REPUBLIC OF TURKEY
MUĞLA SITKI KOÇMAN UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF CIVIL ENGINEERING

AN EXPERIMENTAL STUDY ON REDUCING THE GROUND BORNE VIBRATIONS USING RUBBER CHIPS BARRIERS

MASTER OF SCIENCE THESIS

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DECEMBER 2018
MUĞLA

MUĞLA SITKI KOÇMAN UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

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Defence Date: 27/12/2018

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27/12/2018

ABSTRACT

AN EXPERIMENTAL STUDY ON REDUCING THE GROUND BORNE VIBRATIONS USING RUBBER CHIPS BARRIERS

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December 2018, 85 pages

Ground borne vibrations generated by construction works, vehicle traffic and machines have begun to create problem to dwellers and environment with rapid urbanization. Isolation of the source or wave barriers is commonly preferred by engineers to reduce the effect of those vibrations. Recently, studies on the isolation of ground vibrations by wave barriers have increased considerably. Most of those studies concentrate on numerical analysis and there are only few experimental studies testing the isolation performance of wave barriers. In the present study, isolation performance of open and rubber chip filled trench are investigated by full scale experiments and numerical modeling.

In field tests, ground vibration measurements are performed by using sources having different frequencies, in the presence and absence of the wave barrier. The vibration isolation performance of trench type wave barriers is assessed based on those measurements. As a result of the assessment, it is determined that the trench depth and vibration source working frequency are the main parameters affecting the efficiency of wave barrier. Besides, site experiments show that the isolation performance decreases as away from the trench. Moreover, even though open trench is more effective on reducing ground borne vibrations, as the normalized trench depth increases isolation performance of rubber chip filled trench barrier approaches the performance of open trench barrier.

Field experiments are modeled and validated by using finite element method for making a parametric study. Numerical analyses are applied for different source working frequencies to clarify the effect of normalized trench depth on isolation efficiency of trench type wave barriers. Consequently, obtained findings are compared with the previous reported studies and simple relationships are recommended to engineers for the preliminary design of open and rubber chip filled trenches.

Keywords: Vibration Isolation, Wave Barrier, Wave Propagation, Rubber Chips, Attenuation.

ÖZET

KAUÇUK YONGA BARİYERLER KULLANARAK YER KAYNAKLI TİTREŞİMLERİN AZALTILMASI ÜZERİNE DENEYSEL ÇALIŞMA

Mohammad Mouaz HASSOUN

Yüksek Lisans Tezi
Fen Bilimleri Enstitüsü
İnşaat Mühendisliği Anabilim Dalı
Danışman: Doç. Dr. Deniz ÜLGEN
Aralık 2018, 85 sayfa

Hızlı şehirleşme ile birlikte, inşaat çalışmaları, araç trafiği ve makinelerin oluşturduğu yer titreşimleri çevre ve çevre sakinleri için problem yaratmaya başlamıştır. Bu yer titreşimlerinin etkisini azaltmak için genellikle kaynağın yalıtımı veya dalga bariyerlerinin kullanımı tercih edilmektedir. Son zamanlarda, yer titreşimlerinin dalga bariyerleri ile yalıtımı üzerine çalışmalar oldukça artmıştır. Bu çalışmalar çoğunlukla sayısal modelleme üzerine yoğunlaşmış olup, dalga bariyerlerin yalıtım performansını irdeleyen sadece birkaç deneysel çalışma bulunmaktadır. Mevcut çalışmada, içi boş ve kauçuk yonga dolu hendeklerin titreşim yalıtım performansı tam ölçekli saha deneyleri ve sayısal modelleme ile incelenmiştir.

Saha çalışmalarında, farklı frekansa sahip kaynaklar ile dalga bariyeri varken ve yokken yer titreşim ölçümleri yapılmıştır. Elde edilen bu ölçümler doğrultusunda hendek tipi dalga bariyerlerinin titreşim yalıtımı performansı değerlendirilmiştir. Yapılan değerlendirme sonucunda, hendek derinliğinin ve titreşim kaynağı çalışma frekansının dalga bariyeri verimliliğini etkileyen en önemli parametreler olduğu belirlenmiştir. Ayrıca, saha deneyleri yalıtım performansının hendekten uzaklaştıkça azalttığını göstermiştir. Buna ek olarak, içi boş hendek tipi dalga bariyeri titreşimleri azaltmada daha etkili olmasına rağmen, normalize hendek derinliği arttıkça, kauçuk yonga dolu bariyerin yalıtım performansı içi boş dolu hendeğe yaklaşmıştır.

Parametrik bir çalışma yapmak amacıyla, saha deneyleri sonlu elemanlar yöntemi kullanılarak sayısal olarak modellenmiş ve doğrulanmıştır. Normalize hendek derinliğinin, hendek tipi dalga bariyerlerinin yalıtım verimliliği üzerine olan etkisini açıklığa kavuşturmak için, farklı kaynak çalışma frekanslarında sayısal analizler gerçekleştirilmiştir. Sonuç olarak, elde edilen bulgular daha önce raporlanan çalışmalarla karşılaştırılmış ve mühendislere içi boş ve kauçuk yonga dolu hendeklerin ön tasarımında uygulamak üzere basit ilişkiler önerilmiştir.

Anahtar Kelimeler: Titreşim Yalıtımı, Kauçuk Yonga, Dalga Bariyeri, Dalga Yayılımı, Azalım.

Dedicated to the memory of my mother, **Zoka**.

ACKNOWLEDGEMENT

I would like to thank my supervisor *Assoc. Prof. Dr. Deniz Ülgen* for guiding, teaching, and leading me throughout this dissertation. He did provide me with unlimited patience, support and assistance.

Thankfulness is expressed to *Assist. Prof. Dr. Altuğ Saygılı*, for the educational and intellectual values he granted me. Lots of gratitude is stated to *Res. Assist. Onur Toygar,* and *Res. Assist. Selda Durmaz* for the technical help and guidance they gave throughout the numerical and experimental work.

I am thankful to examining and evaluating committee members. Specifically, *Assoc. Prof. Dr. Berna Unutmaz* for the contributions and suggestions she did provide regarding improving this dissertation.

Thanks to all department and faculty members for their cooperation and help. Special Thanks to *Assoc. Prof. Dr. Reşat Ünal* who has been my mentor since my very beginning in Muğla University. Thanks to my friends who stepped beside me during field experiments: *Oways*, *Najjar*, *Belal,* and *Omar*.

Gratitude is expressed to my uncle *Nihad karkoukli* who kept motivating me to work harder. Thankfulness is also expressed to my close friends: *Saad, Bashar, Yaser, Ahmad,* and *Hamed*.

Sincerely, gratefulness is expressed to my sisters (*GHADIR*, *SHAHED*, and *NAWAR*) and to my father for their continuous support and encouragement. Finally, I am beholden to the person I will always miss, to my ***MOTHER***, and to her *immortal soul*.

The research leading to these results has been funded from Muğla Sıtkı Koçman University Scientific Research Projects with the BAP Project Code: 17/263. The financial support from BAP Coordinatorship of Mugla Sıtkı Koçman University is gratefully acknowledged.

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ρ	Density of the Soil
Ɣ	Unit Weight of the Soil
ν	Poisson's Ratio
λ_R	Rayleigh Wave Length
a	Acceleration
A_{max}	Maximum Normalized Acceleration
A_R	Amplitude Reduction Ratio
A_{my}	Average Amplitude Reduction Ratio in Y direction
A_{mx}	Average Amplitude Reduction Ratio in X direction
A_{ry}	The vertical amplitude reduction ratio
A_{rr}	Amplitude reduction ratio for circular footings isolated by annular trench
d_t	Trench Depth
D	Normalized Trench Depth
E	Elasticity Modulus (Young's)
f	Frequency
G	Shear Modulus
K	Ratio of Rayleigh Wave Velocity to Shear Wave Velocity
Lt	Distance between Vibration Source and Wave Barrier
L	Normalized Distance between Vibration Source and Wave Barrier
S_V	Vertical Component of Shear Wave Velocity
S_H	Horizontal Component of Shear Wave Velocity
T	Period
V_R	Rayleigh Wave Velocity
V_S	Shear Wave Velocity
W_t	Trench Width
W	Normalized Trench Width
BEM	Boundary Element Method
FEM	Finite Element Method
SBFEM	Scaled Boundary Finite Element Method (SBFEM).

GWT	Ground Water Table
MASW	Multichannel Analysis of Surface Waves
PPV	Peak Particle Velocity
SC	Clayey Sand
CH	highly plastic clay
CL	Low Plastic Clay
UPS	Uninterruptible Power Supply
Z	Impedance of a material
I.R	Impedance Ratio of two materials
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
E_n	Energy transmission coefficient
PL	Plastic Limit
LL	Liquid Limit
SPT	Standard Penetration Test
RPM	Revolution Per Minute
Kw	Kilo watt
L_{max}	Mesh size element limitation
L_S	Shear wavelength
SRM	Sand Rubber Mixed

1. INTRODUCTION

In a normal, stable soil system; the vibrations can be generated due to passing trains, construction activities, earthworks like pile driving and hammer excavators, and highways' traffic. All these sources produce vibrational waves with low-normal intensity that lead to frequencies less than 100 Hz. Vibrations create undesired motion in the surrounding soil system. This may lead to disturbance to the stable soil and to the surrounding inhabited region and environment. These disturbances appear in many forms: starting by undesired vibrations for residents, and ending with dangerous vibrations for sensitive structures. Like; nuclear plants and monitoring centres which interest in earthquakes and earth motion.

The concept of isolation is obstructing these propagated waves within the soil medium before they reach isolated region. Obstruction in a soil medium can be achieved through creating a discontinuity in the wave path using a wave barrier; where the wave loses the accessibility to isolated region. Thus, the undesired effect of these waves (vibration) is minimized. However, due to the flexible behaviour of waves they can diffract and refract within the barrier medium. Therefore a 100% isolation can never be achieved, and the criteria of isolation evaluation is considered to be the Amplitude of the wave. Filled-in wave barriers and open trenches are the direct application of screening vibrations in soil mediums. This method is applicable for both passive (far field applied isolation) and active (near field applied isolation) isolation. Wave barriers vary as open and in-filled (concrete, water, bentonite, Geofoam, gas cushion, and rubber chip) type trenches in addition to sheet pile walls.

1.1. General overview

Open trench was the first suggested wave obstruction mean, creating a three-dimensional space to prevent waves of passing was an easy procedure. However, open trench is considered as impractical in terms of stability problems and safety.

Thus, in-filled trenches (barriers) are more preferable regarding suitable filling materials. Suitability is more related to the type of the filling-in material if it considered to be soft comparing with soil medium of stiff. Thus, one important parameter comes to the picture in process of selection the barrier fill-in material which is impedance difference. Impedance difference indicates the difference of shear wave velocity and density of materials. Thereafter, impedance product (Z) is defined as multiplication of shear wave velocity ($V_{S)}$ and density of material (ρ). First field study for open trench was built by Barkan (1962). He made some field investigations using full-scale model test in order to study the effectiveness of wave barriers. Efficiency results of open trench with sheet pile walls were found unsatisfactory. This was because of lack in knowledge about propagation of surface waves in the presence of an obstacle. Woods (1968) performed a series of field experiments on vibration screening efficiency of a circular open trench. He defined the criteria to be the average amplitude reduction ratio. Woods (1968) suggested that it should not exceed 25% to achieve efficient vibration isolation. Distinguishing between near-field applied isolation (active) and far-field applied isolation (passive), it was found that for passive isolation a trench of 1.2 λ_R – 1.4 λ_R depth is needed. However, active isolation required trench depth for the criteria is 0.6 λ_R.

