BENEFICIAL USE OF RECYCLED SCRAP TIRE SHREDS TO ISOLATE GROUND-BORNE VIBRATIONS

By

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Written under the direction of Professor Ali Maher

And approved by

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ABSTRACT OF THE DISSERTATION

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Ground-borne vibrations from construction activities, high-speed trains, and machine foundations can adversely affect the operation of sensitive equipment and damage structures. A wave barrier installed near the vibration source or in the area requiring protection can attenuate the vibrations by reflecting or scattering the wave energy. Wave barriers, including piles, sheet piles, and open or in-filled concrete, bentonite slurry or geofoam trench barriers, have been studied comprehensively, with various degrees of success reported. For this dissertation, the beneficial use of tire shreds as an isolation medium in trench barriers was investigated, and design guidelines were developed.

The performance of in-filled tire-shred trench barriers was comprehensively studied through numerical and experimental investigations. Two- and three-dimensional finite element models were developed using the ABAQUS package. The numerical models were validated, either through reference models or field measurements. The models were initially used to study the influence of geometrical parameters on the effectiveness of in-
filled trench barriers for screening active (near-field) vibrations and for the design of a full-scale experimental program.

Based on the findings of the numerical investigation, a full-scale experimental study was designed and implemented to study the performance of in-filled tire-shred trench barriers. Because of the size of the tire shreds used in this study (50mm and 200mm), a full-scale study was warranted. Conventional construction equipment was used for the trench installation and placement of the tire shreds. A series of tests was conducted for open and in-filled trench barriers (with circular, semi-circular and linear configurations) to assess the performance of tire shreds relative to air, which is the most effective isolator, for full and partial isolation. The experimental study confirmed that the screening effectiveness of in-filled trench barriers is comparable to that of open trench barriers.

A parametric study was conducted to investigate the influence of key dynamic soil properties on the performance of in-filled trench barriers. For partial isolation cases, the limits of the effectively screened area behind a semi-circular and linear trench barrier were accurately delineated. Guidelines for the design of in-filled trench barriers were then developed.
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I would also like to thank Mr. Jack Whitman Sr., President of Edgeboro International Inc. for providing access to the test site and for installation of the trench barriers to perform the experimental study.

And lastly, I would like to express my gratitude to my parents and to my wife whose support and encouragement throughout this work was invaluable. I’m indebted to them forever.
DEDICATION

To my parents

To my wife, Jilla

To my daughter, Lillian
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CHAPTER ONE

RESEARCH PROBLEM DEFINITION AND SCOPE

1.1 Research Problem Definition

Ground-borne vibrations from construction activities, high speed trains, and machine foundations can affect sensitive equipment, damage structures, and disturb people in residential areas. If properly designed, wave barriers to reflect or scatter wave energy are simple and effective solutions for isolating vibrations. Wave barriers include piles, sheet piles, and open or backfilled trenches. The performance of the wave barrier is influenced by its composition, geometry, and location. While piles or sheet piles are not as effective as trench barriers for isolating low frequency vibrations, they may be the only practical solution where very deep trench barriers are required.

Trench barriers can be either open or backfilled. Although open trenches are the most effective isolators (air is the best isolator), maintaining an unsupported open trench permanently is not practical for stability and safety reasons. Therefore, they should be filled with a medium suitable to their applications. The feasibility of using bentonite slurry, concrete, and geofoam as isolation mediums for trench barriers has been comprehensively studied in the past. It should be noted, however, that the beneficial reuse of tire shreds as an isolation medium has not been well evaluated. As a result, an effort was made to narrow the information gap by conducting comprehensive research into the use of tire shreds as an isolation medium for trench barriers.
Scrap tires can no longer be used for their original purpose due to wear or damage. In 2013, the United States generated approximately 233 million scrap tires, according to Rubber Manufacturers Association (RMA), [RMA 2014]. Historically, scrap tires were landfilled or stockpiled, creating environmental and aesthetic problems, but recently-passed laws prohibit those practices. In 2013, industries reused 96 percent of the scrap tires entering the market, but 10 million scrap tires were still landfilled (RMA 2014). Currently, beneficial reuse of scrap tires includes fuel, stamped/punched products, electric arc furnaces, and civil engineering applications.

This dissertation evaluates a new application for the beneficial reuse of scrap tire shreds as a medium for infilling isolation trenches. If proven effective, utilizing scrap tire shreds in vibration isolation applications could potentially reduce the number of scrap tires landfilled annually and provide a cost-effective isolation medium. Vibration isolation measures currently in use, such as concrete or steel piles, sheet pile walls, and trench barriers filled with bentonite slurry or concrete, are all costlier than tire shreds for in-filled trench barriers.

To this end, the performance of tire shreds as an isolation medium was thoroughly investigated through comprehensive numerical and experimental investigations. Guidelines for the design of in-filled tire-shred trench barriers were also developed and issues of constructability were assessed during the full-scale experimental program.
1.2 Objectives and Scope of Work

1.2.1 Objective

This dissertation discusses the need to identify new beneficial reuse applications for scrap tires, in order to reduce the number of scrap tires landfilled annually. Following that is a discussion of vibration isolation measures currently in use, including piles, sheet piles, and open and in-filled trenches. Currently, a gap exists in the available research concerning the feasibility of using tire shreds for vibration isolation applications. To address this gap, research was conducted to numerically and experimentally investigate the feasibility of using scrap tire shreds for fill in trench barriers. In addition, the research was used to develop guidelines for the design of the most effective tire-shred trench barriers. The research specifically included the following objectives:

- Numerically evaluate the performance of in-filled tire-shred trench barriers of different geometries for screening ground-borne vibrations in active (near-field or at-source) isolation cases.
- Experimentally investigate the performance of open and in-filled tire-shred trench barriers for screening ground-borne vibrations in three dimensions. Various geometries (depth, width, and location), were investigated, as was angular length, circular (full isolation), linear or semi-circular (partial isolation). Different sizes of tire shreds were also investigated.
- Perform a comprehensive parametric study to examine the influence of the dynamic properties of soil and tire shreds on the effectiveness of the in-filled tire-shred trench barrier in providing vibration screening.
- Provide guidelines for the design of in-filled tire-shred trench barriers
1.2.2 Scope

The scope of work for achieving these objectives was as follows:

a) Numerical investigation, including the development of 2D and 3D finite element models using the ABAQUS package, to investigate the performance of open and in-filled tire-shred trench barriers. Geometrical parameters (depth, width, and location) were investigated, as was angular length, circular (full isolation), semi-circular and linear (partial isolation). The numerical investigation provided guidelines for the design of the experimental investigation and the scope of the parametric study. The Spectral Analysis of Surface Waves (SASW) method was used to measure the shear wave velocity in soil and tire shreds, providing a key dynamic material property for input into the numerical models.

b) Experimental investigation, including full-scale field testing of open and in-filled tire-shred trench barriers to examine in 3D the performance of the trench barriers in providing active screening of ground-borne vibrations. In-filled trench barriers with various angular lengths (circular, semi-circular and linear, providing full and partial isolation scenarios) were compared to open-trench barriers of the same geometry to evaluate the effectiveness of tire shreds as an isolating medium relative to air, which is the most effective isolator.

c) Parametric study to investigate the influence of key dynamic soil properties on the performance of in-filled tire-shred trench barriers. Parameters included bulk density, shear wave velocity, Poisson’s ratio, and material damping ratio. The influence of angular length on the screening effectiveness of the trench barrier was also comprehensively investigated, and correlations between the angular length and the limits of the effectively screened area behind the trench barrier were delineated.
d) Develop guidelines for designing the most effective in-filled trench barriers, based on geometry, native soil conditions, site constraints, and vibration frequency.

1.3 Outline of the Thesis

This thesis is prepared in accordance with the requirements and guidelines of the Graduate School of Engineering at Rutgers, The State University of New Jersey.

It includes seven chapters and presents comprehensive numerical and experimental investigations on the vibration screening achieved by in-filled tire-shred trench barriers; it also makes recommendations for design aspects of these barriers. The seven chapters of the thesis are organized as follows:

In chapter one, the problem of ground-borne vibration isolation is defined. In addition, the chapter describes the current status of recycling and disposal for scrap tires in the United States. Identifying the need for further beneficial use of these materials, the chapter outlines a creative solution in which scrap tires could be used as in-fill for trench barriers to provide vibration isolation. Finally, the chapter introduces the scope for achieving this objective.

Chapter two presents an overview of the various types of wave barriers currently used to screen ground-borne vibrations. First, general background information on the propagation of seismic waves within elastic half-space, and characteristics of seismic waves, is presented. This is followed by a discussion of the conventional methods for screening undesirable surface waves. The chapter also presents a literature review of previous works concerning the screening of ground-borne vibrations using trench barriers and piles. Finally, information related to the beneficial use of tire shreds for engineering applications
is presented, and the engineering properties of tire shreds as an isolation medium are discussed.

Chapter three presents the methodology for investigating the performance of in-filled tire-shred trench barriers for active (near-field) isolation of ground-borne vibrations. The investigation consisted of three parts, numerical and experimental programs and a parametric study, each of which is described in detail in the subsequent chapters.

Chapter four provides the results from a numerical investigation that examined the influence of geometrical parameters on the performance of in-filled trench barriers in screening vibrations. Two- and three-dimensional numerical finite element models were developed to study the influence of geometrical dimensions such as depth, width, location, and angular length.

The influence of angular length [circular (full isolation), semi-circular and linear (partial isolation)] was examined in 3D, but the 2D axisymmetric and plane strain models provided comparable results for analyzing the influence of geometrical dimensions. The numerical study provided guidelines for the design of the experimental study and highlighted the scenarios that required further investigation through the full-scale investigation and the parametric study.

Chapter five presents the results of an experimental study on the performance of in-filled trench barriers. The influence of geometrical parameters, such as depth, width and location, on the performance of the trench barriers was examined. This chapter also outlines the design of the experiments, the location and conditions of the test site, the material properties, and the instrumentation employed. Finally, chapter five presents and discusses the findings from the study.
The experimental program was designed to validate the findings of the numerical investigation and to study the scenarios that could be investigated only in full-scale, such as the effectiveness of different size tire shreds.

Open and in-filled trenches with three different geometries and angular length, i.e., circular, semi-circular and linear were employed to a) investigate the effectiveness of tire shreds as an isolation medium relative to air and b) investigate the influence of angular length on the screening effectiveness of trench barriers (full and partial isolation). To evaluate the influence of tire-shred size in trench performance, two different tire-shred sizes (50mm and 200mm) were tested. Vibration frequencies used during the field experiments were in the 20Hz to 160Hz range—the low side corresponding to train or traffic from heavy vehicles, and the high side corresponding to machine foundation vibration frequency.

In Chapter six, results are presented from a comprehensive parametric study evaluating the influence of geometrical parameters and material properties on the performance of in-filled trench barriers to provide active isolation of vibrations. The key geometrical parameters considered were trench depth, width, and location and full or partial isolation. The influence of key dynamic soil properties, such as shear wave velocity, bulk density, damping ratio and Poisson’s ratio were also investigated.

The 2D axisymmetric model was used to perform parametric studies related to trench geometrical dimensions and material dynamic properties. For partial isolation cases, the 3D model was utilized, although the 2D model was used to examine the influence of key dynamic properties of soil, such as shear wave velocity, bulk density, damping ratio and Poisson’s ratio. Finally, in chapter seven, general conclusions are presented regarding the effectiveness of in-filled tire-shred trench barriers for vibration screening, and design
guidelines are provided. In addition, recommendations are made for future research to complement this study.
CHAPTER TWO

LITERATURE REVIEW

This chapter provides an overview of ground-borne vibration screening using various types of wave barriers. First, the chapter introduces general background information on the characteristics of seismic waves and the propagation of seismic waves within elastic half-space. A discussion of the conventional methods for screening undesirable surface waves follows, since the structure’s foundation and sensitive equipment are typically placed near the Earth’s surface. Next, a literature review of the studies related to the use of in-filled trenches and piles to screen ground-borne vibrations is presented.

The chapter concludes with general information on the beneficial use of scrap tires and in particular their use in engineering applications. This includes a discussion of engineering properties of interest for tire shreds used as a vibration screening medium. Case studies are presented on the use of tire shreds in highway embankment construction, as bridge abutment backfill, and as a vibration isolation medium underneath light rail tracks.

2.1 Wave Propagation in Elastic Half-space

Earthquakes, machine foundations, pile-driving operations and heavy vehicle traffic can generate elastic waves, which travel through the half-space medium as either body waves or surface waves. The effects can range from simply being a nuisance to producing structural damage and impacting the operation of sensitive equipment. In the analysis of seismic wave propagation, the Earth is often assumed to be a homogeneous, isotropic
elastic half space.

Screening the surface waves is the primary concern when isolating vibrations, as these waves primarily affect the structures situated at or near the ground surface and carry almost two thirds of the wave’s energy.

The elastic half space theory describes the two types of elastic waves: body waves and surface waves. Characteristics of each are briefly described below.

2.1.1 Body Waves

Body waves generated by a surface footing consist of P waves and S waves, which travel through the Earth as shown in Figure 2.1.

![Distribution of Waves from a Circular Footing on a Homogeneous, Elastic Half Space (After Woods 1968)](image)

**Figure 2.1 - Distribution of Waves from a Circular Footing on a Homogeneous, Elastic Half Space (After Woods 1968)**

P-waves, also referred to as primary, longitudinal, or compressional waves are a type of
body wave that travels through the half space; in an earthquake, these are the first waves to arrive. This is due to the fact that geologic formations are stiffest in compression. P-wave propagation velocity can be expressed as:

\[ V_p = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\rho} = \sqrt{\frac{\lambda + 2G}{\rho}} \]

2.1

Where \(E\) is Young’s modulus, \(\nu\) is Poisson’s ratio, \(\rho\) is unit weight, \(G\) is shear modulus and \(\lambda\) is Lame’s constants defined as:

\[ G = \frac{E}{2(1+\nu)} \quad \lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \]

2.2

A P-wave is formed from alternating compressions and rarefactions or from primary waves, as shown in Figure 2.2. As it has the highest velocity, it is therefore the first wave to be recorded. In isotropic and homogeneous solids, the mode of propagation for a P-wave is always longitudinal; thus, the particles in the solid vibrate along the axis of propagation (the direction of motion) of the wave energy. Like sound waves, P-waves can travel through solids and fluids.

S-waves, secondary waves, or shear waves are another type of elastic body wave and can move through the body of a half-space like P-waves. The S-wave moves as a shear or transverse wave, so motion is perpendicular to the direction of wave propagation. These waves cause shearing deformation as they travel through a medium. S-waves are the second to arrive on an earthquake seismogram, after P-waves, because S-waves travel more slowly through rock. Shear wave velocity can be expressed as:

\[ V_s = \sqrt{\frac{G}{\rho}} \]

2.3

The relationship between P-waves and S-waves can be expressed in terms of Poisson’s
ratio:

\[ \frac{V_p}{V_s} = \sqrt{\frac{2(1 - \nu)}{1 - 2\nu}} \]

As transverse waves, S-waves exhibit properties, such as polarization, that are similar to other transverse waves. S-waves polarized in the horizontal plane are classified as SH-waves. If polarized in the vertical plane, they are classified as SV-waves. When an S-wave or a P-wave strikes an interface at an angle other than 90 degrees, a phenomenon known as mode conversion occurs. If the interface is between a solid and liquid, S becomes P or vice versa. Even if the interface is between two solid media, mode conversion occurs. If a P-wave strikes an interface, four propagation modes may result: reflected and transmitted P, and reflected and transmitted SV. Similarly, if an SV-wave strikes an interface, the same four modes occur in different proportions. Unlike P-waves, S-waves cannot travel through liquids, since liquids have no shearing stiffness.

![Diagram of particle motion during passage of P-waves and S-waves](image)

*Figure 2.2 - Particle Motion During Passage of P-waves and S-waves*
2.1.2 Surface Waves

Surface waves result from the interaction between body waves and surface layers of the Earth. The most important surface waves include Rayleigh waves and Love waves. Rayleigh waves are produced by the interaction of P-waves and SV-waves with the Earth's surface and are similar to waves produced by a rock thrown into a pool. Rayleigh waves include both longitudinal and transverse motions that decrease exponentially in amplitude as distance from the surface increases. There is a phase difference between these component motions.

Rayleigh waves are named after Lord Rayleigh, who predicted their existence in 1885. In isotropic solids, these waves cause the surface particles to move in ellipses in planes normal to the surface and parallel to the direction of propagation with the major axis of the ellipse being vertical, as shown in Figure 2.3. At the surface and at shallow depths, this motion is retrograde, meaning the in-plane motion of a particle is counterclockwise when the wave travels from left to right, as shown in Figure 2.1. At greater depths, the particle motion becomes prograde. In addition, the motion amplitude decays as the depth into the material increases. The depth of significant displacement in the solid is approximately equal to one wavelength.

Rayleigh waves have a velocity slightly less than shear waves by a factor dependent on the elastic constants of the material. Wave velocity of Rayleigh waves can be expressed as \( V_R = k V_R \) where \( k \) is a constant ranging from 0.87 and 0.95, depending on Poisson's ratio of the soil. The typical velocity of Rayleigh waves in the ground is on the order of 50–300 m/s. The relationships between Poisson's ratio and velocities of propagation for P, S and Rayleigh waves in elastic half-space are shown in Figure 2.5.
Since Rayleigh waves are confined near the surface, their in-plane amplitude when generated by a point source decays only as $1/R^{0.5}$ (vs. $1/R$ for body waves), where $R$ is the radial distance. Surface waves therefore attenuate more slowly over distance than do bulk waves, which spread out in three dimensions from a point source.

