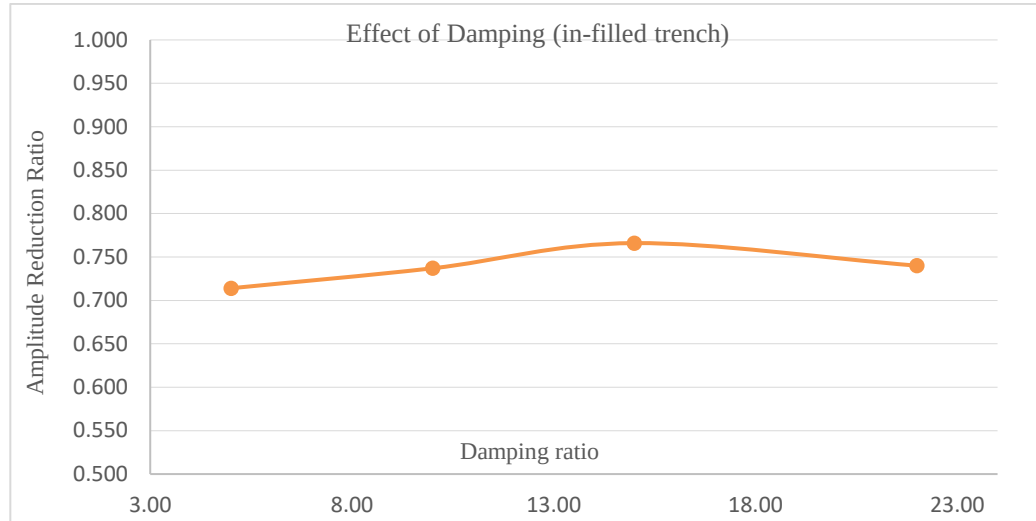


Figure 127: Effect of damping ratio on amplitude reduction ratio for in-filled trench

5.7 RESULTS AND DISCUSSION:

Isolation response of rectangular in-filled trenches in an elastic, isotropic, and homogeneous half-space is numerically studied in this work in 3D context. Softer barrier is considered in this study as such barriers are found to provide significantly better screening effect than stiffer barriers. The key results and crucial observations of this study are summarized as follows:

1. It can be conceived that an open trench is a special case of an in-filled trench of $V_b / V_s \approx 0$. Vibration attenuation is caused only when the backfill is either softer or stiffer than the surrounding half-space. In order to achieve a good degree of isolation, the shear wave velocity ratio, V_b / V_s of backfill should be around 0.3 or preferably less. It can also be concluded that in-filled trenches can isolate the vertical vibration component more effectively.
2. The effect of barrier location on its screening effectiveness depends on the barrier depth and width and also on the component of vibration under consideration. In case of the vertical vibration component, deeper ($d \geq 0.75$) barriers are more effective in passive cases. However, variation in screening effectiveness from active to passive cases decreases as the trench width increases from = 0.3 to 0.5. The

- exceptions are the cases of shallow ($D = 0.5$) trenches where variation of amplitude in vertical direction is inconsistent with L and no firm conclusion can hence be made. In most of the observations, other than $D = 0.5$, the screening effectiveness increases up to $L = 2$ to 3 and thereafter remains virtually constant.
3. So far as the horizontal vibration component is concerned, better isolation effect is noted in passive cases when the trench is narrow ($W = 0.3$). In these cases, amplitude reduction factor decreases with L , roughly up to 2 and remains constant thereafter. However, for wider trenches ($W = 0.5$) the trend is highly irregular and such conclusions are difficult to make.
 4. Increase in barrier depth not necessarily decreases amplitude in vertical direction. To obtain optimum screening effect in vertical vibration case, a particular trench depth must be accompanied by a specific width and vice-versa. There exists a certain value of D/W at which a softer barrier yields optimum efficiency irrespective of the cases whether active or passive. In most of the observations, this critical D/W value lies roughly within a range of 1.2 to 1.6 . However, the effect of W is pronounced only in active cases and has little significance in passive cases. In all cases, $W = 0.8$ can be considered as limiting barrier width beyond which increasing the same has little to no effect on amplitude.
 5. The %age efficiency of all the in-filled material derived is as shown in Table 23.

Table 24: Protective Efficiency of Barriers (%age):

Trench Type	1st Location	2nd Location	3rd Location	Average
1. Open Trench	54.12%	52.80%	52.95%	53.29%
2. Crumbed Rubber	47.82%	44.40%	48.73%	46.83%
3. Rice Husk	44.00%	49.97%	44.15%	46.23%
4. Saw Dust	43.52%	44.30%	48.52%	45.82%

5.9 CONCLUSION:

Numerical validation of results of experimental study has been carried out and found that the variation is not beyond unreasonable limit. The influence of various parameters such as the frequency, aerial extent of the reduction zone, trench dimensions, trench location, Poisson's ratio of soil, and in-fill material properties such as the wave velocity, density, and damping have been investigated. Important observations are summarized as follows:

6. For practical purposes, the influence of the Poisson's ratio of the soil can be ignored.
7. The effect of the frequency is taken into account by normalizing the dimensions of the trench with respect to the Rayleigh wavelength.
8. For open trenches, the depth 'd' is the governing factor; the width 'w' is not important, except for shallow depths.
9. For in-filled trenches, both depth and width are equally important.
10. For in-filled trenches, the effect of the shear modulus and density of the fill material (compared to the soil) must also be considered.

It should be noted, however, that in many practical cases it seems to be appropriate to perform a more detailed investigation of the structure/soil/trench system under consideration similar as it has been done in this contribution. Designing the optimum trench with respect to its depth and width study should be performed for each particular case.



CHAPTER-6

Conclusion, Future Scope and Social Impact



6.1 CONCLUSION

A full-scale experimental study was carried out to investigate the protective effectiveness of open and in-filled trench wave barriers with in-filled material as Crumbed rubber, Rice husk and Saw dust which helps in scattering the steady state vibration induced by machine foundations, etc. In order to simulate the machine foundations vibration, an electro-mechanical oscillator was used. A detailed investigation on the reduction of foundation vibrations due to a harmonic load which is produced by electromechanical oscillator using a trench wave barrier has been presented. The wave barriers protective effectiveness was evaluated based on the achieved reduction in soil particle amplitude through a parametric study by changing the exciting frequency and the location of the source of vibration. Considering the same experimental work conditions, to verify the field test results 3D finite element models have been developed to simulate numerically, the open and in-filled trench barriers behaviour in scattering surface steady state waves. The effectiveness of using open or in-filled trench as a reduction measure has been demonstrated through a site measurement study depending on the obtained results. Time dependent displacement values are reduced for both cases of active and passive isolations. In this case wave absorption plays very important role. Using open or in-filled trench barriers can reduce the vibrations of a structure and the resulting internal forces significantly. The use of an open trench is more effective than using an in-filled trench but its practical application is limited to relatively shallow depths. On the other hand, using softer backfill material increases the effectiveness of in-filled trench and allows for larger trench depth with no supporting measures of the vertical walls of the trench. Moreover, the waste materials used in these trench barriers will add economy to the application. The barriers have been found to be generally more effective in passive isolation compared to active isolation for both measurement points. It should be noted, however, that in many practical cases it seems to be appropriate to perform a more detailed investigation of the structure/soil/trench system under consideration similar as it has been



done in this contribution. Designing the optimum trench with respect to its depth and width study should be performed for each particular case.