Haupt (1995) made a theoretical study for the parameters affecting the isolation efficiency of an open trench considering some previous studies of Woods (1968), Barkan (1962).

Regarding realistic studies, Ulgen and Toygar (2016) have performed an experimental study on screening efficiency of EPS Geofoam. Due to its light weight and low density, Geofoam is classified as soft fill-in barrier material. Ulgen and Toygar (2016) found that the screening effectiveness of open trenches and Geofoam wave barriers are very close to each other. The vibration amplitudes reduced by 67% or higher when the normalized depth D is 1 or 1.5 for both cases.

On the other hand several numerical analyses have been performed using finite element method (FEM) and boundary element method (BEM) for the sake of understanding the isolation mechanism and efficiency of open trenches and filled-in wave barriers. Beskos et al (1986a), Ahmad et al (1996), Shrivastava et al (2002), Thompson et al (2015), and Syed (2016) have performed series of numerical analyses to study the screening efficiency of wave barriers regarding an isotropic, homogenous, and viscoelastic soil profile. Authors have realized that open trenches provide better screening performance against vibrations when compared to filled-in barriers.

Regarding filled-in barriers, Saikia (2016) has made a finite element modelling on PLAXIS2D, finding that softer in-filled trench barriers of impedance ratios lying between 0.08-0.17 exhibit isolation effectiveness comparable to open trenches. Furthermore, Isolation efficiency of in-filled trenches increases with decrease in impedance ratio.

Another soft filled-in material barrier are rubber chips. They are lightweight material that can be collected from the industries' wastes and scrap. They are classified as environmental friendly material and recyclable.

Although it is a newly studied fill-in material, rare studies have focused on its screening efficiency to vibrations into soil mediums. Mahdavisefat et al (2017) have performed an experimental study on screening efficiency of sand-Rubber mixed wave barriers. They found that 30% rubber SRM-filled trench performs very similar to the open one. However, increase in rubber content increases the energy absorption capacity which will improve the performance.

Andersen and Nielsen (2005) have also employed a coupled finite element-boundary element model. In-filled trenches have been assumed to be isotropic, homogeneous, and linear elastic mediums. A 6 m deep open trench was modelled filled with rubber chips and concrete in two different stages. He showed that for higher frequencies the two barriers perform equally well. Precisely, rubber chip-filled trench performs better than the concrete barrier at the frequencies 10 and 40 Hz.

Throughout a deep survey to the relevant literature, it was observed that there is lack in experimental studies in general, specifically, for experimental studies focusing on vibration screening efficiency of open trenches. Furthermore, there is no single experimental study on the vibration isolation of soil using rubber chip-filled wave barrier. Even though the experimental study of Mahdavisefat et al (2017) regarded the sand rubber mixture as fill-in-trench material.

Rubber chips are cheap, light weigh, and loose material that can form a practical alternative to be filled-in trenches. They are being collected from disposal of industries and factories, and they have been classified as environmental friendly material due to their recyclability. From technical point of view, rubber chips can provide good vibration isolation for soil mediums. They are abundant, easy to handle, sustainable, and effective isolator when filled-in trenches for the sake of isolating soil mediums against vibrations.

1.2. Objective of this Study

Current study concentrates on studying the screening efficiency of open and rubber chip-filled trenches experimentally. The object of this study is:

-To assess the vibration screening efficiency of open trench for a specific site location and soil profile.

- To assess the vibration screening efficiency of rubber chips barriers.

-To make a parametric study in the screening efficiency of wave barriers by simulating the model numerically.

-To recommend a preliminary design approach for open and rubber chips barriers.

Eventually, the effect of excitation frequency and screening effectiveness of rubber chips wave barriers and open trenches were evaluated under harmonic simulated vibrations. The results were assessed in comparison with the numerical and experimental studies and findings that published in literature.

Further experimental studies on screening efficiency of rubber chips barriers are needed in order to form deeper ideas about the behaviour of this practical material. Its softness, abundance, environmental friendship, and sustainability make rubber chips good alternative for screening vibrations into soil mediums.

1.3. Outline of the Thesis

This study is introduced into six chapters. Chapters are summarized as following:

- Chapter 1 gives brief information for the vibration isolation of ground-borne vibrations, the existed gaps and lacking in literature, and the need for current study are described. The scope and object of this study is illustrated.

- Chapter 2 provides a detailed survey for literature review. Wave propagation behaviour and mechanism in soil mediums are explained. Isolation performance of different type wave barriers and the influence of the dominating parameters and factors are discussed.

- Chapter 3 introduces a description of soil profile and layering, field test procedure, and properties of test equipment. Experimentation steps and methodology are demonstrated.

- Chapter 4 includes the findings of obtained results from the present study. The vibration screening efficiency of open and rubber chip-filled trenches at several testing levels is discussed. Results of the present study are compared with the ones published in literature.

- Chapter 5 gives a simulating numerical study for the current experimental study. Details of the modelled profile, defining materials, and excitation frequency are described. The numerically obtained results have been compared with the experimental ones.

- Chapter 6 presents summary of the current study in its experimental and numerical branches. It concludes the outcomes and remarks relevant to the vibration isolation performance of open trenches and rubber chips barriers. Recommendations for future investigations and studies are provided.

2. LITERATURE REVIEW

2.1. Origin of Vibrations

Vibration is a mechanical phenomenon that occurs in bodies and mediums. They can be generated due to many sources and emitting origins. Due to periodic force that being applied to a static body or system, series of oscillations occur in that medium.

Considering a stable soil mass, vibrations create undesired motion in the system which may lead to disturbance to the stable soil and to the surrounding inhabited region and environment. These disturbances appear in many forms starting by undesired vibrations for residents ending with dangerous vibrations for sensitive structures like nuclear plants and monitoring centres which interest underlies in earthquakes and earth motion.

In a normal, stable soil system; the vibrations in can be generated due to passing trains, construction activities, earthworks like pile driving and hammer excavators, and highways' traffic. All previous sources produce vibrations with low-normal intensity that lead to frequencies less than 100 Hz.

Soil compactors are considered as oscillation sources where they can produce vibrations with variable frequencies and allow the researcher to study the behaviour of a soil mass under vibration. Moreover, lots of studies were built considering compactors with specific range of frequency generated by 1 KN intense force.

Çelebi et al (2009) performed an experimental realistic study which contained a series of field tests on a foundation vibration using a dynamic shaker which generates harmonic force of maximum amplitude of 250N that produces vertical harmonic vibrations in the certain frequency range 10-100 Hz to obtain Rayleigh wavelength within the interval 1.98-7.92 m.

Tsai and Chang (2009) have studied the Effects of open trench siding on vibration-screening effectiveness using the two-dimensional boundary element method utilizing a 2D frequency-domain BEM. They considered the amplitude of harmonic force F to be 1 KN and so the corresponding vibration frequency is 50 Hz and the obtained Rayleigh wavelength λ_R = 5m.

2.2. Behaviour of Waves Propagating in Soil

The induced vibrational waves in a soil medium due to periodic loads, do propagate in an elastic form (elastic waves). An elastic wave is defined as "the motion in a medium in which, when particles are displaced, a proportional force to the displacement does act on particles to recover them in the original positions they were in". Herein, once a material does have an elasticity property, and its particles in a certain region are set in vibratory motion, this certainly leads to forming and propagating an elastic wave within the medium.

An elastic wave can be categorized as:

- Body wave.
- Surface wave.

Body waves generally consist of combinations of the primary waves (P-waves) compressional waves with respect to particles, and the secondary waves (S-waves) which are defined as the waves that propagate only in solid mediums (materials). Furthermore, a shear wave (S-waves) comprises of two components: a horizontal wave and a vertical one. Moreover, the resultant magnitude of these two component can be expressed and calculated by the following formula:

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (2.1)$$

Where, G is the shear modulus of soil

ρ is the density of soil

When the body waves pass within a soil medium, they propagate in many directions. Then, whenever they reach the ground surface they behave in the same way that Rayleigh waves behave. These Rayleigh waves are classified as type of surface waves which pass near surfaces of solid mediums. They contain longitudinal and transversal motions that have the possibility to decrease exponentially in the amplitudes they have as distance to the surface increases.

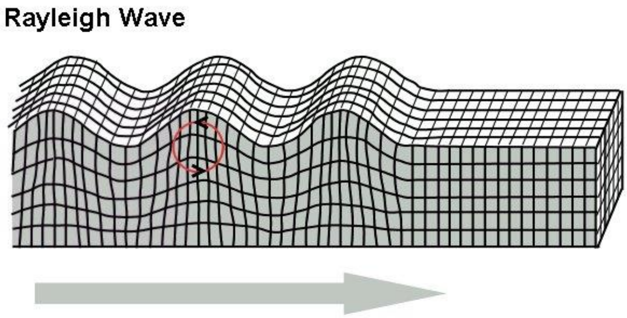


Figure 2.1. A Rayleigh wave propagation

2.3. Obstruction of Waves

The resultant surface waves (Rayleigh waves) propagate in the soil medium and affect more soil in the direction of propagation. For a habitant region, vibrations induced by these waves are non-preferable; however, the need to isolate these waves comes to the picture.

The methodology in isolation is obstructing these waves within the soil medium before they reach the aimed-to-isolate region. Obstruction in a soil medium can be achieved through creating a discontinuity in the wave path using a wave barrier; where the wave loses the accessibility to aimed-to-isolate region. Thus, the undesired effect of these waves (vibration) is minimized. However, applying the aforementioned mechanism does not achieve 100% isolation, because somehow; the waves still have some chance to reach the "after barrier" region and this occurs due to the flexible behaviour of waves that can diffract and refract within the barrier medium. Therefore 100% isolation can never be achieved, and the criteria of isolation evaluation is considered to be the Amplitude of the wave.

Comparing the wave amplitude before and after placing the barrier helps to evaluate how effective was the barrier, a ratio defined as "Amplitude Reduction Ratio" is considered to judge the efficiency of the isolation.

Tsai and Chang (2009), also Alzawi and El Naggar (2009) have emphasized the suggested limitation of Woods 1968 which implies the amplitude reduction ratio to be 0.25 to obtain an efficient wave barrier.

Wave barriers as approach of vibration isolation are not totally perfect; lots of points related to the practicality of these barriers should be considered. Regarding the case of open trench barrier the cautions of stability, safety, and performance are increased. Moreover, the sustainability of filled-in barriers has some concerns and doubts.

In the numerical study that they have performed, Beskos et al (1986a) have indicated that disregarding side instability problems of open trenches, they were found to be much more efficient than the in-filled trenches.