**Rayleigh Wave**

![Rayleigh Wave Diagram]

*Figure 2.3 - Particle Motion During Passage of Rayleigh Wave*

Love waves, named after Edward Love, are horizontally polarized surface waves, as shown in Figure 2.4. A Love wave is a result of the interface of S-waves guided by anelastic layer, which is attached to an elastic half space on one side while bordering air on the other side. Love waves are surface seismic waves that cause horizontal shifting of the Earth during an earthquake. Love waves travel with a lower velocity than P- or S-waves, but faster than Rayleigh waves. These waves are observed only when there is a low velocity layer overlying a high velocity layer/sub layers. The particle motion of a Love wave forms a horizontal line perpendicular to the direction of propagation (i.e., these are transverse waves) and the amplitude decreases rapidly with depth.

Since Love waves travel on the soil surface, the amplitude of the waves decreases exponentially with the depth of an earthquake. Given their confinement to the surface, however, their amplitude decays only at $1/R^{0.5}$, where $R$ represents the distance from the source of vibration.
2.1.3 Damping of Wave Energy

As shown in Figure 2.1, body waves propagate radially outward from the source along a hemispherical wave front, while surface waves propagate radially outward along a cylindrical wave front. As the waves travel outward, the density of the wave energy
decreases. This phenomenon is referred to as geometrical damping, which can be expressed as \(1/R\) (except along the surface which is \(1/R^2\)). The geometrical damping law for Rayleigh waves is expressed as \(1/R^{0.5}\) (Bullen 1955); therefore, they attenuate more slowly than body waves. The decrease in amplitude of the vertical component of Rayleigh waves due to geometry can be expressed as:

\[
\frac{A}{A_o} = \sqrt{\frac{R_o}{R}}
\]

\[2.5\]

\(R_o\) = distance from source to point on known amplitude

\(R\) = distance from source to the point of interest

\(A_o\) = amplitude of the vertical component of Rayleigh wave at distance \(R_o\) from the source

\(A\) = amplitude of the vertical component of Rayleigh wave at distance \(R\) from the source

The expression for Rayleigh wave attenuation, taking into account material damping, which is the absorption of energy from the materials that the wave travels through (including soil, since soil is not a perfectly elastic material) is as follows (Bornitz 1931):

\[
\frac{A}{A_o} = \sqrt{\frac{R_o}{R}} e^{-\alpha (R-R_o)}
\]

\[2.6\]

\(\alpha\) = coefficient of attenuation (unit of 1/distance). Barkan (1962) suggested values of \(\alpha\) ranging from 0.1 to 0.4 (1/feet) for various soil types. In a homogeneous isotropic half-space having Poisson’s ratio of \(\nu=1/4\), the distribution of energy between Rayleigh, S and P waves is 67\%, 26\% and 7\%, respectively (Miller and Pursey, 1955). Since Rayleigh
waves carry two thirds of the wave’s energy, it is critical to screen Rayleigh waves for mitigation of ground-borne vibrations.

2.2 Vibration Isolation

Vibration isolation becomes necessary when the amplitude of the ground-borne vibrations cannot be tolerated by nearby structures or machinery. Since most footings for buildings and machinery are located near the Earth’s surface, mitigating seismic waves propagated along the surface is the main concern of vibration isolation. According to Woods (1968), the effective screening of vibrations is the reduction of vibration amplitude to 25 percent of the no-screening amplitude.

Isolating structures and machine foundations from ground-borne vibrations has been attempted many times, with varying degrees of success reported. Examples of isolation systems included narrow sheet-pile supported trenches, slurry or concrete filled trenches and thin-wall hollow cylindrical or concrete piles. The concept of vibration isolation using trenches or piles is dependent on the barrier’s ability to intercept, diffract, and scatter the waves (Woods 1968). This can be accomplished by creating discontinuity in the medium within which the waves propagate: in other words, replacing soil within a trench with a material that has a different shear wave velocity and density. The usefulness of the wave barriers is directly related to their ability to isolate surface (Rayleigh) waves.

2.2.1 Active and Passive Isolation

The isolation of elastic waves can be grouped into two main categories: a) active isolation (near-field), and b) passive isolation (far-field). In active isolation, the barrier is placed close to or surrounds the vibration source, as shown schematically in Figure 2.6. Passive
isolation involves placing the barrier at points remote from the vibration source but near the site for which the vibration amplitude should be reduced, as shown in Figure 2.7.

Figure 2.6 - Active Isolation by a Circular Trench Surrounding Vibration Source (After Woods 1968)

For passive isolation, the incident waves to be screened are mostly Rayleigh waves. Placement of an open or in-filled trench is equivalent to creating a discontinuity for the wave within the half space. The process of wave reflection, refraction, and transmission near a trench is rather complex. Richart et al. (1970), Haupt (1978) and Fuyuki et al. (1980) studied this phenomenon and concluded that a) Rayleigh waves are partially reflected and
partially transmitted (in the case of in-filled trenches), and b) body waves (P and S) radiate outwards from the trench (either reflected or transmitted). Figure 2.8 shows the reflected and transmitted Rayleigh and body waves in the vicinity of an in-filled trench. The transmitted body waves are converted to Rayleigh waves at some distance beyond the trench.

![Figure 2.8 - Waves Generated due to Incident Rayleigh Wave Intercepted by an In-filled Trench (After Ahmad et al. 1990)](image)

For active vibration isolation in cases where the trench and vibration source are closely spaced, the wave propagation problem is more complex. It involves reflection, refraction, diffraction, and mode conversion. It is therefore more appropriate to perform 3D analysis to model the wave propagation near a trench, while a 2D plain strain analysis may suffice for passive isolation.

In the following section, several case histories on the vibration screening efficiency of open and in-filled trench barriers and concrete or tubular steel piles are presented. Many researchers have performed numerical modeling to evaluate the effectiveness of those screening measures with regard to their geometry and fill material characteristics.
2.2.2 Case Histories

The case histories presented in this subchapter cover a wide range of experimental and numerical modeling studies assessing the effectiveness of open and in-filled trench barriers and driven piles at isolating ground-borne vibrations. Case histories related to trenches barriers are reviewed first, followed by case histories concerning driven pile barriers.

2.2.2.1 Open and In-filled Trench Barriers

Dolling (1965, 1970) conducted field investigations to study the effectiveness of trench barriers and provided some guidelines for barrier shape and size. Figure 2.9 shows the comparison of the results obtained by Dolling, Woods (1968) and Haupt (1981) on the isolation effect of an open trench, based on its normalized depth. To account for the vibration frequency effect, the normalized depth/width of trenches with respect to the Rayleigh wavelength ($\lambda_R$) is typically used (since wavelength is inversely related to frequency).

Woods (1968) conducted a field study to investigate the effectiveness of open trenches in reducing vertical ground motion induced by surface (Rayleigh) wave energy radiating from a vibration source. Effectiveness in Woods’ study was defined as a reduction of ground motion ‘$A_R$’ to 25 percent of no trench motion.

Reduction factor ‘$A_R$’ is defined as the ratio of the vertical displacement component of the soil surface in the presence of a trench over the displacement without a trench. The average surface amplitude reduction factor for a trench is defined as $\bar{A}_R = (1/A) \int_A A_R \, dA$ where $A$ is the screened area behind the trench. Other researchers later used this definition as the criterion for evaluating the effectiveness of vibration isolation barriers.
Woods reported the following conclusions:

1) For active isolation, and for full circle trenches, $R/\lambda_R$ (R denotes trench radius) ranges from 0.222 to 0.91, and for $H/\lambda_R$ (H denotes trench depth), depths range between 0.222 and 1.82. Additionally,

a) A minimum depth of $H/\lambda_R = 0.6$ is required for a trench to satisfy the $\bar{A}_R < 0.25$ criterion.

b) The zone screened by a full circle trench extends to a distance of 10 wavelengths ($10\lambda_R$) from the vibration source.

For partial circle trenches, assuming the same range of distances and depths, conclusions were as follows:

a) A minimum depth of $H/\lambda_R = 0.6$ is required for a trench to satisfy the 0.25 criterion.

b) The screened zone for a partial trench (area outside the trench extended to $10\lambda_R$) was bounded on the sides by radial lines from the center of the vibration source through points 45° from the ends of the trench.
c) Partial circle trenches having an angular length of less than 90° did not provide effective screening.

d) Amplification of vibratory energy occurred on the open side of the trench.

2) For passive isolation, Woods used straight open trenches. R/λ values were in the range of 2.22 to 9.1, and H/λ ranged from 0.444 to 3.64. The following conclusions were made:

a) Larger trenches were required at greater distances for effective screening; HL/λ² value (L denotes the trench length) should be at least 2.5 for R=2λ and at least 6 for R=7λ.

b) For trenches located between 2 to 7 times R/λ, H/λ = 1.33 is required.

c) Magnification of vertical motion occurs in zones in front of and on the side of the trenches.

d) Sheet-wall barriers were not as effective as open trenches in screening surface waves.

e) Trench width had little influence on the effectiveness of open trenches for W/λ between 0.13 and 0.91.

Haupt (1978) used the FE method to study the screening effectiveness of concrete barriers with various shapes and stiffness. He concluded

a) The special shape of the barrier, compared against rectangular barriers, will not enhance the screening effect and may add to construction cost.

b) For passive isolation, an increase in the screening effectiveness of a barrier is proportional to the increase in its cross sectional area.

c) Concrete barriers are more effective for active, rather than passive, isolation.

d) Narrow soft barriers (w/λ<0.2) are not effective for active isolation, regardless of their depth.
Haupt (1981) performed tests in model scale (Figure 2.10) to investigate the vibration isolation effect of various measures, including solid barriers such as concrete core walls, open trenches, and rows of boreholes. Due to the size of the test facility, vibration frequencies in the range of 240 to 400Hz, corresponding to low wavelengths, were used in the study.

![Figure 2.10 - Cross Section and Plan View of Test Facility (After Haupt 1981)](image)

Haupt reported the following findings:

a) The screening effect of solid obstacles, such as concrete barriers, is not a function of the cross sectional shape but the normalized cross sectional area (in the direction of wave propagation).

b) For rows of boreholes stabilized by plastic tubes, an increase of the isolation effect with an increase in the normalized shielded area was observed.

c) The screening effect of open trenches is increased with normalized depth.

Ahmad and Al-Hussaini (1990) studied the effectiveness of rectangular open or in-filled trenches using Boundary Element Method (BEM) to reduce ground vibrations caused by
propagating surface harmonic Rayleigh waves. The problem of passive isolation under plane-strain conditions using open and concrete filled trenches was considered. They provided design expressions for estimating the vibration screening effectiveness of rectangular trenches in homogeneous soil deposits, taking into account geometrical and material parameters. Their study included cases in which soil was layered, and they evaluated the effects of layering on the performance of a trench as a wave barrier. A schematic diagram of the problem studied is shown in Figure 2.11.

Ahmad and Al-Hussaini reported the following:

a) Open trenches can effectively isolate ground-borne vibrations ($\bar{A}_R < 0.25$) if the trench’s normalized depth ($D=d/\lambda_R$) is higher than 0.8. The normalized width ($W=w/\lambda_R$) is important only for shallow depths ($D<0.8$).

b) For in-filled trenches, dimensionless depth and width should be higher than 1 and 0.8, respectively.

c) For in-filled trenches, both depth and width are equally important.
d) The influence of Poisson’s ratio of the soil can be ignored while the effect of shear wave velocity and unit weight of the fill material (relative to the soil) must be considered.

e) For layered systems, if the lower layer has a lower stiffness than the upper layer, the effect of layering can be ignored; otherwise, the layering effect must be accounted for and addressed by building a deeper trench.

Ahmad and Baker (1995) performed an experimental investigation and numerical modeling, evaluating the role of various geometrical and material parameters of concrete and soil-bentonite filled trench barriers in screening ground-borne vibrations. They concluded that a concrete trench barrier with a normalized depth and width of 1.2 and 0.35 (trench length of 0.5 to 1.0 and source-to-trench distance of 0.21 to 0.38 for an active case, and 2.7 to 6.3 for a passive case) will result in an $\bar{A}_R$ of 0.3 or lower.

Al Hussaini and Ahmad (1996) performed a numerical investigation evaluating active isolation of a machine foundation through the use of in-filled trench barriers in a three-dimensional viscoelastic half space. The effects of various geometric and material parameters on the performance of the in-filled trench barrier were studied for both concrete and soil-bentonite. The following conclusions were made:

1) For the concrete filled barrier,

   a) The optimum range of normalized distance between the source and the barrier ($L$) which provides optimum screening is $0.2 \leq L \leq 0.375$.

   b) The efficiency of the barrier increases with depth until an optimum depth is reached. The optimum depth is a function of the shear wave velocity ($V_s$) ratio of concrete and soil, and depends on the trench width for shallow trenches.

   c) For a $V_{s\text{-barrier}}/V_{s\text{-soil}}$ value larger than 5 and preferably larger than 7.5, screening effectiveness is optimum.
d) The efficiency of the concrete filled barrier increases with width. The influence is greater for barriers located close to the source (L= 0.1), but for widths beyond 0.5, the effect of width is minimal.

2) For a soil-bentonite barrier,

   a) A normalized barrier depth of 0.8 or more is required for effective screening (0.1< $\bar{A}_R$ <0.4).

   b) The ratio of $V_{s\text{-barrier}}/V_{s\text{-soil}}$ should be 0.2 or less for effective screening.

Using a 2D numerical finite/infinite scheme, Yang and Hung (1997) studied the effectiveness of three different wave barriers, including open trench, in-filled trench, and elastic foundation, for active isolation of ground vibrations caused by the passage of a train. The schematic is shown in Figure 2.12. The geometric and material parameters of the three barriers investigated included distance to rail; depth, width, and thickness; damping ratio; shear modulus; mass density; and Poisson’s ratio. The findings of the study are as follows:

![Figure 2.12 - Typical Model of the Problem (After Yeong and Hung 1997)](image-url)
a) Trench dimension is a key factor in effective vibration screening. Long wavelengths could not be effectively screened by trenches due to limitations in trench depth.

b) Width is not important in open trenches (except for shallow trenches), while it is important for in-filled trenches.

c) For in-filled trench barriers, the dimensionless depth and width should be more than 1 and 0.3, respectively, to be efficient.

d) Among soil parameters, only Poisson’s ratio is a critical factor for active isolation problems, damping ratio and density play only marginal roles.

Adam and Estroff (2005) performed a similar 2D numerical investigation evaluating passive screening of train-induced building vibrations by using open and in-filled trench barriers. A coupled BE-FE algorithm was applied for the numerical model of the soil-structure system, as shown in Figure 2.13.

![Figure 2.13 - Numerical Model of the Considered Soil-structure System](After Adam and Estroff, 2005)
The variables in their study included trench dimensions, trench distance from the building, and backfill material properties. Axial and shear forces for two columns and acceleration for a girder was monitored. The following conclusions were made:

a) Open or in-filled trench barriers reduced the vibrations impacting the structure up to 80 percent.

b) Increasing depth has far more effect than increasing width.

c) Increasing the distance between the open trench and the building decreases the effectiveness of the trench due to an increase in the resulting scattered horizontal motions. This behavior is less pronounced for in-filled trenches.

d) The use of raft foundation instead of strip footing can reduce building vibrations significantly.

Massarsch (2004) studied the effectiveness of gas cushion screening for mitigating vibrations from train traffic. The gas cushion is manufactured of a thin, multi-layered plastic-aluminum foil with individual gas-tight cells. The gas cushion is typically installed within self-hardening cement-bentonite slurry for ease of installation and protection. Figure 2.14 shows the cross section for a gas cushion screen system (one of the most recent types available) and its installation.
In Sweden and Germany, gas cushion screen systems have been used in several full-scale projects in different soil conditions. Massarsch reported that the isolation effect of a gas cushion screen is comparable to an open trench. The relative vibration amplitude is shown in Figure 2.15 as a function of depth, and the results are compared to the previous works by Dolling and Beskos et al.

Figure 2.14 - Cross Section and Installation of Gas Cushion Screen System  
(After Massarsch 2004)

Figure 2.15 - Isolation Effect of Gas-filled Cushions in Different Soils and Vibration Sources (After Massarsch, 2004, Dolling 1970 and Beskos 1990)
Alzawi and El Naggar (2012) performed a field study to investigate the effectiveness of open and geofoam in-filled trenches in screening ground-borne vibrations. The trench barrier geometry and the trench distance to the source were the main variables in the study. A numerical model was prepared using the FE ABAQUS package to study the effect of varying trench geometry and soil parameters. Alzawi and El Naggar concluded the following:

a) The field results show that geofoam can screen up to 68 percent of the ground-borne vibrations.

b) The wave barrier effectiveness (open or geofoam in-filled) is influenced by its normalized depth (should be \( d/\lambda_R \geq 0.6 \) to be effective) and location.

c) For open trenches, a deeper trench is required as the distance between the vibration source and trench increases. This was not the case for the geofoam filled trench.

### 2.2.2.2 Driven Pile Barriers

Piles are considered an alternative to trench barriers since they can be driven very deep into the soil using conventional pile driving techniques, whereas there are practical limitations for trench depths. Studies show, however, that trenches serve as more effective wave barriers.

Barkan (1962) reported on an unsuccessful application of a sheet pile wall barrier to isolate a building from traffic-induced vibrations. Woods, Barnett and Sagesser (1974) evaluated a row of piles as a vibration barrier. They used the principle of holography to observe vibrations in a model half-space to develop the criteria for cylindrical voids to be used for passive isolation. The values of normalized depth and length were kept at 1.4 and 2.5, respectively. Woods et al. suggested that a row of cylindrical holes may act as an isolation
barrier if $D/\lambda_R \geq 1/6$ and $S_n/\lambda_R < 1/4$ where $D$ is the diameter of the cylinder and $S_n$ is the (c-c) spacing between the cylinders.

Lia and Sangrey (1978) used an acoustic model, generating sound waves in a fluid medium to assess rows of piles as barriers for passive isolation. They confirmed that the values of $D/\lambda_R \geq 1/6$ and $S_n/\lambda_R < 1/4$, as suggested by Woods et al., are generally valid. They also suggested that those barriers are not effective if $S_n$ exceeds $0.4 \lambda_R$.