6.2 FUTURE SCOPE OF STUDY

The present study was based on in-filled material in trench wave barriers and it is found that the in-filled materials are quite effective in vibration screening. In the line of further method of vibration screening, the study can be extended in using solid piles as shown in Figure 128. It is the case of Passive Screening by use of Pile Barriers. There may be situation in which Rayleigh wavelength may be in the range of 40 to 50m. For such a case, the open trench will be effective if its depth ranges from 53-66m (i.e. $1.33\lambda_R$). Open trenches (filled or unfilled) with such deep depths are not practical. For this reason, possible use of rows of piles as an energy barrier has been studied by Woods et al. (1974) and Liao and Sangrey (1978). Woods et al. (1974) used the principle for holography and observed vibrations in a model half space to evaluate the effect of void cylindrical obstacles on reduction of vibration amplitudes. A box of size 1000mm x 1000mm x 300mm deep filled with fine sand constituted the model half space. In the figure, D is the diameter of void cylindrical obstacle and SH is the spaces between two consecutive void holes through which energy can pass through the barrier. The numerical evaluation of barrier effectiveness was made by obtaining the average of the values of ARF obtained on several lines beyond the barrier in a section $\pm 15^\circ$ of both sides of an axis through the source of disturbance and perpendicular to the barrier. In all tests H/λ_R and L/λ_R were kept as 1.4 and 2.5 respectively. The isolation effectiveness may be defined as

$$\text{Effectiveness} = 1 - A_R$$

6.3 SOCIAL IMPACT

Application of projects related to vibration screening and isolation from unwanted vibration effects have social impact and are significant because they protect human health and safety, improve the quality of life in urban areas and enable the high-precision technologies that underpin highly sensitive modern medical

equipment while in operation.

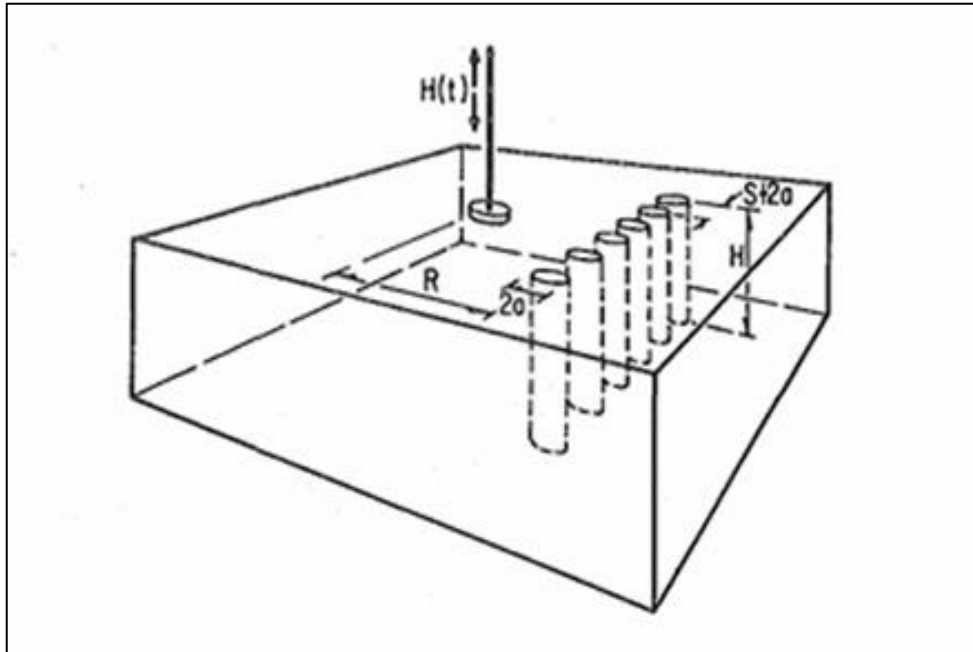


Figure 128: Barrier of Piles as Isolation System (Oscillating force is shown at a distance R from barrier)

The social impetus for these projects is a direct response to the negative consequences of unwanted mechanical vibrations, which can be a nuisance, a health hazard, or a threat to structural integrity and equipment functionality.

1. Protecting public health and safety:

Prolonged exposure to mechanical vibration, particularly in occupational and urban settings, has serious health consequences. Vibration isolation projects address these issues by:

- **Preventing whole-body vibration (WBV):** Drivers and heavy machinery operators are at high risk for WBV, which can lead to fatigue, back pain, spinal disorders, and problems with the digestive system. Vibration isolation systems in vehicles and equipment protect workers by cushioning them from these harmful vibrations.



- **Mitigating hand-arm vibration syndrome (HAVS):** Workers who regularly use hand-held power tools, such as chainsaws or road drills, are susceptible to HAVS. This condition causes nerve and vascular damage in the fingers and hands, leading to reduced dexterity and grip strength. Anti-vibration gloves and low-vibration tool designs powered by isolation technology reduce the risk of this debilitating condition.
- **Improving urban quality of life:** Dense urban environments generate significant vibrations from sources like heavy traffic, subway systems, and construction. These vibrations can cause annoyance, disrupt sleep, and decrease concentration. Projects to isolate buildings and transit tracks from vibration significantly improve the living and working conditions for urban dwellers.
- **Increasing structural resilience:** In seismically active regions, vibration isolation techniques like base isolation systems protect large structures, such as buildings and bridges, from earthquake damage. By decoupling the structure from ground motion, these systems reduce the transmission of seismic energy and protect public safety.

2. Enabling advanced technology and innovation:

Vibration screening and isolation is critical for the reliable operation of sensitive equipment, making projects in this field essential for medical utility, high-tech industries and scientific research. Key applications include:

- **Medical equipment:** Precision in healthcare is paramount, and sensitive diagnostic tools like MRI machines must be isolated from vibrations to ensure accurate results. High-tech manufacturing of medical devices and surgical robots also relies on vibration-free environments to maintain product reliability.



- **Precision manufacturing:** In industries like semiconductor fabrication, even microscopic vibrations can ruin a product. Active vibration isolation systems are used to stabilize equipment during lithography and inspection, which increases manufacturing yields and reduces costs.
- **Scientific research:** Labs conducting nanotechnology, microscopy, and laser experiments require ultra-stable conditions. Vibration isolation platforms protect delicate equipment from environmental disturbances, allowing for accurate data collection and driving scientific discovery.
- **Aerospace and defense:** Sensitive electronics, avionics, and instruments used in aircraft and other vehicles are protected from harsh vibrational and shock-loading environments to ensure safety and operational integrity.

3. Promoting economic efficiency and sustainability:

By protecting machinery, vibration isolation projects contribute to greater economic stability and reduced resource consumption.

- **Reduced maintenance and costs:** Prolonged vibration exposure can cause excessive wear and tear on machinery, leading to frequent and costly repairs or premature equipment failure. Vibration isolation extends equipment life, reduces maintenance costs, and minimizes operational downtime, increasing productivity and profitability.
- **Resource conservation:** Increased equipment longevity from vibration isolation reduces the need for replacements, which conserves the raw materials and energy used in manufacturing new machinery. This contributes to more sustainable industrial practices.

Optimized productivity: Vibration isolation improves working conditions and enables more precise work, which translates to increased efficiency and higher-quality output across various industries.