2.4. Wave Barriers

As previously mentioned, propagated body waves in soil behave as Rayleigh waves close to the surface include longitudinal and transversal motions. Where, there is a phase difference between the longitudinal and transversal component motions. In case of an isotropic solid, surface waves propagation (Rayleigh waves) leads to move the surface particles in elliptic planes in parallel to the wave propagation direction and in perpendicular (normal) to surface. As shown in Figure 2.2 the major axis of the ellipse coincides the vertical axis, while it minor axis is over the horizontal axis. A decay in this motion is captured near to the surface. However, this particle motion is progressive as the depth to the surface increases. Moreover, it is found that the resultant depth of considerable displacement that occurs in a solid particle is almost equal to the wavelength.

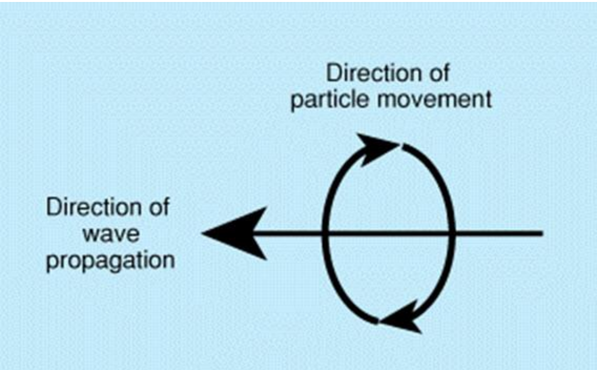


Figure 2.2. Rayleigh wave direction

In isotropic, linear elastic materials, Rayleigh waves have a speed given by the secular equation:

$$(2 - V_R^2)^2 = 4\sqrt{1 - V_R^2} * \sqrt{1 - X.V_R^2} \tag{2.2}$$

$$V_R^2 = \frac{V}{C_2} \tag{2.3}$$

$$X = \frac{C_2^2}{C_1^2} \tag{2.4}$$

$$C_1^2 = \frac{2\mu(1-\gamma)}{\rho(1-2\gamma)} \tag{2.5}$$

$$C_2^2 = \frac{\mu}{\rho} \tag{2.6}$$

By squaring both sides and omitting the V_R^2 factor, the secular equation is recast as:

$$V_R^6 - 8V_R^4 + 8(3 - 2X)V_R^2 - 16(1 - X) = 0 \tag{2.7}$$

Running the equation and finding the solution gives a direct relation between Rayleigh wave velocity and shear wave velocity of soil as follow:

$$V_R = \frac{0.87+1.12\gamma}{1+\gamma} \tag{2.8}$$

The formula is applicable only for Poisson's ratio $\gamma > 0$ with an error about 0.46%

It can be seen that Rayleigh waves are dominating in the soil media, this simply leads to the major manner for the barrier with which is Rayleigh wavelength. As it was mentioned before; the function of the barrier is to create a discontinuity in path of the Rayleigh wave, most of researchers in order to ease and facilitate their studies they normalize all parameters and terms of barrier by Rayleigh wavelength λ_R.

When comparing the displacement penetrations of waves in case of long and short wavelengths, it was found that the resultant penetration into the earth corresponding to the long wavelengths is deeper than the one obtained for short wavelengths. Furthermore, it was found that a long wavelength wave (generated by low frequencies) travels and propagates faster than the short wavelength wave (produced by high frequencies). Thus, it can be stated that the most critical parameter regarding the wave propagation mechanism and the vibration source is Rayleigh wavelength. However, this can justify the normalization of the other parameters in the study with respect to λ_R.

Understanding the function and application of the barrier is meant to be detailed enough with respect to the Rayleigh wavelength provided in order to achieve a good isolation. Another term that can be capable to describe the Rayleigh wavelength is its amplitude that was studied by Richart et al (1970) and obtained in a chart with the normalized depth of the barrier in order to distinguish the components of a Rayleigh wave.

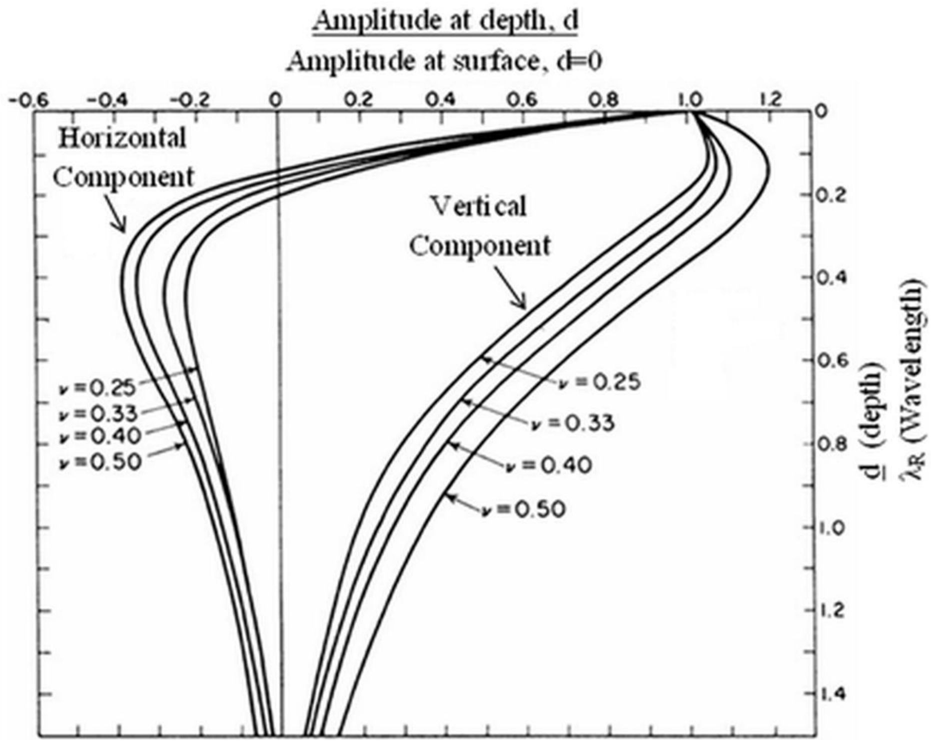


Figure 2.3. Amplitude ratio vs. dimensionless (normalized) depth for Rayleigh wave in a homogenous half-space (Richart et Al. 1970)

It is worth mentioning that all vibration origins and sources are being placed on the ground surface or within very shallow depths (about 0.5 m), this can clearly show that Rayleigh waves are totally dominating in the vibration isolation concept. In addition, and from parametric point of view, volumetric dimensions of the barrier (length, width, and depth) should be normalized with respect to Rayleigh wavelength that can directly be calculated from the formula:

$$\lambda_R = \frac{V_R}{f} \tag{2.9}$$

Where;

V_R: is the Rayleigh wave velocity of soil.

f: is the generated vibration frequency.

From the chart in figure 2.3, it can be stated that the vertical amplitude is much larger than the horizontal amplitude, therefore; researchers generally tend to isolate the vertical component of Rayleigh wave due to its significant amplitude with respect to the horizontal one.

It is important to be said that in Richart et al (1970) study the soil half-space was assumed to be homogenous, uniform, isotropic, and elastic. In other words, the soil condition of material and layering was idealized and this is not the real case generally.

2.4.1. Open Trench

Open trench was the first suggested wave obstruction mean, creating a three-dimensional space to prevent waves of passage looked an easy mission. First study for open trench field was built by Barkan (1962), he made some field investigations using full-scale model test in order to study the effectiveness of wave barriers, due to lack of knowledge about propagation of surface waves in the presence of an obstacle, as he says, the efficiency results of open trench with sheet pile walls was unsatisfactory. Woods (1968) performed a series of field experiments on vibration screening efficiency of a circular open trench defining the amplitude reduction ratio and considering the criteria to be as the average amplitude reduction ratio that should not exceed 0.25 to achieve efficient vibration isolation, he distinguished between near-field applied isolation (active) and far-field applied isolation (passive) and considered a shallow trench with 1.2 m depth with relatively short Rayleigh wave that varies between 0.34 m and 0.7 m, he found that for passive isolation a trench of 1.2 λ_R – 1.4 λ_R depth is needed, where for active isolation the required trench depth for the criteria is 0.6 λ_R.

Beskos et al (1986a) have made a numerical study using boundary element method performing a parametric study to assess the importance of various geometric, material and dynamic input parameters. Soil material was assumed to be a linear elastic or viscoelastic, homogenous and isotropic half-space, considering an isolation efficiency of 75% which corresponds to Amplitude reduction ratio $A_R = 0.25$ to judge the successfulness of screening; they found that depth of open trench should be at least 0.6 $\lambda_{R.}$ Moreover; they noticed that for an open trench, there is a slight decrease of A_R with L (distance from source) for all values of normalized depth D and this decrease becomes more significant for higher values of T. they stated that disregarding the presented wall instability problems, open trenches are more effective than in-filled trenches. Haupt (1995) made a theoretical study for the parameters affecting the isolation efficiency of an open trench considering some previous studies of Woods (1968), Barkan (1962).

Haupt (1995) found that active isolation measures are placed in the near field of a wave source at a maximum distance about 1.5λ_R - 2 λ_R ; where an amplitude reduction factor calculated over a length of about 1 λ_R turns to be $A_R = 0.26$. He noticed that amplitude immediately behind the trench is much lower than at a greater distance; however open trenches have a reducing effect of the maximum vibration values at least equals to 0.3. Moreover, the satisfactory isolation effectiveness -which is specified by $A_R = 0.25$- is reached in active and passive case at a normalized depth about D=0.8. Describing the behaviour of waves, Haupt (1995) illustrated that at the front face of the open trench a part of Rayleigh wave energy is reflected. However, for shallow trenches, a significant portion of Rayleigh wave energy was allowed to pass below the trench.

Ahmad et al (1996) performed a numerical study on the effectiveness of open trenches as wave barriers by utilizing a three-dimensional BEM algorithm "BENAS," that has been used to perform an extensive parametric study. The soil was modelled as: a homogeneous, isotropic viscoelastic half-space, while a rigid surface foundation subjected to vertical periodic load was considered to be the vibratory source. Dimensions like depth and width of barrier, distance from source to the open trench, and diameter of footing surface (source) were all normalized in term of Rayleigh wavelength. Through Ahmad et al study it was found that amplitude reduction ratio depends on the size of footing (source) and the distance of the barrier from that source. The normalized distance of barrier from the source in addition to the normalized source dimension were also basic parameters to obtain the normalized optimum depth D for maximum screening efficiency. However, in this study a result was stated that deeper trenches are needed at closer source locations, also it was discovered that waves reflected from the trench becomes more prominent as the distance between the source and the trench lessens.

Shrivastava et al (2002) have written a paper examining the effectiveness of open trench for screening Rayleigh waves due to impulse loads for 3D problems using a computational scheme that involves the use of a 3D finite element method (FEM) with eight-nodded brick element. In their study the soil has been idealized as linear and isotropic continuum and assumed to be sand-silt with cohesion of 33.16 kPa and internal friction angle about 38'. Experiments were restricted for vertical vibrations only using a vibration exciter as a source. The results were normalized with respect to Rayleigh wavelength λ_R. The geometrical parameters of the trench (length L and Depth D) have been also normalized with respect to Rayleigh wavelength.