Kattis et al. (1999) numerically studied the wave screening effectiveness of a row of piles in three dimensions by using BEM computer code. In the study, the piles were assumed to be tubular or solid and had square and circular cross-sections. Their screening effectiveness, however, as shown by Kattis et al, is not as good as trench barriers. The results of parametric studies evaluating the effectiveness of various pile configurations and types for passive vibration isolation are shown in Table 2.1. A schematic diagram of the problem studied is shown in Figure 2.16.

For the row of piles, the average surface amplitude reduction factor $A_R$ behind the trench is defined as $\bar{A}_R = (1/A) \int_A A R dA$ where $A$ is the area behind the trench enclosed by the semicircle with a radius of $l/2$ (one half of the length of the row of piles). The study shows that $\bar{A}_R$ decreases with an increase in the number of piles or with a decrease in the spacing between piles.
Figure 2.16 - Cross-section and Top View of the Pile Barrier isolation System (After Kattis et. al. 1999)

Table 2.1 - Average Surface Amplitude Reduction Factor $\bar{A}_R$ for the Various Pile Barrier Vibration Isolation Systems (After Kattis et. al. 1999)

<table>
<thead>
<tr>
<th>Number of piles</th>
<th>Type of pile material</th>
<th>Type of pile cross-section</th>
<th>Average surface amplitude reduction factor ($\bar{A}_R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Open</td>
<td>Circular</td>
<td>0.926</td>
</tr>
<tr>
<td>6</td>
<td>Concrete</td>
<td>Circular</td>
<td>0.755</td>
</tr>
<tr>
<td>6</td>
<td>Open</td>
<td>Square</td>
<td>0.868</td>
</tr>
<tr>
<td>6</td>
<td>Concrete</td>
<td>Square</td>
<td>0.721</td>
</tr>
<tr>
<td>8</td>
<td>Open</td>
<td>Circular</td>
<td>0.812</td>
</tr>
<tr>
<td>8</td>
<td>Concrete</td>
<td>Circular</td>
<td>0.712</td>
</tr>
<tr>
<td>8</td>
<td>Open</td>
<td>Square</td>
<td>0.698</td>
</tr>
<tr>
<td>8</td>
<td>Concrete</td>
<td>Square</td>
<td>0.675</td>
</tr>
<tr>
<td>10</td>
<td>Open</td>
<td>Circular</td>
<td>0.648</td>
</tr>
<tr>
<td>10</td>
<td>Concrete</td>
<td>Circular</td>
<td>0.624</td>
</tr>
<tr>
<td>10</td>
<td>Open</td>
<td>Square</td>
<td>0.642</td>
</tr>
<tr>
<td>10</td>
<td>Concrete</td>
<td>Square</td>
<td>0.620</td>
</tr>
</tbody>
</table>

The general wave screening behavior of piles in vibration isolation is similar to that of trenches, with the latter proving more effective than piles as wave
barriers.

b) Length, width, and depth of a row of piles influence its vibration isolation effectiveness in a manner similar to trenches, while the cross sectional shape of the piles plays no significant role.

c) The most important parameter influencing the screening effectiveness of a row of piles is their spacing; piles are effective when spacing is small.

2.3 Scrap Tires

This subchapter provides information related to the beneficial use of scrap tires in civil engineering applications, the engineering properties of scrap tires, and the current state of practice. As the name suggests, scrap tire is tire that can no longer be used for its original purpose due to wear or damage (ASTM D 6270, 2008). A few case studies are reviewed; these relate to beneficial use of scrap tires as backfill behind retaining walls, road embankment lightweight fill, and fill underneath light rail tracks for attenuation of vibrations from train traffic.

2.3.1 Current Beneficial Use Practice of Scrap Tires

At the end of 2013, the US generated approximately 233 million scrap tires, out of which 224 million entered the market, according to Rubber Manufacturers Association (RMA), [RMA 2014]. Tires are composed of natural and synthetic rubber elastomers derived from crude oil. Other polymers, metals, and additives are also used in the manufacturing process to enhance performance. Tires are made of stable chemicals to withstand harsh environmental conditions and can be considered inert, since it takes hundreds of years for tires to decompose. This property of tires makes them suitable for engineering applications.
Historically, scrap tires were landfilled or stockpiled, creating environmental and aesthetic problems. Most states in the US have passed laws making such practices illegal. In 2013, 96 percent of scrap tires entering the market were recycled or beneficially re-used, up from 17 percent in 1990 (RMA 2014):

- 130 million (57.8%) were used as fuel
- 59.5 million (26.6%) were converted into ground rubber and recycled into products
- 15 million (6.7%) were exported
- 10.5 million (4.7%) were recycled or used in civil engineering applications
- 9 million (4.0%) were recycled and used for stamped/punched products, electric arc furnaces, reclamation, and agricultural and baled tire uses

There were 20 million scrap tires land disposed in 2013 that could be put to some beneficial use. This study was designed to identify a new engineering application beyond what is currently being practiced for unused scrap tires.

### 2.3.2 Application in Civil Engineering

Scrap tires are currently used in various civil engineering applications. Due to their extensive use, the standard ASTM D 6270 entitled, “Standard Practice for Use of Scrap Tires in Civil Engineering Applications” was prepared to provide guidance for testing the material properties of scrap tires and a description of construction practices. The standard provides a list of terms and definitions for scrap tires used in civil engineering applications as follows:

- Scrap tire: a tire, which can no longer be used for its original purpose due to wear or damage
- Shredded tire: size-reduced scrap tire where the reduction in size was accomplished by a mechanical processing device, commonly referred to as a
shredder

- Tire chips: pieces of scrap tires that are generally between 12mm and 50mm in size and have most of the wire removed
- Tire shreds: pieces of scrap tires that are generally between 50mm and 305mm in size

Beneficial use of scrap tires (in the form of tire shreds or tire chips) in civil engineering applications include the following:

a) *Subgrade Fill and Embankments*,

Tire shreds can be used as lightweight fill for the construction of road embankments on soft soils. Tire shreds are viable in this application due to their low unit weight (less than 40 percent of conventional fill material unit weight) and low cost compared to conventional construction fill.

b) *Backfill for Retaining Walls and Bridge Abutments*

Tire shreds can be used as backfill for retaining walls and bridge abutments. The low unit weight of tire shreds reduces the active lateral stress and allows for the construction of thinner walls. Tire shreds are free draining so they reduce the potential for hydrostatic pressure build-up behind the retaining walls. They also provide good thermal insulation.

c) *Subgrade Insulation for Roads*

In cold regions, excess water is released when subgrade soils thaw. Placing a 15- to 30cm-thick layer of tire shreds under the road can prevent the subgrade soils from freezing. In addition, due to the high permeability of this layer, it acts as a drainage layer preventing damage to the road surface.

d) *Septic System Drain Field*
Scrap tires have been used in the construction of drain fields for septic systems in a few states. They can replace traditional stone backfill material at a lower cost. For this application, tire shreds must be clean-cut, of uniform size, and cheaper than stone.

e) Landfills
Scrap tires can be used as a lightweight backfill in gas venting systems and leachate collection systems. They may also be used in landfill capping and closures, and as a material for daily cover.

f) Asphalt Rubber
Scrap tires have been extensively used in producing asphalt rubber. Arizona and California use up to 10 million tires annually in highway construction (EPA 2007). The ground rubber can be blended with asphalt to enhance its durability, reduce noise, reduce costs, and decrease skid distance. It can also be used in lieu of aggregate.

g) Other Uses
These include providing drainage around building foundations, crash barriers around racetracks, and erosion control/rainwater runoff barriers. They can also be used for boat fenders and as a substitute for gravel.

With regard to environmental impact, scrap tires when used in civil engineering applications have minimum impact on soil or groundwater quality since they are manufactured from stable chemicals. A comprehensive literature review was performed by the University of Maine in 2007 and found that, “Tire Derived Aggregate (TDA) have a limited effect on drinking water quality and fresh water aquatic toxicity for a range of applications. TDA is unlikely to increase the concentration of substances with primary drinking water standards above those naturally occurring in the groundwater. It is likely
that TDA will increase the concentration of iron and manganese, but the data indicates that these elements have limited ability to migrate away from the TDA installation.

2.3.3 Engineering Properties of Tire Shreds

A wealth of information on the engineering properties of tire shreds is available. Various field and laboratory testing has been performed by government and private agencies and educational institutions. Tire shreds are comparable to coarse gravel and crushed rock, since they are also coarse grained, with the difference that tires are deformable and have a much lower unit weight than mineral aggregate. The most commonly studied engineering properties of tire shreds include

- Particle size distribution
- Bulk Density (loose and compacted)
- Shear strength
- Long-term and short-term deformation and compressibility
- Thermal conductivity, and
- Hydraulic conductivity

When evaluating tire shreds to use as trench backfill to provide vibration screening, the particularly relevant properties to be studied include particle size, bulk density unit weight, dynamic shear modulus, Poisson’s ratio, and damping ratio. In this study, to estimate the shear modulus of native soil and tire shreds, the SASW method was employed. The methodology is fully described in Chapter 5.

The tire shreds used in this research were uniformly graded and consisted of two sizes, 50mm and 200mm, produced in a tire shredding facility in southern New Jersey. The steel wires were mostly removed. No direct measurement of unit weight or Poisson’s ratio was
made in the field or laboratory, therefore typical values provided in the literature for similar tire-shred sizes were used in the numerical investigation, as detailed in Chapter 4.

Material damping is a frequency-dependent parameter, with a typical value of 5 percent used in most studies. A discussion on the damping ratio adopted for the frequencies used in this study is presented in chapter 4.

### 2.3.4 Case Studies

The primary civil engineering applications for tire shreds are in landfill drainage layers or in highway construction, where they serve as lightweight fill for highway embankments and retaining walls. Three case studies on the beneficial use of tire shreds are presented herein, in which tire shreds serve as 1) lightweight fill for highway embankment construction, 2) bridge abutment backfill, and 3) a soft medium for isolating train-induced vibrations.

The performance of tire shreds used as lightweight fill for the construction of two 10m-high highway embankments in Portland, Maine was studied by Humphrey et al. (1998). The site was underlain by 13m of weak marine clay, meaning the placement of embankments would result in an unsatisfactory factor of safety for slope stability. Tire shreds were selected as lightweight fill due to their relatively low cost and environmental benefits. Tire shreds were placed using conventional equipment in 30cm layers to the full height of the embankment. No post-construction issues were reported. Temperature monitoring showed no evidence of self-heating during or after construction.

Using tire shreds as backfill for retaining walls due to their low unit weight and drainage properties is practical and sensible. Tire shreds were used as backfill in a test wall constructed at the University of Maine (Tweedie, et al. 1998) and behind the north
abutment of a bridge in Topsham, Maine (Humphrey et al. 1998). Stress monitoring showed that at-rest and active lateral stresses were 45 percent and 35 percent, respectively: less than that of typical granular backfill.

Tire shreds were also used to reduce lateral earth pressures on a rigid frame bridge in Topsham, Maine (Humphrey 1998). Due to the rigidity of the frame, active lateral stresses could not be developed if granular backfill was used and at-rest lateral pressure had to be considered requiring thicker walls. The solution was to place 1m of tire shreds against each abutment wall so compressibility of the tire shreds would allow movement of backfill towards the bridge and relaxation of lateral stresses to active state. Stress monitoring showed much lower stresses on the sections of the wall where tire shreds were utilized as backfill.

Wolfe, et al. (1999) investigated the effectiveness of tire shreds in attenuating ground-borne vibrations from train traffic. Tire shreds were placed beneath ballast and tie rail along an 80m stretch of a light rail transit track in Santa Clara, California. Both the performance and the associated cost of using tire shreds were compared to conventional track isolation systems, such as ballast mat (rubber material applied beneath ballast layer of the track) and the floating slab track-bed (in which the track is fastened onto a concrete slab that is supported on rubber pads). Wolfe et al. concluded that the use of tire shreds to attenuate ground-borne vibrations is very effective in the vibration frequency range above 31.5 Hz and marginally effective for the 12.5 to 31.4 Hz range. Moreover, the cost of using tire shreds for isolating ground-borne vibrations is significantly less than conventional methods.
CHAPTER THREE

METHODOLOGY

In this Chapter, the methodology for investigating the performance of in-filled tire-shred trench barriers for the active (near-field) isolation of ground-borne vibrations is described. The investigation consisted of three main parts, numerical and experimental investigations and a parametric study.

In the numerical investigation, two- and three-dimensional numerical models were developed to examine the influence of geometrical parameters on the performance of the trench barriers. The models were validated using field measurements and reference models developed by others. The numerical investigation provided guidelines for the design of an experimental investigation and the parametric study.

In the experimental program, the performance of open and in-filled tire-shred trenches with different angular lengths, i.e., circular, semi-circular and linear (full and partial isolation) were investigated in full-scale, in 3D. The influence of geometrical dimensions such as trench depth, width, and distance to the excitation source was studied for a range of harmonic excitation frequencies. Considering the size of tire shreds (50mm and 200mm) used in this study as an isolation medium, a full-scale study was warranted to properly assess the performance of each size tire shred.

A parametric study followed the experimental investigation; this used the developed models to further examine the influence of key parameters, such as trench geometry, partial or full isolation, and soil material properties, on the performance of the trench
barriers. Parameters that could not be studied during the experimental investigation, such as variations in native soil dynamic properties, were comprehensively studied during the parametric study.

The following sections describe in further detail the methodology adopted to implement the experimental and the numerical investigations as well as the parametric study.

3.1 Numerical Investigation

A numerical investigation examined the influence of geometrical parameters on the performance of in-filled tire-shred trench barriers for active isolation of ground-borne vibrations. Two- and three-dimensional finite element models were developed using the ABAQUS finite element package for the numerical investigation. The influence of depth, width, and angular length (full and partial isolation) on the performance of in-filled trench barriers was studied using the numerical models.

The influence of trench angular length had to be examined in 3D, while 2D axisymmetric and plane strain models provided accurate results for the influence of geometrical dimensions. The numerical study provided guidelines for the design of an experimental study. Key parameters influencing the performance of trench barriers were identified for further investigation in the experimental and the parametric studies.

3.1.1 Model Development

The explicit dynamic analysis option in ABAQUS was used, since it is best suited for modeling high-speed dynamic events, such as stress wave propagation in a half space. Chapter 4 details the selection of element size, time increments, and boundary conditions.
An accurate investigation of active (near-field) case typically requires 3D analysis due to 1) the complex nature of incident wave reflection, refraction, and transmission at the interface of the soil and the tire shreds and 2) the co-existence of body and surface waves and the associated mode changes. It is important to note, however, that the results of the 2D axisymmetric and the 3D models were in good agreement when analyzing the influence of geometrical parameters or material properties. Significant computational time was saved by using the 2D model in lieu of the 3D model for analyzing those cases. Partial isolation case requires 3D analysis regardless.

The validation process for the numerical model involved comparing the results produced by the developed model to the results of a reference model developed by others who were analyzing a reference case. Some adjustments were required to increase the level of accuracy. This process is detailed in Chapter 4.

For validating the 3D model, field measurements of soil particle velocity induced by harmonic excitations from a vibrating mass shaker, for free-field conditions, were checked against the results produced by the model for the same conditions and excitation velocity input. As shown in Chapter 4, the results were comparable.

### 3.1.2 Preliminary Parametric Study

A preliminary parametric study was conducted to examine the influence of geometrical dimensions on the trench barrier’s performance. In addition, partial and full isolation achieved by circular, semi-circular, and linear barriers were examined.

The proper selection of key dynamic properties, and shear wave velocity in particular, increases the accuracy of the results produced by the models. There is not a wealth of information available for shear wave velocity in tire shreds, therefore SASW tests were
conducted to measure the shear wave velocity in both tire shreds and native soil. The process is detailed in Chapter 5.

Based on the findings of the preliminary parametric study, the scope of the experimental investigation was defined and a comprehensive parametric study was designed, as described below.

3.2 Experimental Investigation

The experimental investigation was designed so that the influence of geometrical dimensions, angular length, and tire-shred size on the performance of trench barriers could be investigated in 3D. Considering the size of the tire shreds (50mm and 200mm) used in this study as trench fill, a full-scale investigation was warranted to properly examine the performance of tire shreds as an isolation medium.

In this study, open and in-filled trenches with three different angular lengths, circular (full isolation), semi-circular, and linear (partial isolation), were employed to a) investigate the effectiveness of tire shreds as an isolation medium in 3D (i.e., vertical, longitudinal, and transverse direction), and b) investigate the influence of angular length in the limits of the screened zone behind the trench barrier (full and partial isolation).

3.2.1 Tire Shreds as Isolation Medium

The presence of large voids and the deformability of tire shreds suggest that tire shreds could prove to be an effective isolation medium. A full-scale experimental investigation, however, was required to determine their effectiveness.
The screening effectiveness of open and in-filled trench barriers was compared, so that the effectiveness of tire shreds could be examined with respect to air, which is the most-effective isolator. To independently examine the effective of each size of tire shred, one half of each trench (from the bottom to the top) was filled with each tire size (50m and 200mm). The selection of the tire shred sizes used in the study was based on market availability in New Jersey and the associated shredding cost. If both sizes were proven effective, use of the 200mm size would be preferred, due to its lower associated shredding cost.

3.2.2 Geometrical Parameters

Among geometrical parameters, depth is the most significant in governing the performance of trench barriers. Trench angular length (circular, semi-circular, or linear) determines the limits of the effectively screened area behind the trench barrier. To evaluate the influence of geometry and length, circular (full isolation), semi-circular and linear (partial isolation), trenches with geometries as shown in Figure 5.11a, 5.11b and 5.11c were installed and performances were monitored.