REFERENCES

1. Ahmad, S., Al-Hussaini, T.M. and Fishman, K. L. (1996). An Investigation on Active Isolation of Machine Foundation by Open Trenches. *Journal Geotechnical Engg., ASCE.*, No. 122, 454- 464.
2. Ankurjyoti Saikia, 2016, “Numerical investigation on vibration isolation by softer in-filled trench barriers” *Journal of Geo-Engineering Sciences* 3 (2015/2016) pp. 31–42
3. Ashref Alzawi, M. Hesham EI Naggar (2011), “Numerical Investigations on vibration screening by in-filled geofoam barriers”, 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering 64th Canadian Geotechnical Conference, October 2-6, 2011, Toronto, Ontario, Canada
4. Ashref Alzawi, M. Hesham EI Naggar (2011), “Full scale experimental study on vibration scattering using open and in-filled (Geofoam) wave barriers”, *Soil Dynamics & Earthquake Engineering*, 31, 306-317
5. Barkan. D. D., 1962, “Dynamics of Bases and Foundations”, MacGraw-Hill Book Company Inc., 374-406
6. Baker, J.M. 1994, “An Experimental Study on Vibration Screening by in-filled trench barriers, M.Sc. Thesis, State University of New York at Buffalo, USA
7. Beskos, D.E., Dasgupta, G., and Vardoulakis, I.G. (1986a). Vibration isolation using open or filled trenches, Part 1: 2-D homogeneous soil. *Computational Mechanics*, 1(1), 43–63
8. C. Comina and S. Foti, 2007, “Surface Wave tests for Vibration Mitigation Studies”, *Journal of Geotechnical and Geo-Environmental Engineering*, 133 (10), pp. 1320-1324
9. Deniz Ulgen and Onur Toygar, “Investigation on Vibration Isolation Performance of Open Trench Barriers under Impact Loading”, ICESA (2014) International Civil Engineering & Architecture Symposium for Academicians 17-20 May 2014, *Geotechnical Engg.*, pp. 73-80



10. G. L. Sivakumar Babu, Amit Srivastava, K. S. Nanjunda Rao and S. Venkatesha, 2011, “Analysis and Design of Vibration Isolation System Using Open Trenches”, International Journal of Geo-mechanics, ASCE, September 2011, 11(5), 364-369
11. George Gazetas, 1982, “Vibrational Characteristics of soil deposits with variable wave velocity”, International Journal for Numerical and Analytical Methods in Geo-mechanics, Vol. 6, pp. 1-20
12. Giuliano Belinassi et. al. (2019) “Vibration soil Isolation analysis based on a 3-D frequency domain Direct Boundary Element implementation: GPGPU acceleration” 23rd March 2019
13. Haupt, W.A. (1978). Surface waves in non-homogeneous half space. Dynamic methods in Soil & Rock Mechanics, B. Prange, A.A. Balkema Rotterdam, The Netherlands, 335- 367
14. Haupt, W.A., 1995, “Wave Propagation in the ground and Isolation Measures”, 3rd International conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2-7, 1995, volume II, St. Louis, Paper No-SOA11
15. Javier Aviles and Francisco J. Sanchez-Sesma (1988), “Foundation Isolation from Vibration using Piles as Barriers”, J. Eng. Mech., 1988, 1144(11), 1854-1870
16. Mal A. K., Knopoff L., “Transmission of Rayleigh waves at a corner”, Seismological society of America (1966), Volume 56, Number 2, April 1966
17. Miller G. F. , Pursey H. and Crisp Bullard Edward, 1955 “On the partition of energy between elastic waves in a semi-infinite solid” Published: 06 December 1955 <https://doi.org/10.1098/rspa.1955.0245>
18. Massarsch, K.R. 2005, “Ground Vibration Isolation using gas filled cushions” International workshop on the Mitigation and Countermeasures of ground environment, IW-SHHIGA 2005, pp. 123-133
19. Seyhan Firat, et. al., 2010, “Field Experiments on Wave propagation and vibration isolation by using wave barriers”, Propagation in Materials for modern Applications, INTECH, pp-526
20. S. Ahmad, T. M. Al-Hussaini, 1991. “An Experimental Study on Vibration Screening by in-filled



- trench barriers, *Journal of Geotechnical Engineering*, Vol. 117 No. 1, January 1991, Paper no 25416
21. S. E. Kattis et. al., 1999, "Vibration Isolation by a row of Piles using a 3-D Frequency Domain BEM", *International Journal for Numerical Methods in Engineering*, 46, pp. 713-728
 22. Tulika Bose, et. al., 2018, "Efficiency of Open and Infill Trenches in Mitigating Ground-Borne Vibrations" *J. Geotech. Geoenviron. Eng.*, 2018, 144(8): 04018048
 23. Yang Yeong-bin, Hung Hsiao-hui, "Wave Propagation for Train-induced Vibrations: A Finite/infinite Element" 2009
 24. Ahrens John, "Wave Attenuation by Artificial Seaweed", Report No 79-9, June 1976, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir
 25. Klimetos T. And McCann C., "Relationships among compressional wave attenuation, porosity, clay content and permeability in sandstone", *Geophysics*, Vol-55, No.8 (August 1990), 998-1014.
 26. Yanbin Gao et al., "Effect of wave attenuation on shear wave velocity determination using Bender Element Test", *Sensors* 2022, 1263. <http://doi.org/10.3390/s22031263>
 27. Zhifei Shi, Yage Wen and Qingjuan Meng, "Propagation Attenuation of Plane waves in Saturated Soil by Pile Barriers", *International Journal of Geomechanics*, ASCE, ISSN 1532-3641.
 28. Salehzadeh Hossin, "Vibration screening by trench barrier, a review", *Arabian Journal of Geoscience*, November 2017, <http://doi.org/10.1007/s12517-017-3279-3>.
 29. Murad Abu-Farsakh, Sanjay Dhakal et al, "Laboratory characterization of cementitiously treated/stabilized very weak sub-grade soil under cyclic loading" *Soils and Foundations Japanese Geotechnical Society*, 2015:55(3): 504-516.
 30. Morteza Sadeghi, Ebrahim Babaeian, Markus Tuller, Scott B. Jones. "Particle size effects on soil reflectance explained by an analytical radiative transfer model", *Remote Sensing of Environment*, 2018



31. Athanasopoulos George et al., 2000, Effect of soil stiffness in the attenuation of Rayleigh wave motions from field measurement, *Soil Dynamics and Earthquake Engineering*, 19(2000) 277-288.
32. ASTM D6913: Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis
33. ASTM, 2018. Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens, ASTM International, West Conshohocken, PA.
34. Sawdust: Timber Industry Waste. *Dyes Pigments* 63 (3), 243-250.
35. Horisawa, S.M. Sunagawa, Y., Tamai, Y. Matsuoka, T. Miura, M., Terazawa, C., (1999). Biodegradation of non-lignocellulosic substance II: Physical and Chemical properties of sawdust before and after use as artificial soil. *Journal of Wood Science* 45(6), 492-497
36. Ikenyiri, P.N., Ukpaka C.P., 2016. Overview on the effect of particle size on the performance of wood-based adsorbent. *Journal of Chemical Engineering and Process Technology* 7(5), 7-14.
37. Wang, J., Zhong, Z., Ding, K., Li, M., Hao, N., Meng, X., Ruan, R., Ragauskas, A.J., 2019. Catalytic fast co-pyrolysis of bamboo sawdust and waste Tyre using a tandem reactor with cascade bubbling fluidized bed and fixed bed system. *Energy Conversion and Management* 180, 60-71.
38. Naik S. P., Patra N. R. and Malik N., "Cyclic behaviour of late quaternary alluvial soil along Indo-Gangetic Plain: Northern India", *International Journal of Geo-Engineering*, (2022) 13.2 <http://doi.org/10.1186/s40703-031-00167-y>
39. Ashref Alzawi, M. Hesham EI Naggar (2011), Full scale experimental study on vibration scattering using open and in-filled (Geofoam) wave barriers, *Soil Dynamics & Earthquake Engineering*, 31, 306-317.
40. Arnab Sur, Dr. Bappaditya Manna and Shiva Shankar Choudhary (2019), "Prediction of Ground Vibration due to Railway Traffic in MRTS underground cut and cover tunnels", 7th ECCOMAS Thematic Conference on Computational Method in Structural Dynamics and Earthquake Engineering, Crete,



Greece, 34-26 June 2019.