Shrivastava et al (2002) found a good agreement with the Woods' test field results. They also discovered that for lower length of trench (L), there was no change in the amplitude reduction ratio before the trench. However, as the length of trench increases, a significant increase in the displacement before the trench. In other words, any increase in the trench length or depth may lead to decrease in amplitude ratio. It was also shown that width of trench does not appear to be an important parameter. But increase in width appears always beneficial.

Ju (2004) explored the use of a three-dimensional finite-element analysis to model soil vibrations due to high-speed trains on bridges. Finite-element model was large in geometry with 675-m length, 423.75-m width, and 104-m depth and a square element size of 3.75 m, the soil and bridge foundation are modelled by an eight-node 3D solid element. A Surface displacement of a finite-element analysis was performed, in which a 25-m deep open trench is located 50 m from the centreline of railway having a trench width of 3.75 m. The train velocity was assumed to be 300 km/h and the bridge's pier height was 8 m.

Results showed that open trenches can isolate soil vertical vibration; however, their efficiency seems disproportionate to their cost. In order to improve the isolating efficiency, the trenches should be deeper and wider, in other words; geometry of the trench is significant for efficiency. However, for vibration frequency less than 3.3 Hz an open trench cannot isolate vibrations, while it is efficient for frequencies over 4 Hz.

Tsai and Chang (2009) have studied the effects of open trench siding on vibration-screening effectiveness using the two-dimensional boundary element method utilizing a 2D frequency-domain BEM. They have studied the screening effectiveness of the open trench–wall barrier for isolating the vibration induced by a rigid massless strip footing subjected to vertical harmonic loadings. Trench wall and the soil were assumed to be isotropic, viscoelastic, and homogeneous. Trench depth, embedded length, width, and distance of the trench are normalized with respect to the Rayleigh wavelength, and a footing with a fixed width of 2.5 m was used for the strip vibration source footing, which produces harmonic vibrations that results from a 1 KN harmonic force.

Tsai and Chang (2009) assumed the Rayleigh wave velocity of soil V_R to be 250 m/s and the Rayleigh wavelength not to exceed 5 m. the finest element size of mesh was set to be λ_R /40 and average amplitude reduction ratio was adopted. Trench was located at a distance of 20 m from source. The embedded wall length was equal to the open trench depth.

As a result of this study, it was found that if the trench depth exceeds 1.5 λ_R in the open trench–diaphragm wall barrier system, the screening effectiveness will reach that suggested by Woods (1968) which is $A_R = 0.25$. Moreover the study proves that barriers with trench depths greater than 1.5 λ_R will result in a vibration reduction ratio $A_R = 0.1$.

Considering the effect of Rayleigh wavelength, it was found that the effectiveness of reducing vibration amplitude increases with increasing vibration frequency. In contrary, for lower frequency vibration situation, which has a longer wavelength, the screening effectiveness is significantly reduced and a deeper trench is required in order to achieve a well-accepted screening effectiveness.

It was concluded that open trench–sheet piles barrier system provides much better screening effectiveness than a pure open trench barrier system, where it exhibits the most significant screening effectiveness, $A_{ry} = 0.1$ for normalized depth D > 1.5.

Çelebi et al (2009) made a series of field tests on the foundation vibrations generated by electro-dynamic shaker which produces vertical harmonic vibrations in a certain frequency range of 10-100 Hz which make Rayleigh wavelength to vary in the range 7.98m-7.92m. Two footings with dimensions 1.0 m*1.0 m*0.5 m are constructed with clear distance of 25 m, where a distance of 4 m was considered for active isolation case measurements and a distance of 20 for the passive one. They have found that for active isolation minimum depth of an open trench is preferred to be at least 0.6 λ_R at a point having a distance of 10 λ_R away from the trench. However, for passive isolation the depth of trench should be about 1.33 λ_R for a measuring point located at a distance of 2 λ_R - 7 λ_R from the wave barrier, while the width of open trench must be in the range 0.1 and 0.5 λ_R to accomplish such remarkable reduction in vertical soil vibrations. However, barriers have been found to be generally more effective in passive isolation compared to active isolation for both measurement points.

Thompson et al (2015) have studied reducing the railway-induced ground borne vibration by using open trench and soft filled barriers. They used coupled finite element/boundary element models that were expressed in term of axial wavenumber, assuming that a train running on surface railways over a soft ground produces vibrations with frequency less than 40 Hz.

Considering the open trench case, Thompson et al (2015) placed a 0.5 m width open trench 8 m away from train's railway with depths D=1.5, 3, and 6 m. Results of their study showed that rectangular open trench performs best and its depth is most important parameter where deeper trench is more able to attenuate Rayleigh waves with longer wavelengths. In other words, increasing depth of open trench makes it capable to attenuate lower frequencies and improves the attenuation of high frequencies.

In term of isolation efficiency it was found that open trench is efficient when its depth $D > 0.6\ \lambda_R$, the mentioned criteria has been met at about 50 Hz frequency. The study also states that performance of a trench with one or more sides sloping at 45' or 60' to the vertical is very similar to that of vertical-sided trench.

Ankurjyoti Saikia (2016) has written a paper comparing the active vibration isolation of open and in-filled trenches. He analysed using finite element modelling on PLAXIS2D and assuming standard fixity boundary conditions and linear elasticity in the modelled soil half-space. Saikia generated a frequency of 31 Hz and considered the surface displacement amplitudes that being calculated for 10 nodes in order to find amplitude reduction ratio.

Geometry of trench was 3 m deep and 1.5 m wide, trench was located at a distance of 3 m from the source to satisfy the active isolation. Impedance ratio in the case of filled-in barriers was chosen to be in the range 0.08-0.42. Thus, filled-in barriers are soft barriers and being compared with open trench with identical dimensions and location. However, it was found that softer in-filled trench barriers of impedance ratios lying between 0.08-0.17 exhibit isolation effectiveness comparable to open trenches. Furthermore, Isolation efficiency of in-filled trenches increases with decrease in impedance ratio.

Saikia (2016) also discovered that open and softer barriers are more effective in isolating the vertical vibration component than the horizontal. Numerically, within *IR*=0.08-0.17, a trench of depth d = 1λ_R as an active barrier, can screen off nearly 65%-75% of the vertical vibration and 55%-60% of the horizontal vibration.

El Ouhahabi and Krylov (2016) made a reduced scale experimental modelling using ultrasonic Rayleigh wave propagation over seismic barriers. With a scaling factor of about 1:1000, applying a central frequency of 1 MHz, and using an aluminium rectangular blocks having the dimensions of $35 * 25 * 2$ cm where each of these blocks can be considered as an elastic half-space.

Rayleigh wavelength corresponding to the generated frequency was $\lambda_R = 2.9$ mm. Considering 3 systems of suggested barriers: a single trench, three trenches, and six trenches with the same geometry criteria of depth d = λ_R/4, width w = λ_R/2, and constant length $l = 29.4\ m$, the centre to centre distance of each two consecutive trenches is equal to Rayleigh wavelength.

The study results showed that amplitude reduction ratio of single trench is 0.30 while it is 0.1 and 0.04 for three trenches and for six trenches respectively. It was found that there is a reflection coefficient for Rayleigh waves about 0.19 and 0.29 for angles of 30^o and 60^o respectively. It has been noticed that rough surface provides a small attenuation of Rayleigh waves.

Lei He et al (2017) have used a model test box while researching the isolation efficiency of trench in a soil medium to vibrations, they have considered a scale factor of 1:50. Giving a model box with the geometry 2.1 x 1.8 x 1.5 m filled with Beijing silty clay with sawdust. Frame of the model box was made of steel, and its bottom was a steel plate. Sides and bottom of the model box were all covered by polyethylene foam layer of thickness 5 and 10 cm respectively. This was in purpose of avoid boundary reflection of waves. Excitement to model box was achieved using a hammer shock on the surface.

Results of research found that the range of frequency where the isolation can be effective is 40-300 Hz, it was monitored that high frequency wave (100-150 Hz) was isolated more efficiently than low frequency peak (75 Hz). It was stated that increase trench length would help improving isolation effect, however, there is a specific frequency range the isolation would not increase monotonically with trench length.

Syed (2016) made a numerical study of screening effectiveness of open and filled trenches using the scaled boundary finite element. The far-field is modelled using the scaled boundary finite element method (SBFEM). The trainload is simulated using two simultaneously applied concentrated line loads which cover a wide frequency range. An elastic half-space was assumed for the modelled soil. Trench is 3 m deep and 1 m wide, the source from distance for the active isolation case 4 m and 20 m for the passive isolation case, response was evaluated at a point that is 25 m away from the left hand side of embankment.

Obtained results prove that the depth of trench is significant; a 42% reduction in the acceleration amplitude in the case of 3m depth and about 62.5% reduction in the case of 6m depth when compared with no trench case. It was mentioned that and open trench was more effective than filled-trenches. It was found that the active isolation is more effective than the passive isolation keeping all other parameters similar, where open trench leads to about 50 % reduction in the acceleration amplitude for active isolation and about 42 % reduction for passive isolation.

The study clarified that the percentage reduction in the acceleration amplitude in the case of 1 m width is about 62.5% whereas it is 63 % in case of 2 m width when compared with no trench case.

Amir Kamyab Moghaddam (2017) has made a review on the current methods of railway induced vibration attenuations considering wave barriers, specifically open trenches, as an applicable method. Moghaddam (2017) found that increasing the width of the open trench has little influence on vibration attenuation and the performance of trenches with side slopes (45 or 60 degrees) is very similar to that of a vertical trench. In addition, he stated that the ratio of distance to track to depth of trench is an important factor of trench effectiveness, in other words, a deeper trench must be located at further distance from track.

2.4.2. Filled-in Barriers

2.4.2.1. Concrete Barriers

Due to their strength, durability, and practicality; trenches filled with concrete are available alternatives to be wave barriers that can somehow object the propagated

Rayleigh waves within the soil medium. Concrete density is higher than density of soil, thus concrete can be expressed as stiffer material than soil.

In the numerical study that they have performed, Beskos et al (1986a) have reported that in order to achieve an efficient isolation, which was determined to be $A_R = 0.25$ by Richart, Hall and Woods (1970), a concrete filled in barrier must have a rectangular sectional area $D \times W > 1.5$, where D and W respectively, are the normalized depth and width of the barrier normalized with respect to the Rayleigh wavelength.

Al-Hussaini and Ahmad (1996) conducted another numerical investigation on active isolation of machine foundation by in-filled wave barriers. The study was performed in a three-dimensional viscoelastic half-space, while soil was modelled as a homogenous and isotropic. Wave barrier was annular filled with concrete, a wide range of depth and width of trench, location of trench, size of foundation, and shear wave velocity ratio and density ratio between the barrier material and soil.

Source was a rigid circular footing, all dimensions were normalized with respect to Rayleigh wavelength, and amplitude reduction ratio was given by vertical displacement and has been evaluated over a distance extending to 5 λ_R beyond the outer edge of the annular trench.

Through their study, Al-Hussaini and Ahmad (1996) reported that effectiveness of a concrete barrier increases with increased barrier shear wave velocity to soil shear wave velocity ratio V_{SB}/V_{SS}. It is recommended that V_{SB}/V_{SS} be larger than 5 and preferably 7.5 or more. However, any improvement in screening efficiency beyond V_{SB}/V_{SS} = l0 is negligible. Considering width of barrier, it was found that as the barrier width *(W)* is increased, the amplitude reduction capability of a concrete barrier increases. The influence is greater for barriers located close to the source. However, beyond W = 0.5 the effect of width is minimal.