Woods (1968) demonstrated that an open trench is effective if the normalized depth \(D=d/\lambda_R\) is more than 0.6. In this study, the trench depths could not exceed 1.4m, otherwise excavation support would have been required. Excitation frequencies in the 20 to 160Hz range corresponding to \(D\) in the 0.15 to 1.2 range (based on a Rayleigh wave velocity of 182m/s as determined by SASW) were used. It was anticipated that vibrations with frequencies higher than 80Hz (associated with \(\lambda_R=2.25m\) and \(D=0.6\)) would be effectively screened by 1.4m-deep trenches, so the effectiveness of tire shreds and the influence of geometry could be properly investigated. The range of vibration frequency
covers lower frequency vibrations, such as those typically generated by train traffic or pile driving, and higher frequency vibrations, such as those generated by machine foundations.

Time harmonic excitations were generated by a vibrating mass shaker. The vibration source was placed at 2.4m from the trenches (for practical reasons and taking into account the trench width of 1.2m) or at a normalized distance in the $0.25\lambda_R$ to $2.13\lambda_R$ range. In general, this isolation scenario can be considered active (i.e., providing isolation at the source).

Using the particle velocity amplitude measurements in 3D (vertical, longitudinal, and transverse directions) prior to and after trench installation, a reduction factor ($A_R$) for each trench type was calculated so the performance of the trench barriers could be evaluated. Three-dimensional measurements of the soil’s response to harmonic excitation are particularly important for evaluating active isolation, since body waves are present at or near the trench. For passive isolation cases, however, a 2D plane strain analysis is sufficient, since Rayleigh waves oscillating at a plane perpendicular to the half space surface carry the majority of the wave energy at far-field.

3.2.3 Material Properties

Key dynamic material properties, such as shear wave velocity, bulk density, Poisson’s ratio, and damping ratio, affect wave propagation in an elastic half-space. Among those, shear wave velocity is the most critical. Al Hussaini and Ahmad (1996) demonstrated that in-filled trenches are effective if the ratio of shear wave velocity for the fill material over the half space; $V_{s,\text{barrier}}/V_{s,\text{soil}}$ is higher than 5 for stiff barriers or less than 0.2 for soft barriers.
To determine the shear wave velocity by the SASW method, the travel time of a wave (generated by an impact) between two receivers is used to measure wave velocity. Shear wave velocity was measured separately for each tire size and for the native soil. The process is detailed in Chapter 5. For other dynamic material properties, values recommended in literature were adopted.

### 3.3 Parametric Study

A parametric study was conducted following validation of the 2D and the 3D models. The influence of trench geometry, angular length, and soil material properties in the performance of open and in-filled trench barriers was comprehensively investigated. The limits of the screened area behind a partial trench had to be delineated using the 3D model. For other cases related to geometrical parameters and material properties, the 2D and the 3D model results were in good agreement; thus the 2D model was used to save computational time.

Conclusions and recommendations were made based on the findings of the experimental and numerical investigations and the parametric study; these are presented in Chapter 7.
CHAPTER FOUR

NUMERICAL INVESTIGATION

This chapter presents the results of a numerical investigation examining the influence of geometrical parameters on the performance of in-filled tire-shred trench barriers to provide active isolation of ground-borne vibrations. Two- and three-dimensional finite element numerical models were developed using the ABAQUS FE package for the numerical investigation. The influence of depth, width, and angular length (full and partial isolation) on the performance of in-filled trench barriers was investigated by the numerical models.

The influence of trench angular length had to be examined in 3D, while 2D axisymmetric and plane strain models provided accurate results for examining the influence of geometrical dimensions. The numerical study provided guidelines for the design of the experimental study and highlighted the scenarios that required further investigation in full-scale. Key parameters influencing the performance of trench barriers were identified to be further investigated in the experimental and parametric studies.

4.1 Model Development

The finite element program, ABAQUS (Version 6.14-2) was used for the development of the 2D and the 3D models. The explicit dynamic analysis method was used, as it is suitable for high-speed dynamic events such as stress wave propagation in a half space. The soil was modeled as a homogeneous, isotropic, elastic half space. Developing the models
required selecting the element size, time increment, and boundary conditions. The process for selecting each is described below.

### 4.1.1 Element Size and Type

In the 3D model, the soil and the trenches were modeled as 8-noded hexahedron elements, C3D8R. In the 2D plane strain model, 4-noded elements, CPE4, were used. For active isolation and free-field cases, an axisymmetric space using 4-noded axisymmetric elements, CAX4R, was used. Details of the element types used in the models are presented in Table 4.1 and shown in Figure 4.1. The source of excitation was modeled as a vertical harmonic velocity input, applying a maximum velocity of 4e-5m/s. The range of frequencies used (20Hz to 80Hz) represent the vibration frequencies induced by trains or heavy vehicles.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Element Type</th>
<th>Element Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D – Axisymmetric</td>
<td>CAX4R</td>
<td>4-node bilinear axisymmetric quadrilateral, reduced integration</td>
</tr>
<tr>
<td></td>
<td>CINAX4</td>
<td>CAX4 one-way infinite</td>
</tr>
<tr>
<td>2D – Plane Strain</td>
<td>CPE4R</td>
<td>4-node bilinear plane strain quadrilateral, reduced integration</td>
</tr>
<tr>
<td></td>
<td>CINPE4</td>
<td>CPE4 one-way infinite</td>
</tr>
<tr>
<td>3D</td>
<td>C3D8R</td>
<td>8-node linear brick, reduced integration</td>
</tr>
<tr>
<td></td>
<td>CIN3D8</td>
<td>C3D8 one-way infinite</td>
</tr>
</tbody>
</table>

*Table 4.1 - Element Types used in the 2D and 3D Models*
The 2D and the 3D element sizes were selected based on the highest frequency of oscillations and the wave propagation velocity in soil and tire shreds. The use of coarse finite element meshes can result in the filtering of high frequency components, whose short wavelengths cannot be modeled by widely-spaced nodal points. The use of very fine meshes can add significantly to the computation time and cause instability. Kuhlemeyer and Lysmer suggested a maximum element size of one-eighth of the shortest wavelength. Considering a shear wave velocity of 200m/s (Rayleigh wave velocity of 182m/s) and the highest frequency of input motion (160Hz), a maximum element size of 14cm was selected. To save computational time, however, the element size used for frequencies less than 80Hz was 25cm.
To ensure that the selected element sizes provided accurate results, the study compared soil particle velocity amplitudes of harmonic vertical oscillations for three different element sizes in the presence of an open trench. A loading frequency of 50Hz was selected, since it is the same frequency used in the parametric study. The element sizes of 25cm and 5cm for the entire mesh, 5cm in the vicinity of the trench, and 25cm elsewhere were analyzed, as shown in Figure 4.2 through Figure 4.4. The results are presented in Figure 4.5. It was noted that the results varied only marginally for the two element sizes, therefore selecting a 25cm element size was appropriate. Since the shear wave velocity within tire shreds is significantly lower than soil, an element size of 5cm was selected for evaluating the tire shreds only (an element size of 5cm for soil did not improve the accuracy and significantly increased the computational time).

*Figure 4.2 - FEM Mesh, Element Size of 25cm*
Figure 4.3 - FEM Mesh, Element Size of 5cm

Figure 4.4 - FEM Mesh, Element Size of 5cm in the Vicinity of the Trench and 25cm Element Elsewhere
4.1.2 Boundary Elements and Time Increments

To ensure complete energy dissipation at the FE mesh boundaries, non-reflecting semi-infinite elements were introduced. Lysmer and Kuhlemeyer (1969) recommended the introduction of viscous boundaries for analyzing dynamic problems involving infinite continuous systems so that an infinite half space could be properly modeled by an FE model. In this study, the absorbing boundaries using infinite elements presented in ABAQUS Explicit, i.e., CIN3D8 elements in 3D models and CINAX4 and CINPE4 elements in 2D models, were utilized.
Figure 4.6 - CINAX4 and CINPE4 Plane Strain Semi-infinite Elements

Figure 4.7 - CIN3D8 3D Semi-infinite Element

Utilizing non-reflecting infinite elements significantly enhanced the performance of the model by eliminating the reflection of waves at the boundaries. Figure 4.8 shows the vertical particle velocity of a randomly selected spot on the surface of the half space at four meters away from the source of excitation for both infinite and fixed boundary scenarios. A significant number of reflected waves are observed in the case of fixed boundaries, and the effectiveness of infinite boundaries can be noted. Figure 4.9 through Figure 4.12 show the 2D and the 3D FE mesh with infinite elements used to investigate trench barrier performance in active and passive isolation cases.
Figure 4.8 - Wave Reflection for Infinite and Fixed Boundary Cases

Figure 4.9 - Finite Element Mesh of 2D Plane Strain Model for Investigating Passive Isolation Case
Figure 4.10 - Finite Element Mesh of 2D Axisymmetric Model for Investigating Active Isolation Case using Circular Trench

Figure 4.11 - Finite Element Mesh of the 3D Model for Investigating Active Isolation Case using Linear Trench Barrier
A time increment must be selected such that numerical stability and accuracy is maintained. For the models to produce accurate results, the time increments must be quite small so that the accelerations are nearly constant during an increment. A time increment should be selected based on element dimensions, as shown in Equation 4.1 (Valliappan and Murti, 1984).

\[
0.1g/V_P < t < g/V_P
\]

Where \( t \) is characteristic time; \( g \) is mesh dimension and \( V_P \) is compression wave velocity. For this study, the ABAQUS automatic time increments option was used to satisfy Equation 4.1 while numerical convergence was achieved. For an element size of 25cm, the time increment selected was \( 10^{-6} \) sec.
4.1.3 Material Properties

Dynamic material properties such as shear wave velocity, bulk density, Poisson’s ratio, and material damping ratio are important parameters in wave propagation within a half space phenomenon. Among those parameters, shear wave velocity is the most critical (Al Hussaini 1992, Haupt 1978, and others). The performance of in-filled trench barriers is highly dependent on the ratio of shear wave velocity for fill material and native soil. Therefore, as part of the experimental program, shear wave velocity measurements were made using the SASW method. The SASW method is described in detail in Chapter 5. Prior to installation and testing of the trench barriers, shear wave velocity measurements were made for soil and tire shreds to ensure realistic shear wave velocity values were used in the numerical model. Shear wave velocity of 200m/s for the native soil and 18 to 33m/s for small (50mm) and large (200mm) tire shreds were measured. For the parametric study, a shear wave velocity of 18m/s was used for tire shreds, since measurements within small tire shreds were more consistent. The Rayleigh wave velocities assigned to soil and tire shreds were 184m/s and 16.5m/s, respectively.

For Poisson’s ratio and bulk density, values recommended in the literature were used for the models, as detailed in Chapter 5. For the material damping ratio, the relationship between the damping ratio and Rayleigh damping parameters, as shown in Equation 4.2, was used. The Rayleigh damping parameters provide a linear material attenuation.

\[ D = \frac{\eta_1}{2\omega} + \frac{\eta_2\omega}{2} \]  

Where D is the damping ratio, \( \eta_1 \) is mass damping parameter, \( \eta_2 \) is stiffness damping parameter, and \( \omega \) is circular frequency. In the Rayleigh damping approach, mass and stiffness constants are defined to produce an average damping ratio within a bounded
frequency range. In this study, an average damping ratio of approximately 5 percent for the frequency range of 20Hz to 160Hz was used. Natural frequency of the system was determined using linear perturbation frequency analysis in ABAQUS. Rayleigh damping parameters used in the models were $\eta_1=3.466$ and $\eta_2=9.60E-05$. Variations of damping ratio with frequency are shown in Figure 4.13.

![Figure 4.13 - Damping Ratio and Frequency Relationship for the Range of Frequencies used in this Study](image)

### 4.2 Model Validation

The developed 2D and 3D numerical models had to be validated before use in the parametric study. The validation of the 2D models involved analyzing passive and active isolation problems and comparing those results with the results of reference models developed by others analyzing the same problem. Adjustments were made to the the model as necessary.

For the validation of the 3D model, the vibration amplitude attenuation curves produced by the 3D model were compared against actual field measurements.
The process of validation for the 2D and 3D models is described in further detail below.

4.2.1 2D Model Validation

The model was validated using 2D finite element models developed by Kattis et al. (1999), Alzawi and El Naggar (2011), Ahmad and Al-Hussaini (1991) for investigating active and passive vibration isolation cases using trench barriers. The validation process is further described below.

4.2.2.1 Active Isolation

The 2D model developed by Kattis et al. (1999) for investigating an active vibration isolation case was used as a reference when validating the model developed for this study. Geometrical parameters, material properties, input force, and frequency used by Kattis were adopted. The soil was modeled as an elastic, isotropic half-space with shear modulus, $G=132$ MPa, Poisson’s ratio, $\nu=0.25$, mass unit weight, $\rho=17.5$ kN/m$^3$ and Rayleigh damping ratio of $\xi=5\%$.

The source of excitation was modeled as a vertical harmonic load of 1.0kN in magnitude with a frequency of 50Hz, as shown in Figure 4.14. A Rayleigh wave velocity of 253m/s and a wavelength of 5m, corresponding to 50Hz frequency, was used. The normalized trench depth, width, and distance to vibration source were 0.5, 0.06, and 0.4, respectively. The FEM model mesh is shown in Figure 4.15. As shown in Figure 4.16, the results produced by the model are in good agreement with those reported by Kattis and by Alzawi and El Naggar.
Figure 4.14 - Harmonic Vertical Vibration used in the Reference Study
Kattis et al. (1999)

Figure 4.15 - FEM Mesh used for Model Validation
4.2.2.2 Passive Isolation

For the passive isolation case, an Ahmad and Al-Hussaini (1991) reference model was used for validating the 2D model. The soil was modeled as an elastic, isotropic half-space with shear modulus, \( E = 46 \text{ MPa} \); Poisson’s ratio, \( \nu = 0.25 \); mass density, \( \rho = 18 \text{ kN/m}^3 \) and Rayleigh damping ratio of \( \xi = 5\% \). The applied load was modeled as vertical harmonic vibrations with a magnitude of 1.0 kN and with a frequency of 31 Hz, as shown in Figure 4.17. Rayleigh wave velocity and wavelength were assumed as 93 m/s and 3.0 m, respectively. Normalized trench depth, width, and distance from the vibration source were 1.0, 0.1, and 5, respectively.

As shown in Figure 4.18, the results produced by the 2D plain strain model are in good agreement with the Ahmad and Al-Hussaini and Alzawi and El Naggar models.
Figure 4.17 - Harmonic Loading for the Passive Isolation, Comparative Study with Ahmad and Al-Hussaini (1991)

Figure 4.18 - Symmetric FEM Mesh of Passive Isolation
Figure 4.19 - Amplitude Reduction Ratio for Passive Isolation, Comparative Study with Ahmad and Al-Hussaini (1991), Alzawi and El Naggar (2011)

4.2.3 3D Model Validation

To validate the 3D model, the normalized soil particle velocity attenuation curves produced by the 3D model were compared with the normalized attenuation curves obtained from field measurements. Field measurements were made prior to installation of the trench barriers in order to produce attenuation curves for free-field conditions so that the level of screening achieved after trench installation could be gauged. For the soil and tire shreds, dynamic properties used in the numerical model and measurements of shear wave velocity determined by the SASW method were adopted. For other dynamic properties such as damping ratio, Poisson’s ratio, and bulk density, typical values from the literature were adopted, as presented in Chapter 5. The values used in the model were as follows: shear wave velocity $V_s = 200\text{m/s}$ for soil and $18\text{m/s}$ for tire shreds, Poisson’s ratio, $\nu = 0.25$ for soil and $\nu = 0.3$ for tire shreds, mass density $\rho = 1,800\text{kg/m}^3$ for soil and $\rho = 600\text{kg/m}^3$ for tire shreds, and Rayleigh damping ratio of $\xi = 5\%$. 
Figure 4.20 through Figure 4.22 show the field measured attenuation curves and the 3D model results for vertical vibration frequencies of 20, 40, and 80Hz. It was noted that the field and the numerical model results are in good agreement, therefore the 3D model can be used for the parametric study with confidence. Minor discrepancies observed between the results could stem from soil layering and the non-homogeneity of native soil; soil was assumed to be isotropic and homogenous in the model.

![Figure 4.20 - Attenuation Curves from Field Measurements and the 3D Numerical Model (Vertical Vibrations, f=20Hz)](image-url)
Figure 4.21 - Attenuation Curves from Field Measurements and the 3D Numerical Model (Vertical Vibrations, f=40Hz)

Figure 4.22 - Attenuation Curves from Field Measurements and the 3D Numerical Model (Vertical Vibrations, f=80Hz)
4.3 Preliminary Parametric Study

A preliminary parametric study examined the influence of geometrical dimensions on in-filled tire-shred trench barriers providing isolation of ground-borne vibrations. The results of the preliminary parametric study provided guidelines for the design of a full-scale experimental study. The influence of depth, width, location, and angular length (partial isolation) on the performance of trench barriers was investigated. The geometrical dimensions are typically normalized by Rayleigh wavelength to allow comparison of the data, independent of vibration frequency.

Among the geometrical dimensions, depth is the most critical, as reported by several researchers. The vibration velocity amplitude ratio before and after installation of the trench barrier ($A_R$) at various depths was investigated to determine the depth at which effective screening ($A_R < 0.25$) is achieved (trench width and location were kept constant). The influence of trench width, angular length, and location on the performance of the trench barrier was also investigated. The results are presented in the following sections. A comprehensive parametric study examining those parameters in more detail was carried out following completion of the experimental study; those results are presented in Chapter 6.

The 2D axisymmetric model was used for investigating the influence of normalized depth $D (=d/\lambda_R)$ and location $X (=x/\lambda_R)$ in the case of active isolation. The influence of angular length had to be investigated in 3D. It was demonstrated, however, that when investigating the influence of trench geometrical dimensions, the results of the 2D axisymmetric model and the 3D model were in good agreement, as shown in section 4.3.1. Hence, using the 2D model was preferable as it saved computational time.
4.3.1 2D Versus 3D Model

The wave propagation phenomenon in a half space is 3D in nature, and is better modeled in 3D. Al Hussaini and Ahmad (1996) reported that for active vibration isolation due to the presence of body waves at the vicinity of the trench barrier, a 3D analysis is required. For passive vibration isolation, the common opinion is that the Rayleigh waves are dominant in plane form, thus a 2D plane strain model can adequately analyze passive isolation cases.