41. Ashwani Jain, D. K. Soni (2007), "Foundation Vibration Isolation Method", 3rd WSEAS International conference on Applied and Theoretical mechanics, Spain, December 14-16, 2007.
42. Javier Aviles and Francisco J. Sanchez-Sesma (1988), Foundation Isolation from Vibration using Piles as Barriers, J. Eng. Mech., 1988, 1144(11), 1854-1870.
43. Deniz Ulgen and Onur Toygar, Investigation on Vibration Isolation Performance of Open Trench Barriers under Impact Loading, ICESA (2014) International Civil Engineering & Architecture Symposium for Academicians 17-20 May 2014, Geotechnical Engineering section, pp. 73-80
44. G. L. Sivakumar Babu, Amit Srivastava, K. S. Nanjunda Rao and S. Venkatesha, 2011, Analysis and Design of Vibration Isolation System Using Open Trenches, International Journal of Geo-mechanics, ASCE, September 2011, 11(5), 364-369.
45. Ankurjyoti Saikia, 2016, Numerical investigation on vibration isolation by softer in-filled trench barriers, Journal of Geo-Engineering Sciences 3 (2015/2016) pp. 31–42, DOI 10.3233/JGS-150034.
46. Barkan. D. D., 1962, Dynamics of Bases and Foundations, MacGraw-Hill Book Company Inc., 374-406.
47. Seyhan Firat, et. al., 2010, Field Experiments on Wave propagation and vibration isolation by using wave barriers, Propagation in Materials for modern Applications, INTECH, pp-526.
48. R. Massarsch, Man-Made Vibrations and Solutions, 3rd International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, 1993, SOA 9 Geo Engineering, Royal Institute of Technology, Stockholm, Sweden.
49. Shahidani S., Mangi Sjjad Ali, Senin M. S., Salwa S. M. Z., Ibrahim M. H. W., 2019, Characterization of Tyre Rubber Ash and Crumb as fine aggregate resource, Journal of Engineering Science and Technology Vol. 16, No. 1 (2021) 510 - 526.
50. Ikenyiri, P.N., Ukpaka C.P., 2016. Overview on the effect of particle size on the performance of wood-



based adsorbent, *Journal of Chemical Engineering & Process Technology* 7(5), 7-14.

51. Sawdust: Timber Industry Waste. *Dyes Pigments* 63 (3), 243-250.
52. Horisawa, S.M. Sunagawa, Y., Tamai, Y. Matsuoka, T. Miura, M., Terazawa, C., (1999). Biodegradation of non-lignocellulosic substance II: Physical and Chemical properties of sawdust before and after use as artificial soil. *Journal of Wood Science* 45(6), 492-497.
53. Bhushan K. B., Sahu A. K., Goel R., “Geotechnical Characterization of in-filled materials used in Trench Wave Barriers for Vibration Screening” *International Journal for Innovative Engineering and Management Research*, Volume 12, Issue 04, April 2023, pp 343-353.
54. R.D. Woods., Screening of surface waves in soils. *J. Soil Mech. Found. Eng. Div. ASCE* 1968; 94 (4):951–979.
55. W. A. Haupt. Model tests on screening of surface waves. In: *Proceedings of the 10th International Conference on Soil Mech. Found. Eng.*, Stockholm, 1981, vol. 3, 215– 222.
56. S. Ahmad, T.M. Al-Hussaini. Simplified design for vibration screening by open and in-filled trenches. *Journal of Geotechnical Engineering* 1991; 117 (1):67-88.
57. Baker, J.M. 1994, “An Experimental Study on Vibration Screening by in-filled trench barriers, M.Sc. Thesis, State University of New York at Buffalo, USA.
58. Beskos DE, Dasgupta B, Vardoulakis IG. Vibration isolation using open or filled trenches: Part 1:2-D homogeneous soil. *Comput Mech.* 1986; 1(1):43-63.
59. S. Ahmad, T. M. Al-Hussaini, 1991. “An Experimental Study on Vibration Screening by in-filled trench barriers, *Journal of Geotechnical Engineering*, Vol. 117 No. 1, January 1991, Paper no 25416.
60. Haupt, W.A., 1995, “Wave Propagation in the ground and Isolation Measures”, 3rd International conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2-7, 1995, volume II, St. Louis, Paper No-SOA11.



61. Miller G. F. , Pursey H. and Crisp Bullard Edward, 1955, On the partition of energy between elastic waves in a semi-infinite solid, Published: 06 December 1955 <https://doi.org/10.1098/rspa.1955.0245>
62. Woods RD. Screening of surface waves in soils. J Soil Mech Found Div. 1968; 94(SM 4):951-7
63. Bhushan K. S., Sahu A. K., Goel R., titled “Experimental study for Evaluating Performance of In-filled Materials (Crumbed tyre rubber, Rice Husk, and Saw dust) in Trench Wave Barriers for Vibration Screening”, accepted for publication in Indian Journal of Engineering and Material Sciences (IJEMS).
64. Beskos DE, Dasgupta B, Vardoulakis IG. Vibration isolation using open or filled trenches: Part 1:2-D homogeneous soil. Comput Mech. 1986;1(1):43-63.
65. Dasgupta B., Beskos DE, Vardoulakis IG. Vibration isolation using open or filled trenches: Part 2:3-D homogeneous soil. Comput Mech. 1990; 6(2):129-42.
66. Leung KL, Beskos DE, Vardoulakis IG. Vibration isolation by trenches in continuously non-homogeneous soil by the BEM. Soil Dynamics & Earthquake Engineering, 1991; 10(3):172-9.
67. Ashref Alzawi, M. Hesham EI Naggar (2011), Numerical Investigations on vibration screening by in-filled geofom barriers, 14th Pan-American Conference on Soil Mechanics and Geotechnical Engineering 64th Canadian Geotechnical Conference, October 2-6, 2011, Toronto, Ontario, Canada
68. Giuliano Belinassi et. Al. (2019), Vibration soil Isolation analysis based on a 3-D frequency domain Direct Boundary Element implementation: GPGPU acceleration, 23rd March 2019
69. Javier Aviles and Francisco J. Sanchez-Sesma (1988), Foundation Isolation from Vibration using Piles as Barriers, J. Eng. Mech., 1988, 1144(11), 1854-1870
70. Baker, J.M. 1994, An Experimental Study on Vibration Screening by in-filled trench barriers, M.Sc. Thesis, State University of New York at Buffalo, USA
71. G. L. Sivakumar Babu, Amit Srivastava, K. S. Nanjunda Rao and S. Venkatesha, 2011, Analysis and Design of Vibration Isolation System Using Open Trenches, International Journal of Geo-mechanics,