Shrivastava and Rao (2002) performed a three-dimensional numerical study for concrete trenches performance as wave barriers. They monitored that in case of trench filled with concrete, there is always some possibilities for Rayleigh wave to adopt short-cut path to cross the trench along width through concrete, and reach the after trench region. In other words, efficiency of vibration isolation with concrete barriers is affected by the percentage of wave that passes the concrete medium.

Çelebi et al (2009) established an experimental realistic study which contained field experiments on foundation vibration. Vibrations were produced using a dynamic shaker which generates frequencies of the range 10-100 Hz to obtain Rayleigh wavelength within the interval 1.98-7.92 m. Two footings with geometry of $1 \times 1 \times 0.5$ m were constructed with clear distance of 25 m, where a distance of 4 m was considered for the case of active isolation measurements and 20 m for the case of passive one. The screening efficiency of open trench and filled-in trenches (soft and stiff backfills) was examined by conducting field experiments.

Çelebi et al (2009) concluded that a water-filled trench is capable to achieve 200% reduction in the maximum vertical displacement in comparison to the no trench case. Precisely, this is attained at observing time t = 5 s for frequencies 10 and 25 Hz. Furthermore, concrete-filled trench is found to imitate the water-filled trench for these frequencies (10 Hz and 25 Hz).

Syed (2016) made a numerical study of screening effectiveness of open and filled trenches using the scaled boundary finite element method. The far-field is modelled using the scaled boundary finite element method (SBFEM). The trainload is simulated using two simultaneously applied concentrated line loads which cover a wide frequency range. An elastic half-space was assumed for the modelled soil. Trench is 3 m deep and 1 m wide, the source from distance for the active isolation case 4 m and 20 m for the passive isolation case, response was evaluated at a point that is 25 m away from the left hand side of embankment.

Syed (2016) found that for two different backfill materials: a soft soil and concrete. For this analysis, D = 6 m, W = 1 m and L = 20 m. The material properties of soft soil are: *E* = 28 MPa, ρ = 1750 kg/m3 and v = 0.4. The material properties of concrete are: *E* = 25 GPa, ρ = 2000 kg/m3 and v = 0.25. The trench filled with soft soil is more effective in vibration isolation than the trench filled with concrete.

Zoccali et al (2015) have worked on studying the mitigation capacity of vibrations induced by trains regarding filled trenches. They performed an analysis using a finite element model. Validation of the model is achieved by a comparison with a series of in-situ measurements. Judgement and evaluation of the filled-in trenches effectiveness was performed through calculating amplitude reduction A_R, which is defined as $A_R = \frac{PPV_{trench}}{PPV_{default}}$ where, PPV is the obtained peak particle velocity for each single observing point at the case of trench presence and the same value in the same point with no trench. Soil was assumed to be elastic homogeneous, elements have been modelled as three-dimensional solid elements taking into account 8-nodes. Placing of trenches was modelled to be in parallel with the railway at a distance of 9 m away of the middle of the railway track. 16 observing points were taken into account, 8 of them were located on the soil surface, and the other 8 were placed at a depth of 1 m beneath the soil surface. Alignment of the observation nodes was oriented to be perpendicular to the located trenches. The results have shown that increasing the length of trench provides better isolation efficiency, however; this improvement in efficiency is –somehow- affected by the fill-in material used in trench. Precisely, a concrete-filled trench (stiff backfill IR > 1) does have a damping property that contributes in making it more efficient than soft backfills (IR < 1). Furthermore, Zoccali et al (2015) stated that regarding the PPV index, concrete-filled trenches are certainly the best alternative whenever they are placed parallel to railway track and they selected to be long.

2.4.2.2.Geofoam Barriers

Geofoam is a lightweight material, casted in large blocks. It is made of expanded or extruded polystyrene (EPS/XPS) with different densities and textures.

Geotechnical usage and application of expanded polystyrene (EPS) have started in 1960s. Due to its low density, expanded polystyrene was used as a backfill alternative in purpose of reducing the undesired effects to the adjacent soil and to the nearby structures. Numerically, its density can reach 1% of density of soil. Which represents 10% of the density of any other filling alternatives.

Many applications for Geofoam in insulation and isolation were discovered, vibration isolation of soil can be one of them.

Alzawi and Elnaggar (2009) have examined the efficiency of several configurations of Geofoam in an inclusive parametric study. The study was numerically performed using the finite element program ABAQUS in two-dimensional and three-dimensional models. Although that they have modelled the soil to be in an optimized conditions (isotropic, homogenous, and elastic), they normalized all parameters with respect to Rayleigh wave length λ_R. They have modelled the soil and assigned 8 nodes, the nodes have had the first-order hexahedron element in accordance to the relevant properties.

In their simulation, Alzawi and Elnaggar (2009) have assumed a cyclic load with a magnitude of 1 KN to be harmonic making a frequency of 31 Hz in the simulated soil half-space soil. Which corresponds to waves having a uniform Rayleigh wavelength of λ_R = 3 m. Other material properties of the soil were defined to be: Poisson's ratio ν=0.25, shear wave velocity V_S = 101 m/sec, and Rayleigh wave velocity V_R=93 m/sec.

Alzawi and Elnaggar (2009) have concluded that all the proposed Geofoam barrier systems (single or double barriers), in average, do reduce the surface waves giving an isolation efficiency of 38% - 80%. In addition, in the case of low frequencies, Geofoam was found to have a protective performance. Furthermore, double continuous walls system has been found to achieve an effective isolation whatever was the distance to vibration source. In other words, for active isolation the system of double continuous walls was capable to achieve good screening efficiency. On the other hand, for passive isolation conditions, single-continuous wall system was reported as an effective-economic isolator. Not to mention that double-staggered walls system have also achieved good isolation in passive isolation conditions; however, it was found not an economical alternative since more Geofam material is willing to be consumed.

Alzawi and Elnaggar (2010) performed an investigation targeted on both open and in-filled trench with Geofoam material. Considering the Ground vibrations which are being induced by machine foundations, the results from the experimental study revealed that the Geofoam barrier can be considered as an effective alternative for vibration reduction. The barrier can reduce vibrations up to 68%. As a part of this study, the depth of barrier is explored. It is found that they are more effective for normalized depth greater than 0.6.

Amir Moghaddam (2017) made a review study on the current methods of railway induced vibration attenuations. He reported that comparing the performance of water filled and Geofoam filled trenches shows that Geofoam barriers outperforms water filled barriers. However, as the distance from the vibration source increases, both types of trenches perform similarly. At lower frequencies, the effectiveness of both water filled and Geofoam filled trenches are very close but for higher frequencies of excitation source, Geofoam produces better attenuation.

Ekanayake et al (2014) have studied the attenuation efficiency of ground vibrations for different fill-in materials. The study included finite element modelling for the system on a three-dimensional software. The constructed model was validated relying on the results of an experimental study on isolation efficiency of EPS Geofoam filled-in trenches. Then, model was used in purpose of evaluating the screening efficiency of open trench and water-filled trenches. In addition to the EPS Geofoam-filled trenches.

A frequency varies in range of 25-55 Hz was applied to the system and the corresponding Rayleigh wavelength was in the range λ_R =3.91-8.59 m.

Results of this study found that EPS Geofoam is found to be the most efficient fill material. It was also discovered When EPS Geofoam wave barrier is used in active isolation, vibration attenuation is less than that obtained from passive isolation, concluding that the barrier efficiency can be improved by adopting passive isolation.

2.4.2.3. Piles

Aviles et al (1983) have investigated –theoretically- the utility of isolating elastic waves by forming a barrier consists of a line of rigid piles, which have been chosen to be circular in cross-section. Each single pile was assumed to be penetrated in an idealized soil space (elastic, isotropic, homogenous, and unbounded). Aviles et al (1983) have provided a numerical solution in order to solve the two-dimensional problem which considered the issue of spreading of the elastic waves. The effectiveness of pile line barrier was studied taking into account frequencies and variable cases of sites and fields.

The study found that such a pile row alignment can provide a good level of vibration isolation whenever the excitement field produced vibrations having wavelength range within the interval 1-4 times the piles sectional diameter. Moreover, continuous barrier became better isolator to waves (more efficient) of shorter wavelengths.

Aviles et al (1988) presented another theoretical analysis solving the problem of foundation isolation from generated vibrations in neighbourhood using a row of circular piles as wave barriers. In this study two cases were considered: a two-dimensional one with piles of infinite length and incident plane SV waves, and a three-dimensional realistic case having finite piles, incident Rayleigh waves and a free surface.

The study stated that length of a pile must be > 2 λ_R to achieve considerable vibration isolation. It was also suggested to have a barrier width of about 3 times width of the desired to be isolated zone which was found to be located at an optimum distance of 150-250 times radius of pile. The study recommended that to have an isolation effectiveness of 50%; diameter of piles should be > $\lambda_R/4$.

Kattis et al (1998) constructed a three-dimensional model for studying –numerically- the vibration isolation efficiency of a pile row. While modelling, the pile row was simulated by a trench acting as a wave barrier in passive condition. An advanced frequency interval was considered for the boundary element method used in analysis. Results of the study showed that the minimum depth of an effective wave barrier should be 0.8 λ_R. Furthermore, the study found that the geometry of the pile row (depth, length, and width) affects the vibration isolation efficiency in a similar way it does for the common wave barriers (open or filled-in trenches).

Kattis et al (1998) have concluded that as the number of piles in the row increases, the vibration screening efficiency of the system increases. This can be expressed like, as the spacing between two consecutive piles decreases, the vibration isolation capacity to the system increases. However, a maximum practical value of A_R = 0.3 is attained in presence of open piles

Tsai et al (2007) performed a three-dimensional analysis of the screening effectiveness of hollow pile barriers for vertical vibrations. In this study, four types of piles were have been considered: steel pipe piles, concrete hollow piles, concrete solid piles and timber piles.

As results of their comparative study, Tsai et al (2007) found that using steel pipe pile for vibration screening is most effective among the four types of piles studied. Considering other than steel pile, the screening effectiveness of timber pile and concrete solid pile was very similar which might be understandable because the shear modulus of each of timber pile and concrete solid pile are close. The study showed that screening effectiveness of pile barriers is insensitive to vibration frequency.

2.4.2.4.Bentonite Barriers

Bentonite is a clay generated frequently from the alteration of volcanic ash, consisting predominantly of smectite minerals. Due to its low density, bentonite is considered as a soft wave barrier that may be able to attenuate propagated Rayleigh waves into soil.

Çelebi et al (2009) established an experimental realistic study which contained a series of field tests on a foundation vibration using a dynamic shaker generates vertical harmonic vibrations in the certain frequency range 10-100 Hz to obtain Rayleigh wavelength within the interval 1.98-7.92 m. Two footings with dimensions 1.0 m × 1.0 m × 0.5 m are constructed with clear distance of 25m where a distance of 4 m was considered for active isolation case measurements and a distance of 20 for the passive one. Experiments were carried out on site in order to examine the screening efficiency of open and in-filled trench barriers, such as backfilled with water, bentonite (softer materials than soil) and concrete (stiffer material than soil).