The results of an active isolation case analyzed by both 2D and 3D models were compared to explore the feasibility of using the 2D model to cut down on the computational time required to run the 3D model. If the 2D model proved adequate, use of the 3D model would be limited to investigating the influence of trench annular or linear length in the limits of the screened zone behind the trench.

The normalized velocity amplitude attenuation curves for free-field, open and in-filled trenches were produced by the 2D and 3D models. The trenches were placed at distances of 2.4m and 4.2m from the excitation source. The trench depth and width were 2.9 and 1.2m, respectively. The soil was modeled as elastic, isotropic, and homogeneous half space with shear wave velocity $V_S=200$ m/s, soil Poisson's ratio, $\nu=0.25$; soil mass density, $\rho=1,800$ kg/m$^3$; and Rayleigh damping ratio of $\xi=5\%$. For tire shreds, $V_S=18$ m/s and $\nu=0.3$ was adopted. Vertical oscillations frequencies of 20, 40 and 50Hz were utilized.

The results, which are shown in Figure 4.23 through Figure 4.26, indicate that the 2D and the 3D model results are in good agreement. There are minor differences in the amplitudes near the trench; however, the post trench measurements match closely. Therefore, the 2D model was used with confidence for performing the parametric study to investigate the influence of geometrical dimensions of the barrier as well as the material properties of
native soil in active isolation cases. The 3D model had to be used for investigating the effect of trench annular or linear length.

Figure 4.23 - Attenuation Curves from 2D and 3D Numerical Models for Free-field ($f=20\text{Hz}$)

Figure 4.24 - Attenuation Curves from 2D and 3D Numerical Models for Free-field ($f=40\text{Hz}$)
Figure 4.25 - Attenuation Curves from 2D and 3D Numerical Models for open trench
(f=40Hz, x=2.4m, w=1.2, d=2.8m)

Figure 4.26 - Attenuation Curves from 2D and 3D Numerical Models for In-filled trench
(f=50Hz, x=4.2m, w=1.2m, d=2.8m)
4.3.2 Normalized Depth

The influence of normalized depth \( D = \frac{d}{\lambda_R} \) on the vibration screening effectiveness of open and in-filled tire-shred circular trench barriers was investigated; the results are shown in Figure 4.27 and Figure 4.28. The 2D axisymmetric FE model was used for the analysis. The vibration frequencies used were 40Hz and 80Hz. The trench distance from the vibration source to the inside edge of the trench barrier was 2.4m, corresponding to the normalized distance of \( X = \frac{x}{\lambda_R} = 0.55 \) (at 40Hz) and \( X = 1.1 \) (at 80Hz) resembling the active isolation case. The trench width was 1.2m, corresponding to normalized widths \( W = \frac{w}{\lambda_R} = 0.25 \) and 0.5 for the two frequencies used. The normalized width used in the analysis was relatively high to ensure that it would not influence the trench performance and the effect of D could be independently investigated. Native soil dynamic properties were the same as in Section 4.3.1. Material damping, elastic modulus, and Poison’s ratio for the tire shreds were 5%, 505 KPa, and 0.3, respectively.

Figure 4.27 and Figure 4.28 show that open or in-filled trench barriers are generally very effective at screening vibrations. A reduction in vibration amplitude of approximately one order of magnitude was achieved for trenches with \( D \) higher than 0.8. For a shallower trench \( (D=0.4) \), however, the screening was not as effective. The optimum normalized depth, defined as the depth for which amplitude reduction factor \( A_{R_i} \) of 0.25 or less is achieved, had to be further investigated. This was done during both the experimental investigation and the parametric study; the results are presented in Chapters 5 and 6. Since safety dictated that the depth of the trench barrier in the field could not exceed 1.5m without excavation support, the frequency of the vertical excitations varied from 20Hz to 160Hz, corresponding to \( D = 0.15 \) to \( D = 1.2 \), so that a wide range of \( D \) could be investigated.
Figure 4.27 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Normalized Depths (f=40Hz, x=2.4m, w=1.2m)

Figure 4.28 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Normalized Depths (f=80Hz, x=2.4m, w=1.2m)
4.3.3 Trench Barrier Width and Location

The influence of the trench barrier’s width and location on its performance in screening vibrations was investigated. Trench width influences the performance of in-filled trenches, but is not as important for open trenches (Woods 1968, Ahmad and Al-Hussaini, 1996). Ahmad and Al-Hussaini also reported that the influence of width applies primarily to trenches with normalized width $W$ less than 0.3. The effect of width and location on the performance of an in-filled tire-shred barrier is shown in Figure 4.29 and Figure 4.30. Vibration amplitude attenuation curves for free-field and for open and in-filled trenches (widths of 0.6m and 1.2m) are presented. The trench depth was kept constant at 2.8m ($D=0.6$) so the effect of width and trench location could be independently studied. The material properties of soil and tire shreds, and the frequency of the vibrations, remained the same as in Section 4.3.2.

As shown in Figure 4.29 and Figure 4.30, the influence of trench width in the attenuation of vibrations for $W$ of 0.13 to 0.26 is not significant for either of the frequencies investigated (40Hz and 80Hz). Therefore, the trench width adopted was 1.2m for frequencies of 20Hz to 160Hz, corresponding to $W$ in the 0.11 to 0.9 range.

With regard to the influence of trench location, the effectiveness of a trench located at 1.2m and 2.4m (corresponding to normalized distance $X=0.27$ and $X=0.54$) was investigated. Normalized depth of 0.6 and width of 1.2m was adopted. As shown in Figure 4.31 and Figure 4.32, more effective screening is achieved for $X=0.27$ at 40Hz frequency, but the difference in screening effectiveness between the two distances at 80Hz is insignificant. The influence of trench location was investigated in more detail, and the results are presented in Chapter 6. For practical reasons, the trench distance to the excitation source was maintained at 2.4m during the experimental investigation.
Figure 4.29 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Widths (f=40Hz, x=2.4m, D=0.8)

Figure 4.30 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Widths (f=80Hz, x=2.4m, D=0.8)
Figure 4.31 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Trench Distances ($f=40\text{Hz}$, $D=0.8$, $w=1.2\text{m}$)

Figure 4.32 - Attenuation of Vibration Velocity Amplitude vs. Distance for Open and In-filled Trench Barriers at various Trench Distances ($f=80\text{Hz}$, $D=0.8$, $w=1.2\text{m}$)

4.3.4 Partial Isolation

The performance of semi-circular and linear trench barriers in screening vibrations was numerically investigated. The 3D model was utilized to delineate the limits of the area
behind the trench hat is effectively screened ($A_R < 0.25$). Soil dynamic properties used in the analysis were the same as those described in Section 4.3.2.

### 4.3.4.1 Semi-circular Trench

The level of vibration screening achieved behind an open semi-circular trench barrier is shown in Figure 4.33. The shaded areas bound by the contour lines show the ratio of soil surface particle velocity amplitude prior to and after installation of the trench barrier ($A_R$). The excitation source, placed at the center of the circle, generated vertical harmonic vibrations at 40Hz. The trench inside radius, depth, and width were 2.5m, 2.7m, and 1.2m, respectively (corresponding to $X$, $D$, and $W$ of 0.55, 0.6, and 0.25). It was observed that effective screening is not achieved at the edges and at some distance towards the centerline of the trench, due to the “edge effect.” For comparison, Figure 4.35 shows the amplitude reduction in front of and behind a circular trench barrier with the same radius and normalized depth, for which more effective screening is achieved.

Woods (1968) reported that the screened zone by partial trench (area outside the trench extended to 10$\lambda_R$) was bounded on the sides by radial lines from the center of the vibration source through points $45^\circ$ from the ends of the trench. A similar result was obtained in this study, as shown in Figure 4.33, where a line connecting the excitation source to the 0.25 contour line makes an approximately $45^\circ$ angle with the line passing through the end edge of the trench. Screening is more effective for the 80Hz frequency, as shown in Figure 4.34, since $D$ is doubled and high frequency vibrations attenuate faster. For the circular trench barrier (full isolation), however, effective screening is achieved for the entire area behind the trench. The amplification of vibrations was observed in front of the trench, due to the reflection of waves at the interface of the soil and the trench. The performance of open and in-filled semi-circular trench barriers was investigated comprehensively in 3D during
the experimental study and the parametric study; the results are presented in Chapters 5 and 6.

*Figure 4.33 - Amplitude Reduction Factor behind Open Semi-circular Trench (f=40Hz, D=0.6, X=0.55, W=0.25)*

*Figure 4.34 - Amplitude Reduction Factor behind Open Semi-circular Trench (f=80Hz, D=1.20, X=1.1, W=0.5)*
4.3.4.2 Linear Trench

A case of active partial vibration isolation by a linear trench barrier was investigated. The trench length and depth were 5.5m and 2.7m, corresponding to normalized length $L=1.2$ and normalized depth $D=0.6$ for a vibration frequency of 40Hz. The distance between the barrier and the excitation source was 2.4m or normalized distance $X=0.5$. Similar to the semi-circular trench barrier case, the “edge effect” was observed near the edges of the linear trench barrier, as shown in Figure 4.36. As in the case of the the semi-circular trench, the effectively screened area behind the trench is some distance away from the trench edge, for both frequencies. Further experimental and numerical investigation was performed to delineate the limits of the screened area more accurately; the results are presented in Chapters 5 and 6.
Figure 4.36 - Amplitude Reduction Factor behind Open Linear Trench \((f=40\text{Hz}, D=0.6, X=0.55, W=0.25)\)

Figure 4.37 - Amplitude Reduction Factor behind Open Linear Trench \((f=80\text{Hz}, D=0.6, X=0.55, W=0.25)\)
4.4 Design of Experimental Program

Based on the findings of the preliminary parametric study, the experimental program was designed such that a) the findings of the preliminary parametric study was validated in full-scale and in 3D, and b) scenarios that could not be investigated numerically were investigated in the field. For example, the influence of size (50mm vs. 200mm) on the screening effectiveness of tire shreds as an isolation medium could not be examined numerically, since the available information on their dynamic properties was limited. Other geometrical dimensions that required full-scale investigation and were included in the scope of the experimental investigation are described below. More details related to the design of the experimental study are presented in Chapter 5.

4.4.1 Trench Depth

It was shown in the preliminary parametric study that normalized depth (D) is the key parameter governing the performance of open and in-filled trench barriers providing active isolation of vibrations. It was further shown that the trench barrier is effective for D larger than 0.6. For active isolation using circular trench barriers, due to the coexistence of body and surface waves and the reflection and refraction of those at and near the trench, the wave propagation phenomenon is rather complicated. It was determined that a full-scale 3D experimental investigation could provide realistic measurements of the vibrations and better evaluate the performance of the trench barriers. During the experimental investigation, the trench depth could not exceed 1.5m, otherwise excavation support would be necessary for safety reasons. Therefore, a vibration frequency in the range of 20Hz to 160Hz, corresponding to D ranging from 0.15 to 1.2, was adopted so that the influence of various normalized depths could be investigated.
4.4.2 Trench Width

It was demonstrated that width has a marginal effect on the screening effectiveness of open or in-filled trench barriers. A trench width of 1.2m was adopted in the experimental study to allow for the placement of a geotextile separator at the bottom and the sidewalls of the trench and for proper placement of large-size (200mm) tire shreds. The adopted width is large enough that the influence of other parameters, such as depth, angular length, and location can be investigated independent of width.

4.4.3 Trench Barrier Location

A minimum distance of 2.4m had to be maintained between the excitation source and the trench for practical reasons. Active isolation cases were investigated with the frequencies used in the experimental investigation, i.e., in the 20Hz to 160Hz range, corresponding to normalized distance range of $X=0.27$ and $X=2$.

4.4.4 Partial Isolation

The effect of trench angular length (circular, semi-circular, and linear) on the limits of the screened area behind the trench barrier was studied numerically in 3D, as discussed in section 4.3.4. A verification of the findings in full-scale was carried out both experimentally and numerically; the results are presented in Chapters 5 and 6.

4.5 Summary and Conclusions

A numerical investigation examined the influence of geometrical dimensions on open and in-filled tire-shred trench barriers providing active isolation of ground-borne vibrations. On
the basis of the numerical investigation, guidelines for preparing the scope of the experimental investigation and parametric study were determined.

The geometrical dimensions investigated included depth, width, and trench location for circular (full isolation), semi-circular and linear (partial isolation) barriers. Two-dimensional (axisymmetric and plane strain) and three-dimensional numerical models were developed using the finite element package ABAQUS for the numerical investigation. The models were calibrated using reference published models developed by others. The 2D axisymmetric model was used for investigating the influence of geometrical dimension on full isolation cases, while the 3D model was used for investigating partial isolation cases.

Among the geometrical dimensions, trench depth was found to be the key parameter governing the performance of trench barriers. It was demonstrated that normalized trench depth higher than 0.6 is required for effective screening ($A_R < 0.25$). The influence of trench width for open or in-filled trenches is less significant. In terms of trench location for the two distances investigated, the screening was more effective for $X=0.27$ than for $X=0.55$, but only in the case of lower frequency (40Hz vs. 80Hz).

For partial isolation cases, the limits of the effectively screened zone behind the trench barrier were delineated. For semi-circular trench barriers, it is bound between the line going through the centerline and the line 45° from the edge of the trench. Although the same effect was observed for the linear trench and the semi-circular trench, further analysis was required to accurately delineate the limits of the effectively screened area for the linear trench.

The scope of the experimental investigation was designed based on findings from the numerical study. A comprehensive parametric study was then carried out, following completion of the experimental investigation, to further examine the influence of
geometrical dimensions and material properties on the screening effectiveness of in-filled trench barriers.
CHAPTER FIVE

EXPERIMENTAL INVESTIGATION

This chapter presents the experimental program for investigating the performance of in-filled tire-shred trench barriers in screening ground-borne vibrations. Experiment design, test site location and conditions, material properties, instrumentation employed, and the findings are discussed in detail. The performance of open and in-filled tire-shred trenches were monitored in 3D to examine the effectiveness of tire shreds as an isolation medium in comparison with air. The effects of full isolation by circular trench versus partial isolation achieved by semi-circular and linear trenches was also studied.

5.1 Experimental Investigation Design

The experimental investigation was designed so that the influence of geometrical dimensions, angular length, and tire-shred size on the performance of trench barriers could be investigated in 3D.

Trench barriers as a means of vibration screening have been investigated by many researchers (as described in Chapter 2) through laboratory scale tests or numerical modeling, and on a few occasions through full-scale testing. Full-scale studies are costly and require large test areas. For this study, because of the size of the tire shreds used (50mm and 200mm), a full-scale investigation was required to properly assess the performance of the tire shreds as an isolation medium. The rationale for selecting tire shreds in these sizes was determined by market availability and associated shredding
cost. Smaller sized tire shreds, while more expensive to produce do not necessarily provide more effective isolation, as shown in this study.

In this study, open and in-filled trenches with three different angular lengths, circular (full isolation), semi-circular and linear (partial isolation) were employed to a) investigate the effectiveness of tire shreds as an isolation medium in 3D (vertical, longitudinal and transverse directions), and b) investigate the influence of angular length on the limits of the screened zone behind the trench barrier (full and partial isolation). Trench depth was maintained at 1.35m, since excavation support is required for trenches deeper than that. To examine the effect of tire shred size (50mm and 200mm) on trench performance, one half of each trench (from the bottom to the top) was filled with each tire size.

Vibration frequencies used during the field experiments were in the 20Hz to 160Hz range: the lower frequencies representing train or traffic from heavy vehicles, and the higher frequencies representing machine foundation vibrations. Moreover, a wide range of normalized depths and widths could be investigated for this range of frequencies. The source of excitation generating vertical time harmonic vibrations was placed at 2.4 meters from the trenches, thus simulating an active (near-field) isolation scenario, primarily for the lower frequencies. Readings of vibration velocity amplitudes in 3D were taken prior to installation of the trenches (free-field) and after the installation of the trenches, so the amplitude reduction factor $A_r$, could be determined. Post trench installation readings were taken for open and in-filled trenches. Free-field readings were also used in the numerical study, as described in Chapter 4, for validating the 3D numerical model.

Shear wave velocity is a key parameter in wave propagation and governs the reflection, refraction, and transmission of waves at the interface of the soil and the trench barrier. Therefore, the scope of the experimental program included in-situ measurement of shear
wave velocity in native soil and tire shreds using the SASW method. The measured shear wave velocities were utilized in the numerical model, as described in Chapter 4.

5.1.1 Experiment Site Location/Trench Construction

The test site was located in East Brunswick, Middlesex County, New Jersey. Prior to the testing, the test site was grubbed and cleared from vegetation, as shown in Figure 5.1a. The top 0.6m of native soil consisted of stiff brown clay/sandy clay underlain by silty sand. The soil profile within the top 1.5m is shown in Figure 5.1b. A conventional excavator, as shown in Figure 5.2, excavated the trenches.