ASCE, September 2011, 11(5), 364-369

72. S. E. Kattis et. Al., 1999, Vibration Isolation by a row of Piles using 3D Frequency Domain BEM, International Journal for Numerical Methods in Engineering, 46, pp. 713-728
73. George Gazetas, 1982, Vibrational Characteristics of soil deposits with variable wave velocity, International Journal for Numerical and Analytical Methods in Geo-mechanics, Vol. 6, pp. 1-20
74. Ankurjyoti Saikia, 2016, Numerical investigation on vibration isolation by softer in-filled trench barriers, Journal of Geo-Engineering Sciences 3 (2015/2016) pp. 31–42, DOI 10.3233/JGS-150034
75. Tulika Bose et. Al, 2018, Efficiency of Open and Infill Trenches in Mitigating Ground-Borne Vibrations, J. Geotech. Geo-environmental Engineering. 2018, 144(8): 04018048
76. C. Comina and S. Foti, 2007, Surface Wave tests for Vibration Mitigation Studies, Journal of Geotechnical and Geoenvironmental Engineering, 133 (10), pp. 1320-1324
77. Wang JG, Sun W, Anand S. Numerical investigation on active isolation of ground shock by soft porous layers. J. Sound Vib. 2009; 321(3-5):492-509
78. Yang Y, Hung H., A parametric study of wave barriers for reduction of train-induced vibrations. Int J Number Meth Eng. 1997; 40(20): 3729-47
79. Adam M, Estorff O. Reduction of train-induced building vibrations by using open and filled trenches. Comput Structure. 2005;83(1):11-24
80. El Naggar MH, Chehab AG., Vibration barriers for shock-producing equipment. Can Geotech J. 2005; 42(1):297-306
81. Celebi E, Firat S, Beyhan G, Cankaya I, Vural I, Kirtel O., Field experiments on wave propagation and vibration isolation by using wave barriers. Soil Dynamics and Earthquake Engg. 2009; 29(5):824-33
82. Al-Hussaini TM, Ahmad S. Active isolation of machine foundations by in-filled trench barriers. J Geotech Eng. 1996; 122(4):288-94.



83. Alzawi A, El Naggar MH. Full scale experimental study on vibration scattering using open and in-filled (geofoam) wave barriers, *Soil Dynamic Earthquake Engineering*. 2011; 31(3):306-17
 84. Andersen L, Jones CJC, Coupled boundary and finite element analysis of vibration from railway tunnels- A comparison of two and three-dimensional models. *J Sound Vibration*, 2006; 293(3-5): 611-25
 85. Lysmer J, Kuhlemeyer RL., Finite dynamic model for infinite media, *J Eng Mech Div*. 1969;95(EM 4): 859-77
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APENDIX-I: SPECIFICATION FOR GEOPHONE



	HGS (INDIA) LIMITED	
<u>HG-24 Geophone Element</u>  Based on the technology transfer for manufacturing the SM® range of geophones from Sensor® Nederland BV, HGS (India) Limited (erstwhile Geosource India Limited) offers the HG-24 geophone which is a broad bandwidth, low distortion geophone with a unique spring design and an extended frequency response in excess of 240 Hz. It offers all the advantages of low distortion and tight specifications. Applications: 2D and 3D seismic exploration with bandwidth from 10 Hz to 240 Hz. It can be installed in a variety of geophone cases. Features: • Low distortion geophone • Extended spurious frequency over 240 Hz, allowing full bandwidth at 2 ms sampling • Horizontal version available • Rugged design with rotating-coil contacts		



Specifications - HG-24

Frequency	Value
Natural frequency	10 Hz
Tolerance	±2.5%
Maximum tilt angle for specified F_n	15°
Typical spurious frequency	>240Hz

Distortion

Distortion with 17.78 mm/s p.p. coil-to-case velocity	≤0.1%
Distortion measurement frequency	12 Hz
Maximum tilt angle for distortion specification	15°
Typical distortion (string of 12 in series, measured at 12 Hz)	≤0.03%

Damping

Open circuit (typical)	0.25
Damping calibration-shunt resistance	1339 Ω
Damping with calibration shunt	0.6
Shunt for 0.69 damping	1000 Ω
Tolerance with calibration shunt	+5%,-0%

Sensitivity

Sensitivity	28.8 V/m/s
Tolerance	± 2.5%
$R_t B_c f_n$	6,000 Ω Hz
Moving mass	11 g
Max coil excursion p.p.	2 mm

Coil Resistance

Standard	375 Ω
Tolerance	± 2.5%

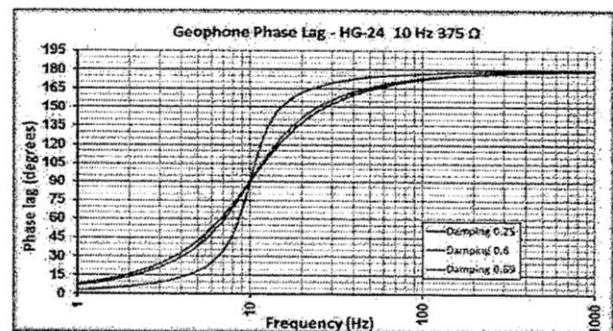
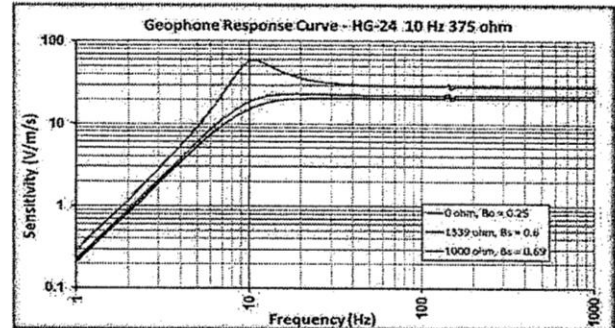
Physical Characteristics

Diameter	25.4 mm
Height	32 mm
Weight	74 g
Operating temperature range	-40°C to 100°C

Warranty Period*	3 Years
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*Warranty excludes damage caused by high voltage and physical damage to the element case.

All parameters are specified at +20°C in the vertical position unless stated otherwise.



Ordering information

Description	Part No.	Direction
HG-24 U 10 Hz 375 Ohm	SG000087	Upright
HG-24 H 10 Hz 375 Ohm	SG000097	Horizontal

India
HGS (India) Ltd
Tel : +91-11-46066604
Fax : +91-11-24333772
Website : www.hgsindia.com

The Netherlands
HGS Products B.V.
Tel : +31 708200820
Fax : +31 708200828
Website : www.hgsproducts.nl