Çelebi et al (2009) found that Bentonite trench barrier gives the best isolation measures in high frequency values of 50, 75 and 95 Hz. Considering the low frequencies; bentonite-filled trench barrier gives the best isolation effect in the frequency of 10 Hz. The reduction efficiency of this trench barrier can reach around 40%.

Al-Hussaini and Ahmad (1996) performed a numerical investigation on active isolation of machine foundation by in-filled wave barriers. The study was conducted in a three-dimensional viscoelastic half-space, while soil was modelled as a homogenous and isotropic. Wave barrier was annular filled with bentonite, a wide range of depth and width of trench, location of trench, size of foundation, and shear wave velocity ratio and density ratio between the barrier material and soil.

Source was a rigid circular footing, all dimensions were normalized with respect to Rayleigh wavelength, and amplitude reduction ratio was given by vertical displacement and has been evaluated over a distance extending to 5 λ_R beyond the outer edge of the annular trench.

Al-Hussaini and Ahmad (1996) found that at such a low value of V_{SB}/V_{SS}. ratio, the soil-bentonite barrier acts very much like an open trench barrier. In addition, for a soil-bentonite barrier, a normalized barrier depth D of 0.8 or more, in general, produces effective screening ($0.1 < A_{RR} < 0.4$).

Zoccali et al (2015) have worked on studying the mitigation capacity of vibrations induced by trains regarding filled trenches. They performed an analysis using a finite element model. Validation of the model was achieved through a comparison with series of in-situ measurements. It was reported that for all filling-in materials, vertical displacements were monitored above and at the foot of the ballast. Nevertheless, in case of a 50 m long trench filled with soil-bentonite mixture the increase was maximized to reach 1.5%. Moreover, the obtained amplitude ratios by the soil-bentonite mixture and the concrete have been found quite similar to each other. However, while analysing the reduction level of velocity in the third octave bands, essential differences in behaviour of isolation of these two materials appear whenever the frequency ranges within the interval 1 Hz – 50 Hz.

2.4.2.5. Water-filled Barriers

Çelebi et al (2009) conducted an experimental realistic study which contained a series of field tests on a foundation vibration using a dynamic shaker generates vertical harmonic vibrations. Çelebi et al (2009) reported that Water-filled trench gives the best screening effect in the range of the excitation frequencies from10 to 50Hz. Moreover, the isolation effect of water-filled trench is more effective for excitation frequency of 25 Hz.

Ju and Li (2011) used three-dimensional time-domain finite-element analyses to study the isolation efficiency of open trenches which are filled with various levels of water. In the study; soil was assumed to be isotropic half-infinite layered. The soil and the foundation of the applied load to the system were modelled using eight-node iso-parametric elements. The result of this study indicates that a water trench can efficiently reduce the X and Z waves on the soil surface which represent the along trench axis and the gravity axis respectively.

Amir Moghaddam (2017) made a review study on the current methods of railway induced vibration attenuations. He reported that comparing the performance of water filled and Geofoam filled trenches shows that at lower frequencies, the effectiveness of both water filled and Geofoam filled trenches are very close.

2.4.2.6.Gas Cushion Barriers

Massarsch (2005) used the boundary element method to compare the vibration isolation effect of an open trench with that of a gas cushion screen. Then, the obtained analytical results were compared with field tests. Massarsch (2005) used cushions composed of flexible, plastic-aluminium laminate. They were inflated to pressure which is equivalent to the surrounding earth pressure. The trench has been filled with a cement-bentonite slurry as a protector.

The performed theoretical study showed that the isolation effectiveness of the gas cushion screen is practically identical to that of an open trench. Comparing the study with results of field tests in clay; it was found that a vibration isolation effect of 50% to 80% can be expected, if the depth of the gas cushion screen was about 1 λ_R.

Jain and Soni (2007) have reviewed the screening of disturbance using different types of wave barriers, where; a vibratory energy affecting structures was carried by surface (Rayleigh) wave that propagates in the zone near the ground surface. As a result of this study, they observed that vibration isolation screen "Vibrisol" which consists of gas-filled panels (gas cushions) forms stable vertical underground screen. This screen has a vibration isolation effect that is very similar to its counterpart in case of an open trench existence.

2.4.2.7. Rubber Chips Barriers

Rubber chips are the aggregates resulting from crushing of the waste tires, they can be used in civil engineering field in geotechnical purposes as a geo-material. For instance, they can be used as lightweight fill materials for embankments.

Rubber chips are an abundant material that can be obtained from the industrial wastes and scrap. They are soft, lightweight material with densities that varies in the range 400-600 Kg/m^3.

Considering the use of rubber chips in vibration isolation of soil, Andersen and Nielsen (2005) employed a coupled finite element-boundary element model of a track and a subsoil for the analysis of a track passes over a half-space and subject to a moving harmonic source. In-filled trenches have been assumed to be isotropic, homogeneous, and linear elastic mediums. Generated frequency was in domain of 10-40 Hz and the corresponding Rayleigh wavelength was 5-20 m. A 6 m deep open trench was modelled filled with rubber chips and concrete in two different stages.

Results of this study showed that at low frequency of 10 Hz, the concrete barriers outperform the rubber chips barriers, this is found to be noteworthy since the rubber chip material damping is larger than material damping of concrete. However, more adjacency in isolation efficiency of concrete-filled trench and rubber chips-filled trench is captured at larger frequencies. In other words, both wave barriers were found effectively isolating with different frequency range. Precisely, for frequencies 10 Hz and 40 Hz, the rubber chip-filled trench was found to be more efficient than the concrete-filled trench. However, at frequency of 20 Hz, a deficiency in the vibration isolation behaviour of the rubber chip-filled trench occur which makes the concrete-filled trench superior (better isolator) at this frequency. Furthermore, for intense frequencies, the deeply excavated open trenches are found better alternative than rubber chip-filled trenches.

Buonsanti et al (2009) made a finite element analysis in an elastic semi-space for the vibration induced from the passage of a high speed locomotive. Rubber chips with 10% damping were defined as wave barriers.

The study found that although rubber chips are material with high damping ratio, it is not necessarily to have a significant vibration isolation efficiency magnitude.

Years later, Zoccali et al (2015) have worked on studying the mitigation capacity of vibrations induced by trains regarding filled trenches. Zoccali et al (2015) concluded that the mitigation capacity of rubber chip was not believe to be meaningful since 4% - 5% isolation efficiency was attained.

Recently, Mahdavisefat et al (2017) have conducted a full-scale experimental study on screening efficiency of sand rubber-mixed filled trenches. Being defined as a lightweight, high energy absorber, and environment friendly material, sand rubber mixture has been used as a fill-in material. Although they used a wide range of frequency 10-600 Hz. Mahdavisefat et al (2017) have reported all results in the range 10 to 400 Hz basing on amplitude reduction ratio that was obtained with respect to peak particle velocity. Results of this study reported that 30% rubber SRM-filled trench performs very similar to the open one, however, increase in rubber content increases the energy absorption capacity which will improve the performance.

2.5. Efficiency Criteria and Types of Isolation

2.5.1. Efficiency Criteria

In favour of studying the vibration isolation conceptually, the propagated Rayleigh wave in soil was analysed to horizontal and vertical component. However, and considering isolation issues, most researches have concentrated on the vertical component if Rayleigh wave.

Ju (2004) had explored the use of a three-dimensional finite-element analysis to model soil vibrations due to high-speed trains on bridges. Finite-element model was large in geometry with 675-m length, 423.75-m width, and 104-m depth and a 90 m deep in-filled trench having a width of 3.75 m and being located 50 m of the railway. It was found that an in-filled trench is more efficient for vertical vibration isolation than horizontal vibration isolation.

Ankurjyoti Saikia (2016) has written a paper comparing the active vibration isolation of open and in-filled trenches. Barrier efficiency was analysed in terms of reduction of vertical and horizontal vibration components.

Both open and softer barriers are more effective in isolating the vertical vibration component than the horizontal. Within IR = 0.08 - 0.17, a trench of depth d = 1 λ_R as an active barrier, can screen off nearly 65%-75% of the vertical vibration and 55%-60% of the horizontal vibration.

Saikia (2014) have performed a numerical study in purpose of evaluating the screening effectiveness of surface waves by double wave barriers. He modelled the system on the finite element software PLAXIS2D, soil was defined in an optimized condition to be elastic, homogenous, and isotropic half-space. The excitement to the system was provided by a steady-state vertical action on the soil half-space. The double wave barriers were modelled and assumed to be filled by a soft backfill material. Results of the study reported that the dual filled-in trenches are more capable to isolate the vertical resultant vibrations than the horizontal ones. Numerically, for dual filled-in wave barrier with a shallow uniform depth of 0.5 λ_R, an isolation efficiency of 80% is gained for vertical vibrations, on the other hand, the attained isolation efficiency for horizontal vibrations was about 63%.

As efficiency criteria, researchers tended to consider the effect of vertical component of Rayleigh wave to the ground surface soil particle. This effect had come in three terms; displacement to soil particle, velocity of soil particle when displacing, and the attained acceleration to the soil particle while starting to displace.

According to each of displacement, velocity, and acceleration a new term was casted as A_R which expresses the amplitude reduction ratio which being used in order to evaluate the isolation efficiency of the provided system of isolation.

Çelebi et al (2009) established an experimental study that considered the ratio of the vertical displacement amplitudes at the point in the presence and in the absence of the trench which were computed from acceleration data. Al-Hussaini and Ahmad (1996) conducted a numerical study on active isolation of machine foundation considered amplitude reduction ratio A_R to be in term of displacement. Shrivastava and Roa (2002) made a three-dimensional numerical study on effectiveness of open and filled trenches, they evaluated the efficiency of isolation in term of amplitude reduction ratio that depended on the maximum obtained displacements. Saikia (2016) built a comparative study using PLAXIS2D. He considered the surface displacement amplitude to form the amplitude reduction ratio as criteria.

In fewer studies, amplitude reduction ratio has been obtained depending on velocity index for soil particles. Alzawi and El Naggar (2009) performed a study evaluating efficiency of using Geofoam as a vibration isolation material they considered the ratio of maximum vertical velocity before and after installation of trench to cast the amplitude reduction ratio. Later, Zoccali et al (2015) have worked on studying the mitigation capacity of vibrations induced by trains regarding filled trenches. They performed an analysis using a finite element model. They defined the amplitude reduction A_R as the ratio of peak particle velocity obtained in a single observation point with the interposition of a trench and the same value in the same point without any trench.

One common approach to obtain the amplitude reduction ratio was in term of acceleration ratios after and before placing the trench or barrier. Syed (2016) considered the acceleration data to form amplitude reduction ratio in the numerical study he made about screening effectiveness of open and filled trenches. He et al 2017 also depended on accelerations while casting A_R to evaluate vibration isolation effect of trenches using a scaled model test.

2.5.2. Active isolation

Active isolation is an isolation system which is being conditioned and directed with respect to the vibration source location. In other words, when a wave barrier is located nearer to the vibration source the system is called active isolation. Here it can be stated that, the criteria of judging the isolation type is the source-barrier distance.

Haupt (1995) found that the passive isolation is less effective than the active isolation for open trenches. However, in case of using a soft infill material, active isolation didn’t perform better than the passive one.