![Figure 5.1a - Test site after Grubbing and Clearing](image)

![Figure 5.1b - Native Soil Profile](image)

The dimensions of the installed trenches are shown in Table 5.1. A trench width of 1.2m was required to allow for proper placement of the 200mm tire shreds and the geotextile fabric. As shown in Figure 5.3a, a separator geotextile fabric was placed to cover the bottom and sidewalls of the trenches prior to backfilling, ensuring that the tire shreds and the native soil would not mix. A conventional front loader filled the trenches with tire shreds, as shown in Figure 5.3b.
<table>
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<th>Trench Configuration</th>
<th>Depth (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Inside Radius/Outside Radius (m)</th>
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</thead>
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<td>5.5</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Circular</td>
<td>1.35</td>
<td>--</td>
<td>--</td>
<td>2.4/ 3.7</td>
</tr>
<tr>
<td>Semi-circular</td>
<td>1.35</td>
<td>--</td>
<td>--</td>
<td>2.4/ 3.7</td>
</tr>
</tbody>
</table>

*Table 5.1 - Dimensions of the Trenches in the Experimental Study*

![Excavation of Trenches using Conventional Excavator](image)

*Figure 5.2 - Excavation of Trenches using Conventional Excavator*

As shown in Figure 5.4a and Figure 5.4b, two sizes of tire shreds, 50mm and 200mm, were used as backfill. One half of each trench (from bottom to the top) was filled with 50mm and the other half with 200mm tire shreds, as shown in Figure 5.5a and Figure 5.5b. Tire shreds were placed inside the trenches with nominal compaction effort. The bulk density assigned to the tire shreds in the numerical model was based on the values published in the literature for loose tire shreds, as described in the following sections.
Figure 5.3a – Placement of geotextile separator

Figure 5.3b – Backfilling of trenches with tire shreds using front loader

Figure 5.4a - 50mm tire shreds

Figure 5.4b - 200mm tire shreds
Shear wave velocity in tire shreds and the native soil was measured by the SASW method. In order to perform the SASW test on the tire shreds, two pits (one for each tire size), 6.5m long, 3m wide, and 0.9m deep, were excavated and filled with tire shreds, as shown in Figure 5.6a and Figure 5.6b. Receiver/impact points were spaced at 0.6m and 1.2m to ensure wave propagation velocity was measured through only the upper 1m, consisting of tire shreds.
5.1.2 Instrumentation

The equipment used for the field-testing consisted of

- Long stroke vibrating mass shaker generating sinusoidal waveforms
- 1D and 3D geophones
- Signal amplifier
- Signal Analyzer

The source of vertical time harmonic excitations was an APS 400 Electro-seis long stroke vibrating mass shaker. Harmonic vertical loading within the frequency range of 20Hz to 160Hz was generated during the field experiments. To ensure proper contact, the shaker was directly placed on the ground surface after the soil surface at the footprint was leveled and cleared from large gravel or debris. An APS 125 model amplifier was used to amplify the signals generated by the signal analyzer before transmitting the signals to the shaker.

Soil vibration velocity amplitudes were measured by a 3D geophone seismometer. The 3D geophone readings were normalized by the readings of the single vertical geophone (placed 4m away from the shaker) to account for the variation in input force due to frequency changes. Photos of the shaker and the 1D and 3D geophones are shown in Figure 5.7. As shown in Figure 5.11, measurements were taken in front of and behind the trenches, starting from 0.6m to 12m from the shaker, at 0.6m intervals and along a number of arrays. Pictures of the signal analyzer and the amplifier used in this study are shown in Figure 5.8.

At each measurement station, 256 data points were collected within a 0.5s span and in three perpendicular directions. A sufficient number of cycles was captured within the selected time span, therefore a longer period of data collection was not necessary considering the storage capacity limitations of the signal analyzer.
5.2 Experimental Study Parameters

5.2.1 Material Properties

The key dynamic material property affecting the performance of in-filled trench barriers is the ratio of shear wave velocity of tire shreds over the native soil. This ratio is also referred to as *Impedance*, which relates the stiffness or softness of backfill material to the native
soil. For a soft barrier, impedance is less than one; for stiff barriers, it is higher than one. For an open trench, the impedance value is zero, since the shear wave velocity of air is zero. The impedance for soil and tire shreds, assuming velocities of 200m/sec and 18m/sec, is 0.07. Therefore, in-filled tire-shred trench barriers are expected to perform almost as effectively as open trenches. This is demonstrated in Section 5.3, where the experimental results are presented and discussed.

Because impedance is a critical factor affecting the performance of in-filled trench barriers, the scope of the experimental investigation included measuring the shear wave velocity of tire shreds and native soil using the SASW method. Other material properties, such as bulk density, Poisson’s ratio, and material damping ratio, are less critical. Therefore, recommended values from literature, as presented below, were adopted and used in the numerical modeling.

The Spectral Analysis of Surface Waves (SASW) is a non-destructive and fast method widely used for determining shear wave velocity in soil or pavement. In this method, transient impulses with different frequencies are applied to the surface generating waves. Two receivers (vertical geophones) located on the ground surface at predetermined spacing capture the vibrations and transmit them to a signal analyzer.

In the next step, cross power spectrum and phase angle information is produced. By knowing the spacing between the geophones, phase velocity for each frequency can be calculated. It is recommended that the receiver spacing vary from 1/3 to 2 times the desired wavelength (Heisey 1981).

With this information, a dispersion curve, which shows a plot of phase velocity versus wavelength can be constructed. By applying an inversion process to the dispersion curve, a shear wave velocity profile can be produced. Several processes were developed to
perform the inversion (Heisey 1982 and Nazarian, 1984); however, this process is currently fully automated. Once shear wave velocity (which is the key input for the numerical models) is determined, shear modulus can be calculated using Equation 2.3.

In the SASW test, the distance between each pair of receivers and the impact point was 0.6m in one set of testing, and 1.2m in the other set. For data processing, the program Matlab was used to generate the dispersion curves. Using the dispersion curve and accounting for the range of frequencies used in this experimental program, a shear wave velocity of 200m/sec was assigned to the native soil. An example of a dispersion curve for the native soil is presented in Figure 5.9.

![Dispersion Curve](image)

*Figure 5.9 - Phase Velocity and Frequency Relationship in the Native Soil*

Once the shear wave velocity is estimated, the Rayleigh wave velocity (=0.91V_S) and wavelength can be determined using equation 5.1.

\[ V_R = \lambda_R f \]  

5.1
SASW tests were conducted on the tire shreds using the same process described above. The Shear wave velocity of 18m/s and 30m/s for 50mm and 200mm tire shreds were measured respectively, as shown in Figure 5.10a and Figure 5.10b. A shear wave velocity of 18m/sec was adopted, due to the consistency of the measurements in 50mm tire shreds.

![Figure 5.10a - Phase velocity for 50mm tire shreds](image1.png)  ![Figure 5.10b – Phase velocity for 200mm tire shreds](image2.png)

For unit weight or Poisson’s ratio of tire shreds, typical values provided in the literature for similar-sized tire shreds were adopted for the numerical analysis. The typical ranges of bulk unit weights for 50-76mm tire shreds in loose state under various overburden stresses are shown in Table 5.2.

As shown in Table 5.2, the bulk density of the tire shreds slightly increases with an increase in size. Vertical stress inside the trenches was less than 5kPa (trench depth limited to 1.35m), thus a bulk density of 600kg/m$^3$ was adopted for the tire shreds.

Poisson’s ratio is the ratio of vertical to lateral strain. It varies between 0 and 0.5, and is stress dependent. Ranges of Poisson’s ratio for tire shreds, as reported by several researchers, are shown in Table 5.3. Poisson’s ratio can be determined indirectly, using
vertical to horizontal stress ratio, or directly in a triaxial cell.

<table>
<thead>
<tr>
<th>Vertical Stress (kPa)</th>
<th>Bulk Density (Kg/m³)</th>
<th>Size (mm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>440-450</td>
<td>50</td>
<td>Westerberg, et al (2001)</td>
</tr>
<tr>
<td>30-50</td>
<td>500-700</td>
<td>50</td>
<td>&quot;</td>
</tr>
<tr>
<td>400</td>
<td>810-990</td>
<td>50</td>
<td>&quot;</td>
</tr>
<tr>
<td>0</td>
<td>505-600</td>
<td>≤ 38</td>
<td>Wei, et al. (1997)</td>
</tr>
<tr>
<td>0</td>
<td>580-630</td>
<td>51</td>
<td>Humphrey et al. (1997)</td>
</tr>
<tr>
<td>9</td>
<td>660-690</td>
<td>51</td>
<td>&quot;</td>
</tr>
<tr>
<td>18</td>
<td>700-730</td>
<td>51</td>
<td>&quot;</td>
</tr>
<tr>
<td>0</td>
<td>630-640</td>
<td>76</td>
<td>&quot;</td>
</tr>
<tr>
<td>9</td>
<td>720-730</td>
<td>76</td>
<td>&quot;</td>
</tr>
<tr>
<td>18</td>
<td>780-790</td>
<td>76</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

*Table 5.2 - Bulk Density of Tire Shreds*

Poisson's ratio of 0.3, as recommended by Edil and Bosscher (1992) and Yang et al. (2002) for the type of tire shreds used in this study, was adopted for the numerical analysis.

A parametric study to demonstrate the influence of material properties on the performance of tire-shred filled trenches is presented in Chapters 6.
<table>
<thead>
<tr>
<th>Stress (kPa)</th>
<th>Size (mm)</th>
<th>Poisson's Ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Stress</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>30</td>
<td>0.45</td>
<td>Humphrey et al. (1993)</td>
</tr>
<tr>
<td>110</td>
<td>38</td>
<td>0.32</td>
<td>Humphrey and Sandford (1993)</td>
</tr>
<tr>
<td>110</td>
<td>51</td>
<td>0.2</td>
<td>“</td>
</tr>
<tr>
<td>110</td>
<td>51</td>
<td>0.3</td>
<td>“</td>
</tr>
<tr>
<td>110</td>
<td>76</td>
<td>0.28</td>
<td>“</td>
</tr>
<tr>
<td>Confining Stress</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>50</td>
<td>0.27</td>
<td>Edil and Bosscher (1992)</td>
</tr>
<tr>
<td>12</td>
<td>50</td>
<td>0.3</td>
<td>“</td>
</tr>
<tr>
<td>18</td>
<td>50</td>
<td>0.17</td>
<td>“</td>
</tr>
<tr>
<td>280</td>
<td>50</td>
<td>0.45</td>
<td>Newcomb and Drescher (1994)</td>
</tr>
</tbody>
</table>

*Table 5.3 - Poisson's Ratio of Tire Shreds*

### 5.2.2 Geometrical Dimensions

Geometrical dimensions such as trench depth, location, and angular length directly affect the performance of trench barriers. Using the dimensions provided in Table 5.1, the normalized geometrical dimensions for the three trench types studied are listed in Table 5.4 and shown in Figure 5.11a, 5.11b and 5.11c.
Figure 5.11a - Circular Trench Geometry and Data Collection Points

Figure 5.11b - Semi-circular Trench Geometry and Data Collection Points
Table 5.4 - Normalized Geometrical Parameters

<table>
<thead>
<tr>
<th>Trench Geometry</th>
<th>Frequency (Hz)</th>
<th>Rayleigh Wavelength $\lambda_R$, m</th>
<th>Trench Normalized Depth $D=d/\lambda_R$</th>
<th>Trench Normalized Width $W=w/\lambda_R$</th>
<th>Normalized Location $X=x/\lambda_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear/</td>
<td>20</td>
<td>9.2</td>
<td>0.15</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Circular/</td>
<td>40</td>
<td>4.6</td>
<td>0.3</td>
<td>0.22</td>
<td>0.52</td>
</tr>
<tr>
<td>Semi-circular</td>
<td>80</td>
<td>2.3</td>
<td>0.6</td>
<td>0.44</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>1.15</td>
<td>1.2</td>
<td>0.88</td>
<td>2.08</td>
</tr>
</tbody>
</table>

5.2.3 Data Processing and Validation

During the experimental study, the quality of recorded data had to be examined to ensure it was not adversely affected by background noise.
Soil particle velocity, induced by harmonic vertical loading of the shaker (at frequencies of 20, 40, 80 and 160Hz), was recorded in 3D in time domain at each pick-up point. These velocities were subsequently converted to frequency domain, using Fast Fourier Transformer. If frequencies other than those generated by the shaker were observed in the recordings, they were filtered out. The cleaned signal was converted to time domain for further analysis. Using the Matlab program, this process was applied to all collected data. The filtered peak particle velocity amplitudes were subsequently used to calculate the amplitude reduction factor $A_R$ and the average amplitude reduction ratio, $\bar{A}_R$. Examples of the data filtering process are shown in Figure 5.12a and 5.12b.

![Figure 5.12a - Noisy and Filtered 160Hz Signal](image)
5.3 Experimental Investigation Results and Evaluation

The results of the experimental investigation are presented and analyzed in this subchapter. To evaluate the vibration screening performance of in-filled trench barriers, the average surface velocity amplitude reduction factor behind the trench, $\bar{A}_R$, was calculated. A trench barrier is considered effective if $\bar{A}_R$ is less than 0.25 (Woods 1968). The relationship between $\bar{A}_R$ and a) normalized trench depth $D$, and b) a normalized trench cross sectional area in the wave propagation direction $A_B (= D \times W)$ are presented herein.

The relationship between $D$ and $\bar{A}_R$ for $D$ ranging from 0.15 to 1.2 for the three trench geometries is shown in Figure 5.13 through Figure 5.21. The smallest $D$ that can satisfy the effective screening criteria is desired. In the case of a circular trench barrier or in the case of vertical vibrations, $D$ should be larger than 0.6 to achieve the $\bar{A}_R$ value of 0.25 or less, as shown in

![Figure 5.12b - Noisy and Filtered 20Hz Signal](image)
Figure 5.13. Woods (1968) reported that D larger than 0.6 is required for effective vibration screening in active isolation cases. For longitudinal and transverse vibrations however, as shown in

*Figure 5.14 and Figure 5.15*, an $\overline{A_R}$ value of 0.25 can be achieved once D exceeds 0.4. In the case of the circular trench, screening effectiveness is not much improved by D values higher than 0.4. It was also noted that the 50mm and 200mm tire shreds were equally effective isolators, and that the open and in-filled circular trenches were equally effective. Figure 5.16, Figure 5.17 and Figure 5.18 show the relationship of D and $\overline{A_R}$ behind the linear trench barrier for vibrations in the vertical, longitudinal, and transverse directions. It was noted that the barrier is effective for vibrations in all directions if D is 0.6 or higher. Taking into account margins of error for the testing, it was also noted that the difference in performance between open and in-filled trenches was negligible, and that 50mm and 200mm tire shreds were equally effective.

Finally, in the case of a semi-circular trench barrier (similar to the other two geometries and as shown in Figure 5.19 through Figure 5.21), the trench barrier is effective for vibrations in all directions once D exceeds 0.6. For the semi-circular trench barrier, the field-collected data along the array through the 200mm tire shreds were poor in quality and therefore are not presented.
Figure 5.13 - Influence of Normalized Circular Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_R$ for Vertical Vibrations

Figure 5.14 - Influence of Normalized Circular Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_R$ for Longitudinal Vibrations
Figure 5.15 - Influence of Normalized Circular Trench Depth ($D$) on Amplitude Reduction Factor, $A_R$ for Transverse Vibrations

Figure 5.16 - Influence of Normalized Linear Trench Depth ($D$) on Amplitude Reduction Factor, $A_R$ for Vertical Vibrations
Figure 5.17 - Influence of Normalized Linear Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_R$ for Longitudinal Vibrations

Figure 5.18 - Influence of Normalized Linear Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_R$ for Transverse Vibrations
Figure 5.19 - Influence of Normalized Semi-circular Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_r$ for Vertical Vibrations

Figure 5.20 - Influence of Normalized Semi-circular Trench Depth (D) on Amplitude Reduction Factor, $\bar{A}_r$ for Longitudinal Vibrations
In addition to normalized depth, the influence of the normalized cross section on the performance of trench barrier was investigated. A normalized cross section (in the direction of wave propagation) of a trench barrier \( (A_b) \) is the product of normalized trench depth \( D \) and normalized width \( W \) \( (d.w/\lambda R^2) \). While the influence of \( A_b \) is expected not to differ much from the normalized depth, there are some slight differences, as demonstrated in Figure 5.22 through Figure 5.31. This is because for in-filled trenches, unlike open trenches, trench width has some influence on the effectiveness of vibration screening, as demonstrated by Al Hussaini, and Ahmad (1996), and as shown in the parametric study in Chapter 6. The normalized trench width for circular and semi-circular trenches is the difference between the inside and outside radius of the trench, as shown in Figure 5.11a, b, c and listed in Table 5.1.

Figure 5.23 through
Figure 5.25 show that the circular trench barrier is effective if the $A_B$ value is higher than 0.3 for vertical vibrations, and higher than 0.2 for longitudinal and transverse vibrations. As with linear trenches, there is marginal difference between the screening effectiveness of open and in-filled circular trenches. For a semicircular trench, as shown in Figure 5.29 through Figure 5.31, $A_B$ should be larger than 0.3 for effective screening in all three directions. Based on the findings of the experimental investigation, Table 5.5 shows the minimum $A_B$ and $D$ values for (open and in-filled) trench barriers to provide effective vibration screening.

Figure 5.26 through Figure 5.28 show the relationship between $A_B$ and $\bar{A}_R$ for open and tire-shred filled linear trench barriers in vertical, longitudinal, and transverse directions. It was noted that the trench is effective if the $A_B$ value exceeds 0.5 for vertical vibrations and 0.25 for longitudinal and transverse vibrations.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Normalized Depth (D)</th>
<th>Normalized Cross Sectional Area (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical</td>
<td>Longitudinal</td>
</tr>
<tr>
<td>Linear</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Circular</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Semi-Circular</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Table 5.5 - Minimum Normalized Depth (D) and Cross Sectional Area (A) of Trenches for Effective Screening of Vibrations in 3D*
The D and $A_B$ presented in Table 5.5 apply to open and in-filled trenches, since the difference in the $\bar{A}_R$ value was negligible for the two cases investigated in this study. Given that air is the best isolator (Rayleigh waves cannot propagate through air), open trenches are expected to be more effective than in-filled trenches. This has been demonstrated by Al Hussaini and Ahmad (1996) and others. In this study, however, the difference in screening effectiveness between open and in-filled trenches was demonstrated to be marginal. This is attributed to the high void ratio of tire shreds and deformability of the tire particles. These findings confirm that tire shreds are very effective vibration isolators.