Version 1.3



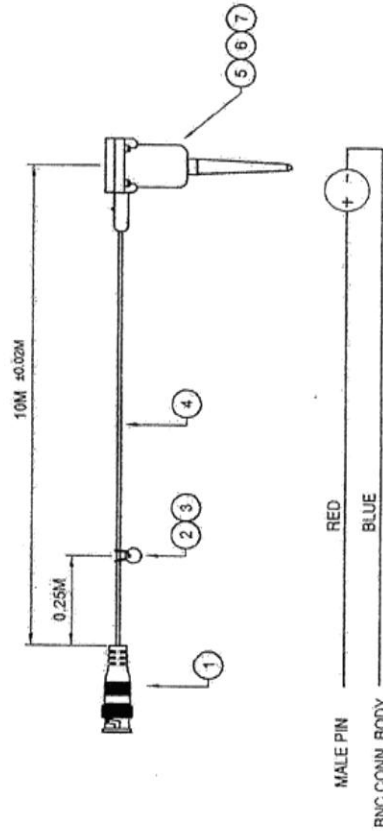
Specifications - HG-7			
Frequency	Value	Value	Value
Natural frequency	20 Hz	30 Hz	50 Hz
Tolerance	±5%	±5%	±5%
Maximum tilt angle for specified Fn	25°	360°	360°
Typical spurious frequency	450 Hz	500 Hz	570 Hz
Distortion			
Distortion with 17.78 mm/s p.p. coil-to-case velocity	<0.2%	<0.2%	<0.2%
Distortion measurement frequency	20 Hz	30 Hz	50 Hz
Maximum tilt angle for distortion specification	20°	360°	360°
Damping			
Open circuit damping	0.68	0.65	0.70
Open circuit damping Tolerance	±5%	±5%	±5%
Resistance			
Standard coil resistance	375 Ω	370 Ω	370 Ω
Tolerance	±5%	±5%	±5%
Sensitivity			
Open - circuit Sensitivity	16.5V/m/s	12.8V/m/s	17.2V/m/s
Tolerance	±5%	±5%	±5%
$R_t B_c f_n$	2777 ΩHz	1740 ΩHz	3060 ΩHz
Moving mass	7.8 g	7.5 g	7.7 g
Maximum coil excursion p.p.	2 mm	2 mm	2 mm
Physical Characteristics			
Diameter	25.4 mm	25.4 mm	26.8 mm
Height	32 mm	32 mm	32 mm
Weight	74 g	74 g	83 g
Operating temperature range	-40°C to 100°C	-40°C to 100°C	-40°C to 100°C
Warranty Period *	2 years	2 years	1 year
*Warranty excludes damage caused by high voltage and physical damage to the element case.			
All parameters are specified at +20°C in the working position unless stated otherwise.			



ID TAG INFO.:	
SIDE 1	PART NO.
SIDE 2	S. NO.
	MONTH/YEAR

REV	DESCRIPTION	APD	DATE

HG-24 U 10 Hz 375 OHM GEOPHONE 1Sx1P STRING SPECIFICATIONS (THEORETICAL VALUE)							
NATURAL FREQUENCY	DAMPING	SENSITIVITY (V/M/S)	STRING RESISTANCE	HARMONIC DISTORTION	TYPICAL CASE TO COIL MOTION	MOVING MASS	TESTING TEMP.
10 Hz. $\pm 2.5\%$	0.25 $\pm 5\%$, -0%	28.8 $\pm 2.5\%$	375 $\Omega \pm 2.5\%$	$\leq 0.1\%$	2mm (p-p)	11 g	-40°C TO +100°C
							+20°C



WIRING

S. NO.	DESCRIPTION	PART NO.	QTY.
7	STEEL SPIKE, 75MM	MK000058	01No.
6	HG-24 U 10 Hz 375 OHM	SG000087	01No.
5	HL-3 LAND CASE ASSY.	AG000014	01No.
4	2 CORE, TCCS, 19x0.16, UF, 5.33MM BLACK CABLE	AC000178	10M
3	ALUMINIUM ID TAG	MK000180	01No.
2	STEEL PICK UP LOOP	MK000491	01No.
1	BNC MALE CONNECTOR, GOLD PLATED	CE001074	01No.
TITLE			
HGS			
HGS (INDIA) LIMITED			
158, SECTOR-4, IMT MANESAR, GURUGRAM-122 050			
REF.			
LAND STRING 1Sx1P, HG-24 U 10 Hz, BNC MALE CONN., 2 CORE, UF, 5.33MM CABLE, 10M			
DATE	20.9.22	APD	
CHD	REW	APD	
SHEET	1 OF 1	DRG. NO.	GP-006036

THIS DRG IS THE SOLE PROPERTY OF HGS (INDIA) LIMITED
UNAUTHORISED USE OF THIS DRG. OR MAKING PRODUCT AS PER
OUR DRG WITHOUT OUR PERMISSION OR ANY MISUSE IS NOT PERMITTED



ANNEXURE-IV



DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi-42

PLAGIARISM VERIFICATION

Title of the Thesis: **Performance of In-filled Materials used as Wave Barrier for Vibration Isolation**

Total Pages: 211

Name of the Research Scholar: **Kumar Shashi Bhushan (2K19/PHD/CE/07)**

Supervisor (s):

- (1) Prof. Anil Kumar Sahu, Professor, DTU, New Delhi (Supervisor)
- (2) Dr. Rajeev Goel, Chief Scientist, CSIR-CRRI, New Delhi (Joint Supervisor)

Department: Civil Engineering

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Paper ID: **IR-MCCE-DELH-290423-1060**



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International Conference on
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of
PRESENTATION

Presented to
Kumar Shashi Bhushan

for presenting a paper entitled “Elastic Surface Wave Propagation in Ground and Effectiveness of Trench Wave Barriers for Diminution of Vibrations: A Review” at the International Conference on Advances in Mechanical, Civil, and Construction Engineering (ICAMCCE) held in New Delhi, India on 29th April, 2023.



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Institute of Research and Journals

ELASTIC SURFACE WAVE PROPAGATION IN GROUND AND EFFECTIVENESS OF TRENCH WAVE BARRIERS FOR DIMINUTION OF VIBRATIONS: A REVIEW

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Abstract - This State of the Art Paper consists of three parts. The first part of this report includes study of Elastic ground wave propagation. It includes study of nature of ground wave radiating from the source, various properties of soil (including dynamic properties) and influence of these properties during wave propagation. The second part covers wave barriers types used in the research work. It deals with results after investigations such as Theoretical and Experimental study carried out in past researches. The end part of the report focuses on recent advances in Vibration Isolation measures. The general purpose of the review is to formalize the screening effect of trench wave barriers and the specific purpose of the review is assign the screened region and reduction in amplitude within this region for different trench layouts to give a threshold trench size.

Notations:

ρ	Mass density of elastic half space
ν	Poisson's ratio
f	Frequency of elastic wave
L_R	Rayleigh wavelength
A_r	Amplification reduction factor
W_d	Normalized depth of trench
W_w	Normalized width of trench
V_p	Velocity of Primary waves
V_s	Velocity of Shear waves
V_R	Velocity of Rayleigh waves

Keywords - Wave propagation, Vibration Isolation, Active isolation, Passive isolation, Rayleigh wave, Normalized depth, Normalized width, Trench Barrier and Efficiency of Screening

1. INTRODUCTION

When there is sudden slip at the faults in the interior of earth, there is release of enormous energy and energy releases in the form of waves. Seismic wave arrives after some time, then after comes stronger waves of low amplitude and then the surface waves of high amplitudes. The surface waves cause the most devastating effects on earth and are responsible for most of the damages on surface of earth as shown in Figure-1.

Standards for design and analysis of foundations subjected to dynamic loads are now prominent and these standards represent an important stage in the state of art. But these standards are not capable for providing solution of each type of problem related to vibration. In a situation, a foundation may designed as per the norms of standards which may reduces the damages to the machinery it supports but this machine may cause vibration problem to the in an around facilities.