Syed (2016) made a numerical study of screening effectiveness of open and filled trenches using the scaled boundary finite element method. He found that the open trench leads to about 50 % reduction in the acceleration amplitude for an active isolation and about 42% reduction for a passive isolation.

2.5.3. Passive Isolation

On the contrary of active isolation, passive isolation is an isolation system which being conditioned and directed with respect to the affected structure's location. In other words, when a wave barrier is located nearer to the aimed-to-isolate region the system is called passive isolation.

Çelebi et al (2009) established an experimental study on vibration isolation using filled-in barriers. They found that considering a soft material, passive isolation is more efficient than active isolation.

2.6. Barrier Efficiency

Variation of wave barrier's efficiency and its sensitivity due to changing the geometrical dimensions and the characteristics of the infill material of the barrier were studied by researchers in order to set the optimum design for the barrier geometry and the ideal material to be used as an infill material.

2.6.1. Geometric Effect

2.6.1.1. Width of Barrier

Considering the minimum dimension of a barrier, which is width, most studies proved that the effect of changing width of barrier is negligible when comparing with other parameter. However, some researchers specified criteria for minimum required width to satisfy good vibration isolation.

Çelebi et al (2009) recommended that to accomplish a remarkable reduction in vertical soil vibration; width of barrier must be between 0.1-0.5 λ_R. However, Haupt (1995) Ahmad et al (1996), Tsai and Chang (2009), and Saikia (2014) found that the effect of width on vibration isolation efficiency of wave barriers is insignificant. Shrivastava and Roa (2002) agreed with that statement except for narrow trenches which, somehow, have better vibration isolation efficiency as the width increases. Moreover, they discovered that any increase in width outside the range 0.3-0.6 λ_R will increase the isolation efficiency of barrier by decreasing the amplitude ratio.

AI-Hussaini and Ahmad (1996) suggested upper limit for width according to its affect over the efficiency of vibration isolation to be 0.5 λ_R, where, any increase in width after that limit will not have a real effect on the amplitude reduction ratio.

Recently, Thompson et al (2015), through a coupled finite/boundary element analysis in a numerical study, stated that width has a small influence on vibration isolation efficiency. Later, Syed (2016) emphasized this numerically in a scaled boundary finite element analysis finding that there is a reduction in the acceleration amplitude in the case of 1 m width is about 62.5% whereas it is 63 % in case of 2 m width when compared with no trench case. However, considering trenches with side slopes of 45' and 60', Moghaddam (2017) have reviewed the current methods of attenuation of railway induced vibration. It was found that performance of a vertical trench is so similar to the inclined ones. It was also stated that in case of open trench any increase in width would have a little influence on vibration attenuation.

2.6.1.2. Length of Barrier

For length of trench, its effect was slightly studied since most of numerical studies were performed in two-dimensional analysis which is a way that disregards length.

Shrivastava and Rao (2002) in the 3D finite element analysis they made, they have found that for smaller length of trench, the amplitude ratio does not change before the trench. However, as the length increases, a considerable increase in displacement before trench is monitored. It was stated that wherever a point is further away from trench, effect of length disappears and displacements become constant. Generally, Increase in length causes decrease in amplitude ratio.

Zoccali et al (2015) have worked on studying the mitigation capacity of vibrations induced by trains regarding filled trenches. They performed an analysis using a finite element model. Throughout their study, Zoccali et al (2015) regarded series of fixed (constant in location) observing points in purpose of studying the mutual influence between length of trench and its in-filled material type. Among this study, it was found that increasing the length of trenches would absolutely provide a better isolation. On the other hand, it was noticed that the improvement amount passing from a length to a longer one found to be extremely influenced by the in-filled material which had been used. Thereafter, Lei He et al (2017) built a scaled three-dimensional model box. They discovered that an increase in the trench length would help improving the isolation effect. However, for a specific frequency wave, the attenuation ratio would not increase monotonically with trench length.

2.6.1.3 Depth of Barrier

Most studies on efficiency of vibration isolation of wave barriers concentrated on the depth variation and they most indicated to the significant role that depth has.

Haupt (1995) showed that the screening efficiency can be obtained within a trench depth of 1.2 λ_R - 1.4 $\lambda_{R.}$ AI-Hussaini and Ahmad (1996) found that in a vibration isolation system, there is a gradual increase in screening efficiency with any increase in depth up to a certain value of normalized trench depth which is defined as optimum depth. After the optimum value of normalized trench depth the amplitude reduction remains more or less uniform. Moreover, the normalized optimum depth is found to be a function of shear wave velocity ratio of barrier to the shear wave velocity of soil. Numerically, a minimum limit of 0.8 λ_R for barrier depth would produce an amplitude reduction ratio A_R in the range of 0.1-0.4.

Ahmad et al (1996) concluded that in order to achieve maximum efficiency, greater depths for trenches are required. Regarding active isolation, it was found that deeper trenches are needed in cases of closer source locations. Shrivastava and Rao (2002) have also indicated that larger depth of trench reduces the displacement after trench. In other words, increasing the depth of trench decreases the amplitude ratio.

Çelebi et al (2009) clarified that at a point 10 λ_R away from the vibration source, a minimum depth for open trench of 0.6 λ_R and 1.33 λ_R is required to achieve a good screening efficiency for active and passive isolation respectively for a measurement region located at a distance 2-7 λ_R away from the trench. Tsai and Chang (2009) recommended the open trench depth to be about 1.5 λ_R stating that the main influential parameter of screening effectiveness of open trench is depth. Considering a system of wave barriers consists of dual trenches, Saikia (2014) have found that depth of trench is dominant in affecting the screening efficiency. Saikia (2014) established an upper limit for trench depth of each of the trenches to be D_d=0.6 λ_R where the screening efficiency remain unaltered beyond the upper limit or marginally increases with further increase in depth of trench. However, Saikia (2014) stated that for a single trench, a greater depth is required when comparing with the dual in-filled trench barriers to satisfy the same targeted degree of isolation.

Thompson et al (2015) considered depth as the most effective parameter. They noticed that while increasing the trench depth the effective frequency range extends to include lower frequencies, and the attenuation performance at higher frequencies is being improved. Building efficiency criteria for 50 Hz frequency, Thompson et al (2015) stated that depth of open trench should be at least 0.6 λ_R. Syed (2016) realized the importance of depth of the open trench among the other geometric parameters. He found that a reduction in the acceleration amplitude of 42% corresponds to 3 m deep open trench, while the reduction percentage exceeds 62% for its 6 m counterpart. Moghaddam (2017) matched the distance to the railway inducing the vibration with the depth of trench creating a ratio which affects vibration attenuation. He recommended to locate deeper trenches at farther distances from the railway.

2.6.2. Characteristics Effect

2.6.2.1. Effect of Shear Wave Velocity

Shear wave velocity is one of the physical properties of the material. It is a key property which helps in evaluating the dynamic response of any material. Shear wave velocity is derivable from the shear modulus formula basing on the maximum shear modulus of the material, in addition to the determined density of it.

$$G_{max} = \rho \, V_s^2 \tag{2.5}$$

Where G_{max} is in Pa, ρ is in Kg/m^3, and V_s is in m/s. considering soils, Hardin and Drnevich (1972) stated that G_{max} and V_s are primarily functions of soil density, void ratio, and effective stress. Furthermore, there are secondary influences include soil type, age, depositional environment, cementation and stress history of soil.

L'heureux and Long (2016) have developed several empirical correlations between shear wave velocity, basic soil properties and geotechnical parameters in Norwegian clays. For material other than soil, Mak and Gauthier (1993) used ultrasonic measurement of longitudinal and shear velocities of materials at elevated temperatures in order to get the shear wave velocities using cylindrical specimens.

2.6.2.2. Effect of Density

It is well-known that density of a material is defined as the mass that it occupies per unit volume. As this mass increases, within a constant volume for sure, the density increases. Studies have showed that as the density of the in-fill material decreases its ability to transmit vibrational waves (Rayleigh waves) decreases. Therefore, some researchers preferred to fill wave barriers using materials having low densities than soil, like: Geofoam, bentonite, and rubber. On the other hand, others have studied the behaviour of screening efficiency using materials denser than soil, for instance, concrete, sheet piles, and water in order to recognize the isolation behaviour.

2.6.2.3. Effect of Impedance Ratio

Impedance is a product of the Rayleigh wave velocity of the material by the density of it.

$$Z = V_R * \rho \tag{2.10}$$

Variations in density or Rayleigh wave velocity lead to changing in impedance which gives changes to the efficiency of the barrier.

Considering a system of open trench or infill barrier with soil, Zoccali et al (2015) established the impedance ratio as shown:

$$I.R = \frac{Z_{barrier}}{Z_{soil}} = \frac{V_{R_{barrier}} * \rho_{barrier}}{V_{R_{soil}} * \rho_{soil}} \tag{2.11}$$

Furthermore, for evaluating behaviour of different materials, Zoccali et al have classified barriers as soft and stiff according to the ratio of impedance magnitude, where:

$$I.R < 1 - -- \rightarrow Soft\ barrier$$

$$I.R > 1 - -- \rightarrow Stiff\ barrier$$

Saikia (2016) built a comparative study using PLAXIS2D. He considered conditions for softer filled-in barriers having impedance ratio within the range 0.08-0.42 to evaluate their effectiveness and to compare with open trench of identical dimensions.

Saikia (2016) found that effectiveness of barriers with impedance ratios within the range 0.08-0.17 are comparable with open trenches. However, isolation efficiency of infill barriers increases with decrease in the impedance ratio.

Massarsch (2005) have studied ground vibration isolation using gas cushions. He noted that the propagated vibration energy can be expressed as an energy transmission coefficient, E_n, that is defined as:

$$E_n = \frac{4 * Z_{soil} * Z_{barrier}}{(Z_{soil} + Z_{barrier})^2} \tag{2.12}$$

Physically, in case of $Z_{soil} = Z_{barrier}$ the value of transmitted energy $E_n = 1$. In other words, this means no isolation effect is achieved. On the other hand, the isolation efficiency is maximized whenever the impedance ratio of the barrier is minimized.

3. FIELD EXPERIMENTS

3.1. Site Location

The location where the experiments were performed was a flat area located in the west of Mugla province which is called Bayir (Figures 3.1 and 3.2). Location has been chosen to be away of from any vibrational disturbances, like; construction activities, highway traffic, or industrial loads.

Figure 3.1. Mugla province, Turkey

Figure 3.2. Location of Experiments in Bayir-Mugla, Turkey

3.2. Properties of Soil

3.2.1. Physical Properties

For determining the physical properties of soil, Toygar (2015) has conducted series of in-situ and laboratory tests. Standard Penetration Test (SPT), Sieve Analysis, and Consistency Limit Test (Atterberg Limits) have been conducted for the top 30 m of the soil profile in order to classify the soil.

Toygar (2015) found that, the first 6 m of soil strata was consisted of clayey sand (SC) which having Atterberg limits as: LL=29% and PL=19%. The next 9 m of the soil strata was found to be low to high plastic clay (CL-CH) that was underlain by very stiff highly plastic clay (CH). Not to mention, that the ground water table was 3.5 m deep (Figure 3.3).