Referring to Table 5.5, it should be noted that higher $A_B$ and D values are required for linear and semi-circular trenches (as opposed to circular trenches) to achieve effective screening. The is due to the "edge effect," since open trench barriers are less effective near the ends, resulting in an $\bar{A}_R$ increase. This is also demonstrated in Figure 5.32 and Figure 5.33. The $\bar{A}_R$ values for 20Hz and 40Hz frequencies are not considered, since the trenches were not effective at those frequencies regardless of the trench geometry.

For the semi-circular trench, the Ar value is higher, well above 0.25, for arrays 1 and 2, which are closer to the edge of the trench (refer to Figure 5.11b for the orientation of the arrays), than the Ar value for arrays 3 and 4. The same is observed for arrays 1 and 5 in the linear trench, as these pass through the end of the trench (refer to Figure 5.11c for the orientation of the arrays). It should be noted that the effectively-screened zone of semi-circular and linear trenches is only about one half of the area behind the trench and symmetrical around the array going through the center of the trench. The boundaries of the screened zone behind semi-circular and linear trenches were delineated more precisely in the numerical investigation presented in Chapter 6.
The findings of the experimental investigation were compared against the results of field tests performed by Woods (1968), Alzawi and El Naggar (2012) and the laboratory scale test of Haupt (1981), as shown in Figure 5.22. The results presented in Figure 5.22 are for vertical vibrations and were selected such that the geometrical dimensions in all cases are relatively similar so that a proper comparison of the results could be made. Site conditions, such as soil type and layering vary for each test site, which could affect the results. Nonetheless, in general, the results of field tests conducted by Woods and Alzawi/El Naggar are in good agreement with the results of this study. The laboratory scale test results published by Haupt are almost twice as high. This, however, could be attributed to the scale and boundary effects in laboratory tests. The results of the three full-scale field experiments confirm that a minimum normalized barrier depth of 0.6 is required for effective screening.

![Figure 5.22 - Comparison of Published Field and Laboratory Scale Test Results for Vibration Screening Effectiveness Open Trench Barriers with Current Study](image-url)
Figure 5.23 - Influence of Normalized Circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Vertical Vibrations

Figure 5.24 - Influence of Normalized Circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Longitudinal Vibrations
Figure 5.25 - Influence of Normalized Circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Transvers Vibrations

Figure 5.26 - Influence of Normalized Linear Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Vertical Vibrations
Figure 5.27 - Influence of Normalized Linear Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$, for Longitudinal Vibrations

Figure 5.28 - Influence of Normalized Linear Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$, for Transverse Vibrations
Figure 5.29 - Influence of Normalized Semi-circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Vertical Vibrations

Figure 5.30 - Influence of Normalized Semi-circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Longitudinal Vibrations
Figure 5.31 - Influence of Normalized Semi-circular Trench Cross Sectional Area (A) on Amplitude Reduction Factor, $\bar{A}_R$ for Transverse Vibrations

Figure 5.32 - Amplitude Reduction Factor, $A_r$ Along Data Collection Arrays for In-filled Semi-circular Trench
Amplification of vibrations in front of trenches was observed for open and in-filled trenches; examples are presented in Figure 5.34. This phenomenon was also reported by Woods (1968). The amplification of vibrations near the trench is due to the reflection of the waves at the soil-trench interface. The undesirable effects of vibration amplification should be considered in the design of trench barriers.

Figure 5.33 - Amplitude Reduction Factor, Ar Along Data Collection Arrays for In-filled Linear Trench

Figure 5.34 - Magnification of Vibration Amplitude in front of Empty or In-filled Trenches
5.4 Summary and Conclusions

The experimental investigation process and results were detailed in this chapter. Open and in-filled tire-shred trench barriers were investigated in the experimental program to examine the influence of the following experimental parameters on the overall performance of in-filled trenches in providing screening of ground-borne vibrations:

a. Geometrical dimensions, such as depth and cross sectional area
b. Trench angular length, i.e., linear, circular, and semi-circular (simulating partial and full isolation)
c. Tire shreds as an isolation medium, at sizes 50mm and 200 mm

The experimental program primarily simulated the case of active isolation, since the normalized distance between the vibration source and trench was in the $0.25 < X(=x/\lambda_R) < 2$ range. The experimental study also included the in-situ measurement of shear wave velocity in the native soil and tire shreds, since shear wave velocity is the key parameter in the wave propagation phenomenon and a key input parameter for the numerical models.

The relationship between the following key parameters was established: normalized trench depth, $D$, and normalized trench cross section, $A_b$, with average amplitude reduction factor, $\bar{A_R}$. The following conclusions could be made for both open and in-filled tire-shred trench barriers, as their performance was almost equal.

For the trench geometries investigated, to effectively screen vertical vibrations, the normalized depth $D$ should exceed 0.6. The same applies to longitudinal and transverse vibrations in linear and semi-circular geometries (partial isolation), except that for circular barriers, the effective depth is 0.4 or higher.
In the case of a linear trench, $A_b$ should exceed 0.5 to provide effective screening of vertical vibrations, whereas for effective screening of longitudinal and transverse vibrations, $A_b$ should exceed 0.25. For circular trenches to be effective, $A_b$ should exceed 0.3 for vertical vibrations and 0.2 for longitudinal and transverse vibrations. Finally, semi-circular trenches are considered effective if $A_b$ exceeds 0.3 for vibrations in all directions.

Circular trench barriers, which provide full isolation, are more effective than semi-circular or linear trenches, since $\overline{A}_r$ is affected by higher $A_r$ readings toward the ends of the partial barrier (edge affect). It was observed that the screened zone for semi-circular and linear trenches is not complete, corresponding to only half of the area behind the trench and symmetrical around the array going through the center of the trench.

In-filled tire shreds trenches are as effective as open trenches in screening ground-borne vibrations. The vibration screening efficiency for 200mm and 50mm tire shreds was demonstrated to be almost the same. Therefore, using 200mm tire shreds is more cost effective due to the lower shredding cost.
CHAPTER SIX

PARAMETRIC STUDY

A comprehensive parametric study was carried out to examine the influence of geometrical parameters and material properties on the effectiveness of in-filled tire-shred trench barriers in providing active isolation of ground-borne vibrations. The key geometrical parameters considered were trench depth, width, and distance to the excitation source as well as full and partial isolation. The influence of key dynamic soil properties, such as shear wave velocity, bulk density, damping ratio, and Poisson’s ratio were also investigated.

The 2D axisymmetric model was used to perform parametric studies related to trench geometrical dimensions and material dynamic properties. Significant computational time was saved using the 2D model for cases that could be modeled in 2D without compromising the accuracy of the results. For the analysis of partial isolation cases, i.e., linear and semi-circular trench barriers, however, the 3D model was required.

Scenarios which could not be investigated in the field due to site constraints were thoroughly studied in the parametric study. Of particular interest were the influence of trench depth and width and the distance from excitation source. For example, the performance of in-filled trenches in far-field conditions was not part of the experimental program but was studied numerically. In addition, the influence of key properties of native soil (as mentioned above) on the performance of trench barriers was investigated.
The frequency used for examining the influence of material properties was 50Hz throughout, so that the effect of material property variation could be studied independent of frequency. The elastic modulus and Poison’s ratio for the tire shreds were kept constant at 505kPa and 0.3. The parametric study results are presented in terms of the relationship between geometry, angular length, and material properties versus the average amplitude reduction ratio $\bar{A}_R$.

Discussions, conclusions, and recommendations based on the findings of the parametric study are provided at the conclusion of this chapter. The parametric study results provide guidelines for designing efficient and cost effective trench barriers.

6.1 Influence of Trench Barrier Dimensions

The influence of normalized depth $D$ and normalized width $W$ on the in-filled circular trench barrier $\bar{A}_R$ is presented and discussed in this section. Native soil dynamic properties were as follows: shear wave velocity $V_S = 200\text{m/sec}$, bulk density $\rho = 1,800 \text{ kg/m}^3$, average material damping ratio $\xi = 5\%$, and Poisson’s ratio $\nu = 0.25$.

6.1.1 Depth and Width

The normalized depth and width of the trench barrier were varied separately, so the influence of each could be investigated independently. The normalized depth varied from 0.4 to 1.5 for three normalized widths of 0.1, 0.3, and 0.5 for two distances of $X=0.7$ (same normalized distance used in the experimental study at 50Hz frequency) and $X=1.2$. Figure 6.1 and Figure 6.2 present the influence of $D$ and $W$ on $\bar{A}_R$ for $X=0.7$ and $X=1.2$, respectively. The results suggest that the trench barrier is effective ($\bar{A}_R < 0.25$) when $D$ higher is than 0.6 and $W$ is higher than 0.2. Similar results were obtained in the experimental investigation, as presented in Chapter 5.
Several studies suggest that width does not have a major effect on the performance of open trench barriers, with the exception of shallow trenches (Woods, 1968; Ahmad and Al-Hussaini, 1996; Yeong and Hung, 1997). Further, width is considered a more important factor for in-filled trenches (Ahmad and Al Hussaini; 1996, Haupt, 1978). Yeong and Hung reported that for in-filled trenches to be efficient, the dimensionless depth and width should be more than 1 and 0.3, respectively. Referring to Figure 6.1 and Figure 6.2, for values of W in excess of 0.2, $\bar{A}_R$ remains mostly unchanged.

*Figure 6.1 - Influence of Normalized Depth and Width on $\bar{A}_R$ (X=0.7, $V_S$= 200m/sec, $\rho$=1,800 kg/m$^3$, $\xi$=5%, $u$=0.25)*
Figure 6.2 - Influence of Normalized Depth and Width on $\overline{A}_R$ ($X=1.2$, $VS=200m/sec$, $\rho=1800kg/m^3$, $\xi=5\%$, $\upsilon=0.25$)

6.1.2 Trench Location

The influence of the normalized trench distance to excitation source ($X$) on $\overline{A}_R$ for various trench depths is presented in Figure 6.3 and Figure 6.4. Normalized width ($W$) was kept constant at 0.3 to ensure that the results were not affected by variations in $W$. For scenarios in which $X$ was less than 2, it was noted that the screening effectiveness of the trench barrier depended highly on $X$ in a complex way. Such dependence can be attributed to the coexistence of surface and body waves and their reflection, refraction, transmission, and mode conversion in the vicinity of the barrier when the barrier and the excitation source are closely spaced. The results suggested that the most efficient screening was achieved with $X=0.3$ and $X=1.2$. For values of $X$ higher than 1.5, the influence of $X$ on $\overline{A}_R$ becomes negligible. Similar results were reported by Al Zawi and El Neggar (2012) for the in-filled geofoam trench barriers.
Figure 6.3 - Influence of Normalized Barrier Distance to Excitation Source on $\bar{A}_R$ ($W=0.3$, $V_S=200m/sec$, $\rho=1800 kg/m^3$, $\xi=5\%$, $\nu=0.25$)

Figure 6.4 - Influence of Normalized Barrier Distance to Excitation Source on $\bar{A}_R$ ($W=0.3$, $V_S=200m/sec$, $\rho=1800 kg/m^3$, $\xi=5\%$, $\nu=0.25$)
6.2 Partial Isolation

Cases of partial isolation, such as isolation achieved by semi-circular or linear trench barriers, were studied in addition to the full isolation (circular trench barrier), which was covered in Section 6.1. Partial isolation achieved by semi-circular and linear open and infilled trench barriers was investigated numerically and experimentally, as described in Chapters 4 and 5. This was investigated in more detail in this chapter, and the relationship between the trench length (angular or linear) and the limits of screened zone behind the trench was established.

Material properties for native soil and tire shreds were the same as those defined in Section 6.1. For a vibration frequency of 50Hz, normalized dimensions were D=0.8, X=1.2, and W=0.3 for both trench types.

6.2.1 Semi-circular Shape Trench Barrier

Figure 6.5 through Figure 6.7 show $A_R$ contour lines in the vicinity of semi-circular trench barriers with various angular lengths. Due to the symmetrical nature of the problem, only one half of the trench barrier was modeled to save computational time. For the analysis, D=0.8 and W=0.3 were adopted, so that the trench barrier performance is only affected by its angular length. The normalized trench to excitation source distance, X, was set at 1.2, which achieved the optimum level of screening, as shown in Figure 6.3.

As shown in Figure 6.5 through Figure 6.7, effective screening does not take place in the area behind the trench bound between the trench edge and at a distance from the edge. Using the $A_R$ contour lines, the relationship between the trench angular length and the limits of the effectively screened area was established for trenches with angular lengths
of 60°, 90°, and 180°. The results are presented in Figure 6.8. Woods (1968) reported that the zone effectively screened by a partial trench (the area outside the trench extended to 10λ_R) was bounded on the sides by radial lines from the center of the vibration source through points 45° from the ends of the trench.

The size of the screened area, as shown in Figure 6.7, however is slightly larger than that reported by Woods. Conservatively, the value recommended by Woods can be adopted and used as a guideline for designing trench barriers for active isolation cases. For an angular trench length of less than 90°, the screened zone is too small to be considered.

*Figure 6.5 - Amplitude Reduction Factor behind Semi-circular Trench Barrier (θ=60°, D=0.8, W=0.3, X=1.2, f=50Hz)*
Figure 6.6 - Amplitude Reduction Factor behind Semi-circular Trench Barrier ($\theta=90^\circ$, $D=0.8$, $W=0.3$, $X=1.2$, $f=50\text{Hz}$)

Figure 6.7 - Amplitude Reduction Factor behind Semi-circular Trench Barrier ($\theta=180^\circ$, $D=0.8$, $W=0.3$, $X=1.2$, $f=50\text{Hz}$)
6.2.2 Linear Shape Trench Barrier

Figure 6.9 through Figure 6.12 show $A_R$ contour lines in the vicinity of an in-filled linear trench barrier with normalized lengths ($L$) in the 0.8 to 2.8 range. Referring to the $A_R$ contour lines, a relationship between trench length and the limits of the screened area behind the trench was established. Defining the effective trench length as the length bound between two radial lines connecting the 0.25 contour to the excitation source, $L_{\text{eff}}$ effective length and trench length ratio ($L_{\text{eff}}/L$) are plotted against trench length and the trench-to-source distance ratio ($L/X$) in Figure 6.13. The relationship can be defined as follows:

$$L/X = 9.56 \left( L_{\text{eff}}/L \right) - 1.9$$

For example, $L_{\text{eff}}$ for a 10m-long trench and trench-to-excitation-source distance of 5m is 4m.
Figure 6.9 - Amplitude Reduction Factor behind Linear Trench Barrier ($L= l/\lambda_R=0.8$, $D=0.8$, $W=0.3$, $X=1.2$, $f=50$Hz)

Figure 6.10 - Amplitude Reduction Factor behind Linear Trench Barrier ($L= l/\lambda_R=1.25$, $D=0.8$, $W=0.3$, $X=1.2$, $f=50$Hz)
Figure 6.11 - Amplitude Reduction Ratio behind Linear Trench Barrier ($L = l/\lambda_r = 2.1$, $D = 0.8$, $W = 0.3$, $X = 1.2$, $f = 50\text{Hz}$)

Figure 6.12 - Amplitude Reduction Factor behind Linear Trench ($L = l/\lambda_r = 2.8$, $D = 0.8$, $W = 0.3$, $X = 1.2$, $f = 50\text{Hz}$)
Figure 6.13 - Effective and Total Linear Trench Length Ratio vs. Total Length and Distance to Excitation Source Ratio

6.3 Influence of Material Properties

The influence of key dynamic soil properties, such as shear wave velocity, bulk density, Poisson’s ratio, and damping ratio, on the vibration screening effectiveness of in-filled tire-shred trench barriers was investigated in this parametric study. Two normalized distances of X=0.3 and X=1.2 were used while studying the influence of material properties, since the most effective screening was achieved at these two distances (as shown in Figure 6.3.)

6.3.1 Influence of Soil Shear wave velocity

Among the dynamic material properties, the shear wave velocity ratio for fill and soil, $V_{S-\text{FILL}}/V_{S-\text{SOIL}}$ (impedance) is the key governing factor in the performance of in-filled trench barriers. Impedance highly affects the amount of wave reflection, refraction and mode conversion at the interface of the soil and the barrier. In this study, the influence of $V_{S-\text{SOIL}}$
in a 100m/sec to 500m/sec range (corresponding to an 0.18 to 0.04 range of impedance) on $\bar{A}_R$ was investigated while $V_{S-FILL}$ remained constant at 18m/sec.

The results for two normalized trench-barrier-to-excitation-source distances of $X=0.3$ and $X=1.2$ are presented in Figure 6.14 and Figure 6.15. It should be noted that $\bar{A}_R$ decreased by almost 50% as $V_{S-SOIL}$ increased from 100m/sec to 200m/sec. This demonstrates the criticality of impedance on the screening effectiveness of in-filled trench barriers. The $\bar{A}_R$, however, remained constant (regardless of $D$) as $V_{S-SOIL}$ increased further. Two other observations can be made: a) the trench barrier is effective for $V_{S-SOIL}$ values higher than 150m/sec, corresponding to impedance of 0.12; and b) there is no noticeable reduction in $\bar{A}_R$ once $V_{S-SOIL}$ exceeds 250m/sec, corresponding to impedance of 0.07 or lower. At this impedance, the in-filled trench is expected to perform similar to an open trench (Al Hussaini and Ahmad 1996) and its effectiveness does not increase further with impedance reduction. Referring to Figure 6.15, at $X=1.2$, the same dependence between $\bar{A}_R$ and $V_{S-SOIL}$ can be observed; hence the same interpretation for $X=0.3$ applies.