Taking another situation in which some zone is required to be free from even ambient vibration as in case of sensitive instruments in hospitals or research locality. Presently, these vibration problems are still under research and clear cut solutions are not

available for them. Further attempts to find out the solutions are still in progress and concerned theoretical and experimental works are going on.

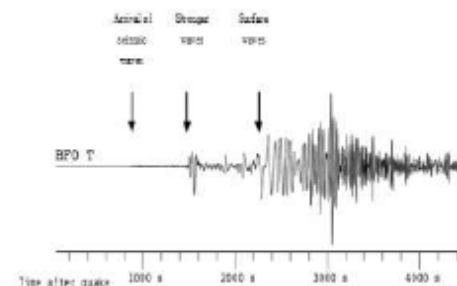


Figure-1: Seismogram recorded by Seismometer for a typical earthquake

(Source: Soil dynamics and-machine foundations by Swami Saran Fig 1.2 Page 3)

For efficient design of foundation isolation system, a logical approach on the basis of cognizance of surface waves in the area of obstruction must be known to the researchers and practitioners. The prime focus of the present review is to get a thorough understanding of mitigation of effect of surface waves by trench wave barriers on the basis of rational approach.



2. Status of Proceedings of 2nd Paper in International Conference: (Presented & Published)



Geotechnical Characterization of In-filled Materials used in Trench Wave Barriers for Vibration Screening

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ABSTRACT:

In-filled materials play a significant role in performance of trench wave barriers for vibration screening. Using waste materials in trench wave barriers as in-filled materials is an eco-friendly and sustainable step in services and application of geotechnical engineering techniques. But how these materials have suitable application in engineering domain, safety and stability, is an important concern. To know its application and comparison with other materials as in-filled materials in vibration isolation, it is required to ascertain its geotechnical properties. In the present paper, the geotechnical characterization of in-filled materials i.e. rice husk, saw dust and crumbed tyre rubber had been carried out. Several laboratory tests had been carried out such as particle size distribution, specific gravity, bulk density, relative density and permeability. Since trench wave barrier is exposed to dynamic loading, its dynamic properties in addition to these properties are also important. Several dynamic tests had also been conducted such as shear modulus, damping ratio, stiffness and shear strain to curtain down the suitability of these materials as in-filled materials which was used in trench wave barriers for vibration screening. Based on the experimental study for performance of in-filled materials in trench barriers, the results indicate that the materials possessed good characteristics of in-filled materials in trench barrier for vibration isolation.

Keywords: Geotechnical characterization, Crumbed tyre rubber, Rice husk, Saw dust, Damping ratio, Shear wave velocity, Shear modulus, In-filled materials, Trench barrier, Vibration screening

Notations:

a_0	Attenuation coefficient
G	Specific gravity
ρ_s	Density of soil
ρ_b	Density of in-filled material in barrier
V_s	Shear-wave velocity
A_r	Amplitude Reduction Ratio
C_u	Uniformity coefficient
C_c	Coefficient of gradation
γ_d	Bulk density (dry)
I_d	Relative Density
$\gamma_{d(max)}$	Dry density (maximum)
$\gamma_{d(min)}$	Dry density (minimum)

1. INTRODUCTION:

The in-filled materials to be used in trench barriers for vibration isolation play a significant role in efficiency of screening. Type of in-filled materials used will finally decide the performance or efficiency of the trench wave barriers with respect to screening. In civil engineering applications, the in-filled materials should have possessed much of desired engineering properties so that suitability of materials for filling in trench wave barriers can be defined. In the experimental study carried out for investigating performance of in-filled materials in vibration screening, the materials used had shown characteristics such that the performance criteria could be ascertained by adhering in the range of the values of these properties. The in-filled materials used in the experimental study in trench

3. Status of Proceedings of 1st Paper in SCI (Expanded) Journal: (Published)



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Numerical investigation for performance evaluation of In-filled materials in vibration screening

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Surface vibrations caused by human activities such as industrial activities, high-speed traffic (e.g. on highways and railways), Piling and blasting during construction and demolition works, usually reach limits where they have become problematic for people and buildings. Very often, it even reaches dangerous limits where they are no longer safe for human life. So many solutions have devised to mitigate effects of vibration and one of them is vibration screening by construction of trench wave barriers. This paper has focused on evaluating screening efficiency of in-filled materials and impact of different parameters of trench wave barriers on efficiency. This paper has presented a numerical study and subsequent validation, 3D finite element study of vibration screening in PLAXIS-3D against stationary surface vibrations using a trench wave barrier filled with an elastic, isotropic, homogeneous half-space. Key parameters have determined studied thereof. The results of numerical and experimental study have found in close agreement.

Keywords: Active Isolation, Amplitude reduction ratio, Efficiency of screening, In-filled materials, Normalized dimensions, Oscillator, Passive Isolation, Raleigh waves, Shear wave velocity, Trench wave barrier and Vibration screening

1 Introduction

Apart from the effects of earthquakes, high-speed traffic, construction and demolition works, vibrating machinery, blasting, underground explosions, etc. are also sources of ground vibration. Excessive ground vibration must be properly blocked or reduced, otherwise, it may cause inconvenience to residents, fatigue to structural and non-structural components of the structures and failure of high-precision equipment. To reduce the effects of vibration, vibration screening measures are an important development in vibration isolation. This measure consists in installing a trench wave barrier with filled materials in the propagation of surface wave from the source to the structure affected. The effect is that the amplitude of the incident wave traveling along the path is greatly reduced. Commonly used types of barriers to mitigate wave amplitudes include open trench barriers, filled trench barriers, gas cushion, solid, hollow, or sheet pile walls. There are two types of isolation, depending on location w.r.t. source of vibration and structure they are protecting. If trench barrier is located near to vibration source, it is called active isolation and if placed close to structure being protected, is called

passive isolation. Energy generated by the surface source is dispersed, creating a combined waveform consisting of all three wave types: Primary waves, Secondary waves, and Rayleigh waves. Miller and Percy¹ generated vibrations by vertical vibration and determined the energy components of these waves in an elastic half-space. Rayleigh waves carry two-thirds (about 67%) of total energy of waves and travel in a half-space near earth's surface. For this reason, vibration screening measures focus on reducing the amplitude of Rayleigh waves. Among surface waves, Rayleigh waves have the property of having the largest amplitude compared to all other waves. This makes them the most destructive of all waves. In addition, Rayleigh waves decay more slowly than all other waves with distance from the vibration source. Here, we present as far as possible the contributions of researchers to the development of vibration isolation technology. According to Woods², the amplitude reduction was measured in rectangular trench of different depths and lengths. Experimental study to evaluate the performance of in-filled materials have already been carried out. Also, parametric study to determine effect of properties of in-filled materials and the screening efficiency in terms of dimension of trench wave barrier has also

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4. Status of Proceedings of 2nd Paper in SCI (Expanded) Journal: (Published)



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Experimental study for performance evaluation of in-filled materials in trench wave barriers for vibration screening

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Vibrations which have been caused by non-seismic factors as high-speed rails, highway traffic, construction activities, machine foundations, blasting, underground explosions, etc. have not been considered safe for human life and structures around. Vibrations which have been generated by these sources have caused of occupant discomfort, settlement and shaking of building foundations, structural and non-structural damages to adjacent buildings, malfunctioning of ultra-sensitive medical equipment, etc. Vibration screeners in form of open or in-filled trench wave barriers have been used to reduce the effects of vibrations. This paper has described an experimental study for evaluating the performance of in-filled materials in trench wave barriers in an elastic, homogeneous and isotropic half space. The in-filled materials used are rice husk, crumbed tyre rubber and sawdust. Key properties of the in-filled materials are have also been determined by geo-technical characterization to ascertain its suitability in terms of properties of in-filled materials. The important factors such as material damping and boundary conditions of soil have also been included. The effectiveness of geometric dimensions of the trench wave barrier, shear wave velocity and location of source from the barrier have also been investigated. In this study, a dimensionless approach have been used, where the geometrical parameters have been normalized by one of the characteristics i.e. wavelength of Rayleigh oscillatory wave in elastic half-space. The influence of parameters related to vibration isolation has been discussed in detail. Recommendations have been provided for the optimal selection of the geometry of trench wave barriers.