Figure 6.14 - Influence of Soil Shear Wave Velocity on $\bar{A}_R$ ($X=0.3$, $W=0.3$, $\rho=1,800$ kg/m$^3$, $\xi=5\%$, $\upsilon=0.25$)
6.3.2 Influence of Bulk Density

The influence of soil bulk density on $\bar{A}_R$ for in-filled trench barriers was investigated. The bulk density of soil varied from 1,500 to 2,000 kg/m$^3$ for $D$ in the 0.6 to 2 range, while shear wave velocity and Poisson’s Ratio remained constant. The range of bulk densities investigated represent loose to very dense soils. Results for trench barriers located at $X=0.3$ and $X=1.2$ from the excitation source are shown in Figure 6.16 and Figure 6.17, respectively. For $X=0.3$, bulk density has almost no influence on $\bar{A}_R$, while for $X=1.2$, the influence is limited to 10% for the range of bulk densities investigated. As a result, for all practical purposes, the influence of bulk density can be ignored.
Figure 6.16 - Influence of Bulk Density on $\bar{A}_R$ ($X=0.3$, $W=0.3$, $V_{S-SOIL}=200$ m/sec, $\xi=5\%$, $\nu=0.25$)

Figure 6.17 - Influence of Bulk Density on $\bar{A}_R$ ($X=1.2$, $W=0.3$, $V_{S-SOIL}=200$ m/sec, $\xi=5\%$, $\nu=0.25$)
6.3.3 Influence of Material Damping Ratio

For materials that are not perfectly elastic like soil, geometric damping and material damping have to be considered in wave propagation problems. The material damping ratio is a key dynamic property of soil which affects the attenuation of Rayleigh waves, even though geometrical damping is the main contributor to the attenuation of Rayleigh waves. In the ABAQUS program, material damping is adopted in the form of Rayleigh damping. Rayleigh damping is frequency dependent, and is associated with two Rayleigh damping parameters for mass and stiffness damping. This was described in detail in chapter 4.

In this parametric study, the influence of the soil damping ratio on $\bar{A}_R$ for various trench depths was investigated. The damping ratio varied from 2.5% to 10% (which is on the high side for soil). Figure 6.18 and Figure 6.19 present the results of the investigation for trench locations of $X=0.3$ and $X=1.2$. It was demonstrated that the influence on $\bar{A}_R$ from increasing the damping ratio is marginal, irrespective of depth; i.e., the performance of the trench barrier does not improve much as the damping ratio increases.

Figure 6.18 - Influence of Damping Ratio on $\bar{A}_R$ ($X=0.3$, $W=0.3$, $V_{S-SOIL}=200$ m/sec, $\rho=1800$ kg/m3, $\nu=0.25$)
6.3.4 Poisson’s Ratio

Poisson’s ratio is the ratio of horizontal to vertical strain under vertical stress. Compression wave and shear wave propagation velocities in soils are related by Poisson’s ratio, so variations in Poison’s ratio can affect wave propagation in a half space. The influence of Poison’s ratio on the screening effectiveness of in-filled trench barriers at two different trench locations (X=0.3 and X=1.2) and for various trench depths is presented in Figure 6.20 and Figure 6.21. It can be observed that changes in Poison’s ratio do not have significant influence on $\bar{A}_R$ regardless of barrier depth, except for values in excess of 0.4. The same observation was reported by Al Hussaini (1992). However, for $\nu$ values larger than 0.4, there is a trend toward increase in $\bar{A}_R$. Nonetheless, for all practical purposes, the influence of Poisson’s ratio on the screening effectiveness of trench barriers can be ignored.
Figure 6.20 - Influence of Poisson’s Ratio on $\bar{A}_R$ ($X=0.3$, $W=0.3$, $V_{S-SOIL} = 200$ m/sec, $\rho=1800$ kg/m$^3$, $\xi=5\%$)

Figure 6.21 - Influence of Poisson’s Ratio on $\bar{A}_R$ ($X=1.2$, $W=0.3$, $V_{S-SOIL} = 200$ m/sec, $\rho=1800$ kg/m$^3$, $\xi=5\%$)
6.3.5 Summary and Conclusions

A comprehensive parametric study was conducted to examine the influence of geometrical parameters and material properties on the effectiveness of in-filled tire-shred trench barriers in providing active isolation of ground-borne vibrations. The key geometrical parameters considered were trench depth, width, and distance to the excitation source and full or partial isolation. The influence of key dynamic properties of soil, including shear wave velocity, bulk density, damping ratio, and Poisson’s ratio were also investigated.

The 2D axisymmetric FE model was utilized for the entire parametric study, except for the analysis of partial isolation cases where the 3D model had to be used. It was demonstrated in Chapter 4 that the results of the 2D and the 3D models are in good agreement; hence significant computational time was saved by using the 2D model.

For the active isolation cases studied, the influence of normalized depth $D$ on the average amplitude reduction factor $\bar{A}_R$ was the most critical. Screening was effective ($\bar{A}_R < 0.25$) for $D$ higher than 0.6. This finding is consistent with the findings from the experimental study. As for normalized trench width ($W$), the influence on $\bar{A}_R$ is negligible for $W$ exceeding 0.2. The most effective screening is achieved with trench-to-excitation-source distance ($X$) at 0.3 and 1.2. For values of $X$ in the 2 to 4 range, changes in $\bar{A}_R$ are insignificant regardless of depth.

For partial isolation cases, semi-circular and linear trenches were investigated and the relationship between the trench angular length and the limits of the screened zone behind the trench were established. For semi-circular trenches, it was demonstrated that the area bounded on the sides by radial lines from the center of the vibration source through points 35° to 40° from the edges of the trench was effectively screened; however, the 45° angle reported by Woods (1968) can be conservatively adopted.
For linear trenches, a relationship between the effective trench length $L_{\text{eff}}$ (the length bound between two radial lines connecting the 0.25 contour to the excitation source) and trench length ratio, $L_{\text{eff}}/L$ and trench-to-source-distance ratio $(L/X)$ was established as shown in Equation 6.1:

$$L/X = 9.56 \left( \frac{L_{\text{eff}}}{L} \right) - 1.9$$

The influence of the dynamic properties of soil, such as shear wave velocity, bulk density, Poisson’s ratio, and damping ratio, on $\bar{A}_R$ was investigated. Among those, the influence of impedance defined as $V_{S\text{-FILL}}/V_{S\text{-SOIL}}$ was the most critical for $V_{S\text{-SOIL}}$ within a 150m/sec to 250m/sec range, which resulted in a 50% reduction in $\bar{A}_R$. The influence of other soil dynamic parameters was demonstrated to be negligible.
CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

The beneficial use of scrap tire shreds as an isolation medium for screening ground-borne vibration was comprehensively investigated. Numerous research cases have been carried out in the past 50 to 60 years on the performance of trench barriers, sheet pile walls and hollow steel or concrete piles as a means of providing vibration screening. Trench barriers, open or in-filled with concrete, bentonite slurry or polystyrene geofoam have also been extensively investigated for their vibration screening performance. Most of those studies, however, consisted of developing numerical models and methodologies to assess the vibration isolation performance of barriers.

On the other hand, although scrap tires have been beneficially used in various engineering applications, such as for rubberized asphalt or light fill, few studies have addressed the feasibility of using tire shreds in vibration isolation applications. A study on the performance of tire shreds as vibration dampers underneath light rail tracks is referred to here (Wolfe, S.L., Humphrey, D.N., and Wetzel, E.A., 2004).

This study provided a deeper insight into the beneficial use of tire shreds in vibration screening applications by conducting numerical and experimental investigations and developing guidelines for the design of in-filled tire-shred trench barriers. A summary of the findings, conclusions, and design guidelines are provided in this chapter.
A comprehensive literature review was conducted on the usefulness of open or in-filled trench barriers in vibration screening applications. Previous studies suggest that, in general, trench barriers are an effective means of providing vibration screening. For in-filled trench barriers to be effective, however, the physical properties of the fill material are very important. Materials such as concrete, bentonite slurry, geofoam, and gas cushion have been studied in detail. The feasibility of using tire shreds for screening ground-borne vibrations, however, has not been comprehensively studied. There is, however, a great deal of information on the numerous engineering applications for tire shreds, such as rubberized asphalt, light fill, or drainage material in landfills. Case studies for these were presented in chapter 3.

An information gap on the beneficial reuse of tire shreds as an isolation medium was noticed, and an effort was made to narrow the gap as much as possible through this research study. The study mainly consisted of numerical and experimental investigations related to the performance of in-filled tire-shred trench barriers in providing active isolation of ground-borne vibrations. A numerical investigation was performed initially to gain a general understanding of the concept and to design a targeted experimental investigation program. Full-scale experimental investigations are costly; hence a well defined and focused scope of testing was required.

Using the ABAQUS FE package, two- and three-dimensional finite element models were developed and validated using reference models developed by others. The 2D model was used for investigating the influence of geometrical parameters on the trench barriers' vibration screening performance. Since it was demonstrated that the 2D and the 3D model results analyzing the influence of geometrical parameters are in good agreement, the 2D model was used to save computational time. For the analysis of partial isolation cases (semi-circular and linear trench barriers) it was necessary to use the 3D model.
Findings of the numerical investigation were tested in full-scale as part of the experimental program. Very good agreement between the findings of the numerical and the experimental investigations was observed, suggesting that the developed 2D and 3D models could be confidently used for further parametric studies. The parametric study thoroughly examined the influence of geometrical parameters, full and partial isolation, and material dynamic properties on the performance of in-filled tire-shred trench barriers. The findings, analysis and design guidelines follow.

The influence of geometric dimensions and angular length (full or partial isolation using circular, semi-circular or linear) was studied using the 2D and 3D models. The geometrical dimensions are typically normalized by the associated wavelength, so their effect can be examined independent of vibration frequency. The shear wave velocity of native soil and tire shreds was measured in-situ, using the SASW method. Therefore, the results of the numerical model are fine-tuned to better match the experimental study results. Field constraints had to be taken into account when selecting the geometrical dimensions used in the investigation, such as depth, width, and trench distance to the excitation source. The findings were as follows:

1. Trench normalized depth D was found to be the key parameter governing the performance of trench barriers and should exceed 0.6 for effective screening.
2. The influence of normalized width for open or in-filled trenches is insignificant. For trench location X, for the two locations investigated, the screening was more effective for X=0.3 than X=0.6, but only at low frequencies (40Hz vs. 80Hz).
3. For partial isolation cases, i.e., semi-circular trench barriers, the effectively screened area behind the trench is bound between the line going through the centerline and the line 45° from the edge of the trench. For a linear trench, while the same effect as for the semi-circular trench was observed, more detailed
analysis was required to accurately delineate the limits of the effectively screened area; this was carried out in the parametric study.

The influence of geometrical dimensions and angular length on the performance of open and in-filled trench barriers was examined experimentally in full-scale. Circular, semi-circular and linear trenches were employed to examine full and partial isolation and to delineate the limits of the screened zone behind the trench barrier for partial isolation cases. By testing the open and in-filled trenches, a comparison between the effectiveness of tire shreds as an isolation medium with the best isolator, air, could be made. 50mm and 200mm tire shreds were used as fill to study the effect of size on screening effectiveness. The depth of the trenches was kept at 1.35m so that excavation support would not be necessary. The trenches were made 1 to 1.2m wide so that a geotextile separator could be placed at the bottom and along the side walls. Additionally, the width allowed for the 200mm tire shreds to be placed properly without adversely affecting the performance of the trench barrier and also allowed for the investigation of other critical dimensions.

Considering the results of the preliminary numerical investigation, trenches had to be deeper than 1.35m for effective screening of low frequency (80Hz or less) vibrations. Therefore, frequencies in the range of 20Hz to 160Hz (wavelengths of 9.2m to 1.15m) corresponding to normalized depths D of 0.15 to 1.2 were used to achieve higher normalized depths. For this range of frequency, W varied from 0.11 to 0.88 and X was in the 0.25 to 2.0 range (for trench-to-excitation-source distance of 2.4m, which was maintained throughout the study for practical reasons). Since X was in the 0.25 to 2 range, this isolation type was considered as active (isolation at source).

The performance of trench barriers was evaluated based on the achieved average amplitude reduction factor, \( \bar{A_R} = (1/A) \int_A A_R \, dA \) at various normalized depths. Another
parameter checked against \( \bar{A}_R \) was the normalized trench cross section \( A_B (=D.W) \). The following conclusions related to the performance of trench barriers were made, these apply to both open and in-filled trenches, since they performed comparably:

1. For effective screening of vibrations in 3D resulting from vertical harmonic excitations, the normalized depth \( D \) shall exceed 0.6. The same applies to longitudinal and transverse vibrations in linear and semi-circular geometries (partial isolation), except for circular barriers for which the effective depth shall exceed 0.4.

2. For circular trenches to be effective, \( A_B \) shall exceed 0.3 for vertical vibrations and 0.2 for longitudinal and transverse vibrations. For a linear trench, \( A_B \) shall exceed 0.5 for effective screening of vertical vibrations, while for longitudinal and transverse vibrations, \( A_B \) shall exceed 0.25. Semi-circular trenches are effective if \( A_B \) exceeds 0.3 for vibrations in all directions.

3. Full isolation (achieved by circular trench barriers) is more effective than partial isolation since \( \bar{A}_R \) is affected by higher \( A_R \) readings near the end of barriers (edge effect). It was observed that the screened zone behind semi-circular and linear trenches is not complete, corresponding to approximately one half of the area behind the trench and symmetrical about the array going through the center of the trench.

4. In-filled tire-shred trenches are almost as effective as open trenches. It was also demonstrated that the 200mm and 50mm tire shreds performed comparably. Thus it is sensible to use large tire shreds for this application, due to their lower shredding cost.

A comprehensive parametric study followed the experimental program. The influence of geometrical parameters and material properties on the performance of in-filled trench
barriers was examined. The key geometrical parameters analyzed were normalized trench depth, width, and distance to the excitation source for both full and partial isolation. The influence of key dynamic properties of soil, such as shear wave velocity, bulk density, damping ratio, and Poisson's ratio were also investigated. A vibration frequency of 50Hz, which is typical of train or traffic from heavy vehicles, was used for the parametric study.

Other than partial isolation cases where using the 3D model was required, the analysis was performed using the 2D axisymmetric model to save computational time. The findings of the parametric study were as follows:

1. For the active isolation case, normalized trench depth $D$ governs the achieved screening level. Screening was effective when $D$ exceeded 0.6. This finding conforms very well to the findings of the experimental study.

2. The influence of $\bar{A}_R$ on normalized width $W$ is negligible for $W$ exceeding 0.2.

3. The most effective screening is achieved when trench distance to the excitation source distance $X$, is at 0.3 and 1.2. For $X$ in the 2 to 4 range, changes in $\bar{A}_R$ are insignificant, regardless of depth. Further distances were not investigated since it would have required excessive computation time.

For partial isolation cases, two geometries, i.e., semi-circular and linear were investigated, and the relationship between the trench angular length and the size of the zone behind the trench that is effectively screened was established.

1. For semi-circular trenches, the area bounded on the sides by radial lines from the center of the vibration source through points 35° to 40° from the edges of the trench was effectively screened; however, the 45° angle reported by Woods (1968) can be conservatively adopted.
2. For linear trenches, a relationship was established between the effective trench length, \( L_{\text{eff}} \) (the length bound between two radial lines connecting the 0.25 contour to the excitation source), and trench length ratio, \( L_{\text{eff}}/L \), and trench to source distance ratio \( (L/X) \). This is presented in equation 6.1.

3. The influence of soil dynamic properties, such as shear wave velocity, bulk density, Poisson’s ratio, and damping ratio on \( \bar{A}_R \), was investigated. Among those, the influence of impedance defined as \( V_{\text{S-FILL}}/V_{\text{S-SOIL}} \) was most critical for \( V_{\text{S-SOIL}} \) within 150 m/sec to 250 m/sec range, which resulted in a 50 percent reduction in \( \bar{A}_R \), while the reduction in \( \bar{A}_R \) for \( V_{\text{S-SOIL}} \) higher than 250 m/sec was marginal.

4. The influence of other soil dynamic properties was marginal.

7.2 Recommendations for future research

Future work to enhance the existing level of knowledge related to the vibration screening effectiveness of in-filled tire-shred trench barriers is proposed. Further research in the following areas is warranted:

1. The scope of the experimental investigation in this research was limited to an active (or near-field) isolation case. Additional full-scale experimental work investigating linear trench barriers in passive isolation (far-field isolation) cases would be beneficial. Deeper trenches than those constructed for this research may be required, thus necessitating additional safety precautions.

2. In a few cases, a heating reaction has been reported in large stockpiles of scrap tires. The thermal resistivity of tire shreds is approximately eight times greater than for typical granular soil, therefore tire shred fill should be designed to minimize the possibility of an internal heating reaction (ASTM D 6270). Possible causes of the reaction are oxidation of the exposed steel belts and oxidation of the rubber. ASTM
D 6270 recommends that the layer thickness be limited to 3m in bulk use applications until or unless further research suggests otherwise. It is proposed that research be conducted by placing (steel free) 200mm tire shreds in a deep trench (5m or deeper) wrapped by an impervious heavy duty geo-membrane liner to limit air access and monitor for any potential heating reaction.

3. It would be beneficial to further quantify dynamic properties of tire shreds, shear wave velocity and bulk density in particular, for use in the numerical models to obtain more accurate results.
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USEPA Website, Link: www3.epa.gov/epawaste/conserve/materials/tires/ Markets and Uses of Scrap Tires


APPENDIX

Wave propagation within the half-space (free-field and with empty trench barrier scenarios)

Wave propagation within the half space for free-field and with the presence of a trench barrier scenarios is shown below. An acceleration impact loading of 100 m/s² was applied, started at 0.05 sec, and reached maximum at 0.075 sec and zeroed at 0.1 sec. Starting from 0.05 sec, wave propagation is shown at 0.01 sec intervals. Assuming Rayleigh wave velocity at 182 m/s and source to the semi-finite boundary of 15m, it takes 0.08 sec for the disturbance to reach the boundary so the time span was chosen from 0.05s to 0.15s.

t=0.052s
t=0.09s

T=0.098s

T=0.098s (scale change)
t=0.156s