Keywords : Active Isolation, Amplitude reduction ratio, Efficiency of screening, In-filled materials, Normalized dimensions, Oscillator, Passive Isolation, Rayleigh waves, Shear wave velocity, Trench wave barrier, Vibration screening

1 Introduction

Reducing the amplitude of wave propagation is a solution to mitigate the vibrational effects caused by non-seismic factors as rail, high speed traffic on highways, construction activities, machine operation, blasting, underground explosions, etc. The present research study comprises of amplitude as the significant characteristics feature in study wave propagation. The reduction of amplitude of wave propagation can be achieved by one of the following:

(a) Changing frequency of waves caused by source of excitation, (b) Shifting of vibratory component and changing orientation, (c) Increasing the dissipation of wave energy in soil, or (d) Obstructing wave propagation path moving towards structure to certain extent

The local subsurface dynamic propagation behavior can also be changed through wave scattering

and reflection and change of mode of vibration in the proximity of source of vibration. This can be achieved by constructing anti vibration trench wave barriers in the wave's path propagating from source of vibration to affected structure. These wave barriers can be placed near the source of vibration is called active isolation (isolation near source) and if the barriers are placed near the structure or around the structure intended to protect from the propagating waves, this isolation is termed as passive isolation (isolation away source). Thus, either active or passive isolation can be used to shield vibrations.

Ashref Alzawi and M. Hesahm E.I. Naggar¹ investigated vibration scattering through a study at test site for determining the trench wave barrier's performance in terms of % age screening efficiency. Open trench barriers, trench filled with geofoam were used to provide some insight and framework of guidelines to implement in design. Experimental studies were conducted for a selected number and type of trenches. The experimental survey included

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Profile of Research Scholar

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2. ROLL NO : 2K19/PHD/CE/07
3. DATE OF BIRTH : 04/07/1978
4. COURSE : Ph.D. (Part Time)
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6. EMPLOYED WITH : CSIR-Central Road Research Institute (C.R.R.I.), New Delhi
7. EMPLOYED SINCE : 1st July 1998
7. POST HELD : Senior Technical Officer (Gr-3)



(B).ACADEMIC DATA:

S. No.	Degree/ Diploma	Class/Grade	University/Institute	Year of Passing
1.	Diploma in Civil Engineering	1 st Division with Distinction 78.50%	Pusa Polytechnic, New Delhi	June'1998
2.	Bachelor of Engineering (Civil Engineering)	Marks obtained 71.90%	Institution of Engineers (India), Kolkata	May'2015
2.	Master of Engineering	Marks obtained 75.00%	Delhi Technological University (Formerly Delhi College of Engineering), New Delhi	July'2017
2.	Doctor of Philosophy (Ph.D.)	Thesis submitted	Delhi Technological University (Formerly Delhi College of Engineering), New Delhi	August'2019 (Enrolled)



(C) PROFESSIONAL DATA:

S. No.	Name of Organization	Period		Designation Held
		From	To	
1.	CSIR-Central Road Research Institute, New Delhi	July 2023	Till date	Senior Technical Officer Gr-3
2.	CSIR-Central Road Research Institute, New Delhi	July 2018	July 2023	Senior Technical Officer Gr-2
3.	CSIR-Central Road Research Institute, New Delhi	July 2015	July 2018	Senior Technical Officer Gr-1
4.	CSIR-Central Road Research Institute, New Delhi	August 2010	July 2015	Technical Officer
5.	CSIR-Central Road Research Institute, New Delhi	July 2002	August 2010	Junior Technical Assistant
6.	Larsen & Toubro Limited, New Delhi	July 1999	July 2002	Junior Engineer
7.	Larsen & Toubro Limited, Mumbai	June 1998	June 1999	Diploma Engineer Trainee

(D) ACTIVITIES IN JOB PROFILE:

- Condition Assessment of the Bridges including Detailed Visual Inspection, Non-Destructive Tests such as Rebound Hammer Test, Ultra Sonic Pulse Velocity Test, Cover measurement, Extraction of Cores for assessing compressive strength of concrete, Preparation of Report suggesting remedial measures for improving the condition of bridges.
- Structural Safety Audit of Bridges, Flyovers, Culverts, Vehicular underpass, etc.



- Executed In-house project titled “Study of Shielding of structures against the vibration due to non-seismic factors and screening/Isolation of the ground waves by trench barriers”
- As a member in the project team for “Creation of Expansion Joint Test Facility as a National Test Facility at CRRI”
- Quality Assurance and Quality Control of Bridges during construction
- Study of Corrosion Susceptibility of Steel reinforcement protected with anti-corrosive coating, special treatment in ordinary and high-performance concrete
- Evaluation of Steel truss bridge (through) and Plate Girder bridge for increased Axle load of Freight Wagons
- Performance monitoring of bridges through instrumentation
- Development of Data Base Management System on Performance Monitoring of Instrumented bridge
- Load Testing of Bridge Span for assessment of load carrying capacity of the structure

(E) TECHNICAL PAPER PUBLICATIONS:

1. Paper on “An Experimental Study to Estimate Loss of Pre-stress and Determining Fundamental Natural Frequency” Published in New Building Materials & Construction World (NBMCW), September 2017 by Bhushan K. S., Goel R. and Kumar Awadhesh
2. International Conference Paper by Bhushan K. S., Sahu A. K., Goel R., titled “Geotechnical Characterization of in-filled materials used in Trench Wave Barriers for Vibration Screening” published in International Journal for Innovative Engineering and Management Research, Volume 12, Issue 04, April 2023, pp 343-353
3. International Conference Paper by Bhushan K. S., Sahu A. K., Goel R., titled “Elastic Surface Wave Propagation in Ground and Efficiency of In-filled Trench Wave Barriers in Mitigating Vibrations: A Review”, published in International Journal in Science, Engineering and Technology, Vol-11, Issue 2, April 2023, pp 60-70.



4. SCI (E) paper by Bhushan Kumar Shashi., Sahu Anil Kumar., Goel Rajeev., titled “Numerical Investigation for Performance evaluation of In-filled Materials in Vibration Screening”, Indian Journal of Engineering and Material Sciences (IJEMS), Vol. 32, October 2025, pp. 607-624 DOI: 10.56042/ijems.v32i05.19314
5. SCI (E) paper by Bhushan Kumar Shashi., Sahu Anil Kumar., Goel Rajeev., titled “Experimental study for Evaluating Performance of In-filled Materials (Crumbed tyre rubber, Rice Husk, and Saw dust) in Trench Wave Barriers for Vibration Screening”, accepted for publication in Indian Journal of Engineering and Material Sciences (IJEMS), Vol. 32, December 2025, pp. 694-711 DOI: 10.56042/ijems.v32i06.19843