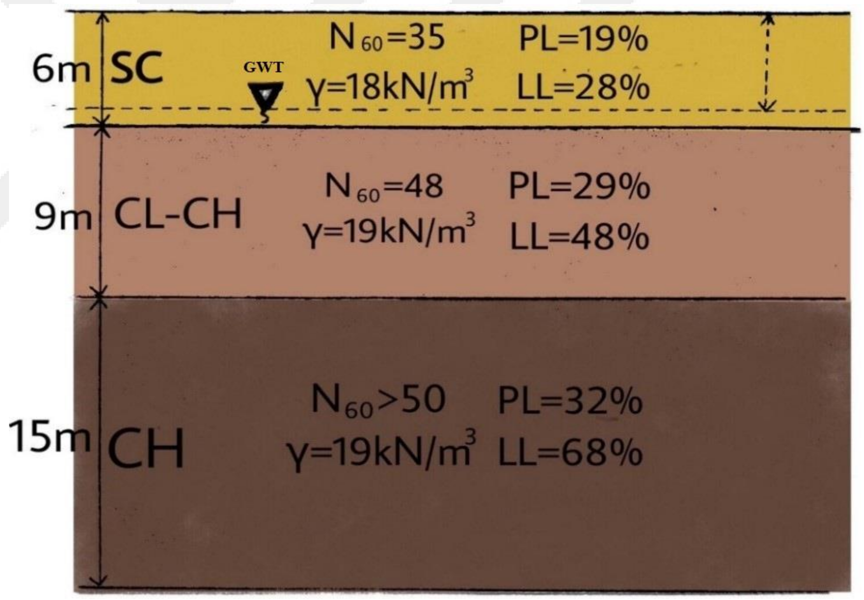


Figure 3.3. Soil Profile and layering

3.2.2. Dynamic Properties

Considering the dynamic properties of the soil, Toygar (2015) made a series of microtremor tests in order to estimate the predominant period of the site in case of low amplitude ambient vibrations. Toygar (2015) found that the predominant period of the site was about 0.32 s. Moreover, Toygar (2015) has determined the surface wave velocity of the soil by conducting the multichannel analysis of surface waves (MASW) tests. Toygar (2015) applied the tests in two directions of the site (north-to-south and east-to-west). He obtained the directional shear wave velocity profile as shown in Figures 3.4-3.5. However, the average shear wave velocity is shown in Figure 3.7.

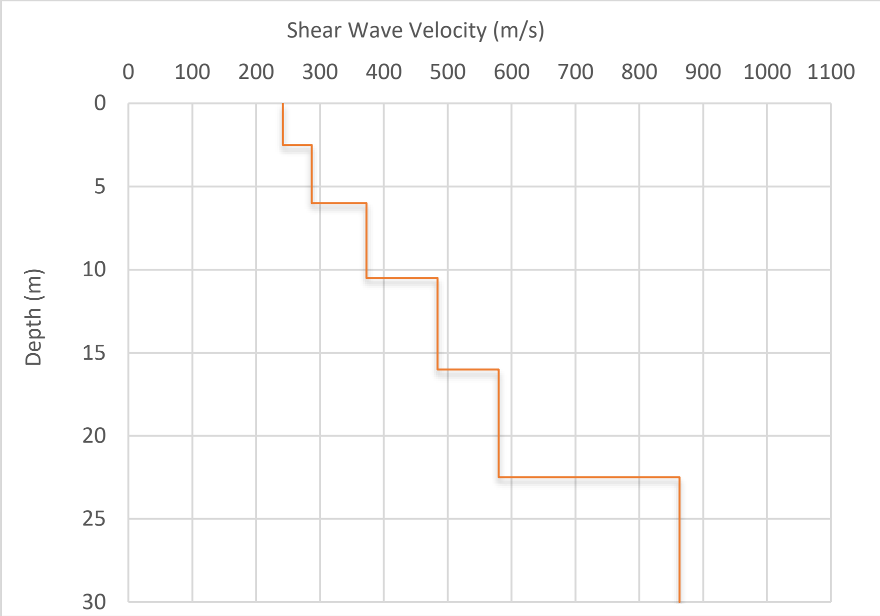


Figure 3.4. Shear wave velocity profile, North-South direction. Toygar (2015)

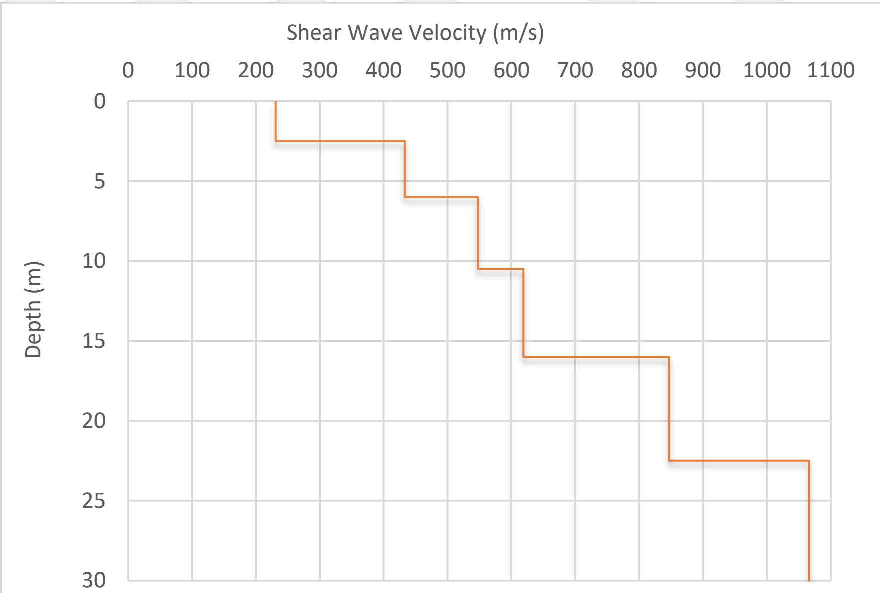


Figure 3.5. Shear wave velocity profile, East-West direction. Toygar (2015)

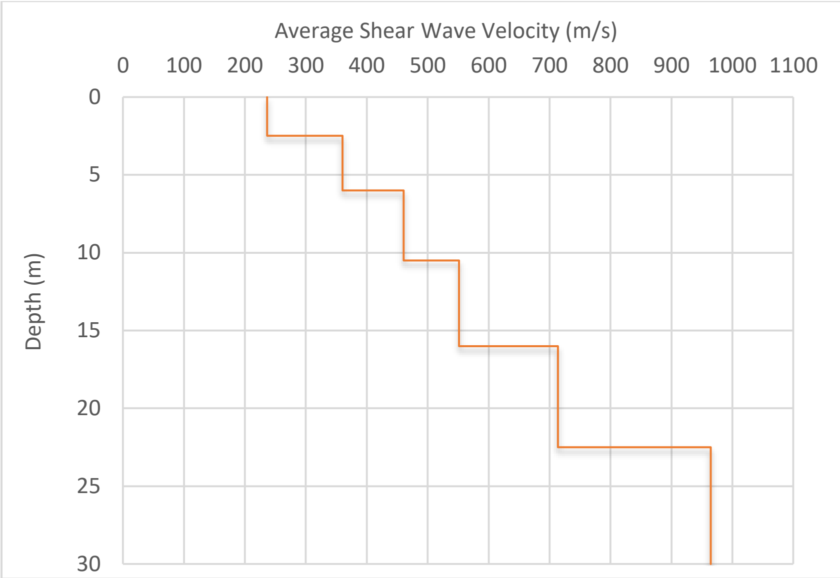


Figure 3.6. Average shear wave velocity profile. Toygar (2015)

3.3. Test Equipment

3.3.1. Vibration Source

An electrical vibrator has been used as vibrational source in field. Vibrator is three-phase input voltage, it was produced by Kemp Mould Electrical Vibration Motors. In addition, a soil compactor was used as a vibration source.

The vibrator has been chosen to provide the experiment system with different frequencies according to their centrifugal force magnitude; in other words, the brought vibrator has centrifugal forces which have a rotation frequency of: 3000 RPM revolution per minute (Figure 3.7). A soil compactor is used as a vibrator (Figure3.8).

Figure 3.7. Kemp mould electrical vibromotor

Figure 3.8. Soil compactor vibrator

The vibrators with the gives RPM's are capable to provide the experiment system with vibrations of frequencies 25, 50, 75, and 100 Hz respectively. Which are simulating the ground borne vibrations of highway traffic, railway, and construction activities.

3.3.2. Power Generator

In order to provide the vibrators on site with the required electrical current, an electrical three-phase power generator has been used.

The generator is a product of the well-known American manufacturer power tool Black & Decker, its model named as BD5500 (Figure 3.9). The generator depends on gasoline as a fuel to provide a voltage of 230/400/12 DC V with a peak power of 5.5 Kw and a rated power of 3.6 Kw. BD5500 weighs 91 Kg with a big gasoline store which extends the running time for the fuel tank up to 9 hours.

Figure 3.9. BD5500 power generator

3.3.3. Sensors (Accelerometers)

A series of six sense boxes of the model MEMM 7001 accelerometers has been used in order to measure the accelerations which have been generated by the vibrator and transmitted within the soil medium (Figure3.10). The accelerometers are able to catch a frequency range of 0-400 Hz with an acceleration rate of -2g up to +2g. Moreover, the accelerometer has high sensitivity is 5μg which gives the possibility to get very low sensation.

The accelerometers have been placed in specific locations with constant distance in between.

Figure 3.10. MEMM 7001 accelerometer

3.3.4. Data Acquisition System

For digitizing the output of the accelerometers, a data logger of the model Test Box 2010 Dynamic data logger has been used (Figure 3.11). The data logger has a resolution of 24 bit ADC, it also provides simultaneous sampling within the range 1 Hz – 2 KHz.

This dynamic data acquisition system has 8 channels, and its input voltage is ±12V, and it was supplied by the three-phase power generator BD5500 that has been used in site.

Figure 3.11. Test Box 2010 dynamic data logger

3.4. Experiments Procedure

In order to evaluate the performance of vibration isolation efficiency, a series of measurements for vibrational parameters at specific points is made. The first measurement is conducted before having any wave barrier embedded in soil, so the attenuation and damping of the vibration waves of the soil skeleton itself is measured.

Procedure is repeated and measurements are conducted for the open trench wave barrier case and for the filled-in rubber chip-filled trench too.

Each measurement is performed through placing the vibration sources on a specific distance of the suggested location of the trench. Vibration sources are to provide the system by vibration frequencies 25, 50, 75, and 100 Hz. This is for the sake of expertizing the screening efficiency of the wave barriers under different intensities of the cyclic loads. Each electrical vibrator is connected to the onsite three-phase power generator BD5500.

Six accelerometer sensors are named from 1 to 6 and located on one alignment with equal distances in between, as shown in Figure 3.12. The accelerometers are connected to the dynamic data logger, which is connected to computer by Ethernet cable. The data acquisition system immediately transmits the obtained data that is expressed in voltage shape to the computer. In order to achieve high accuracy, the accelerometers are set to capture the measurement with a high sampling rate of 200 Hz. Obtained results are saved for each set of measurements for the further operations of filtering.

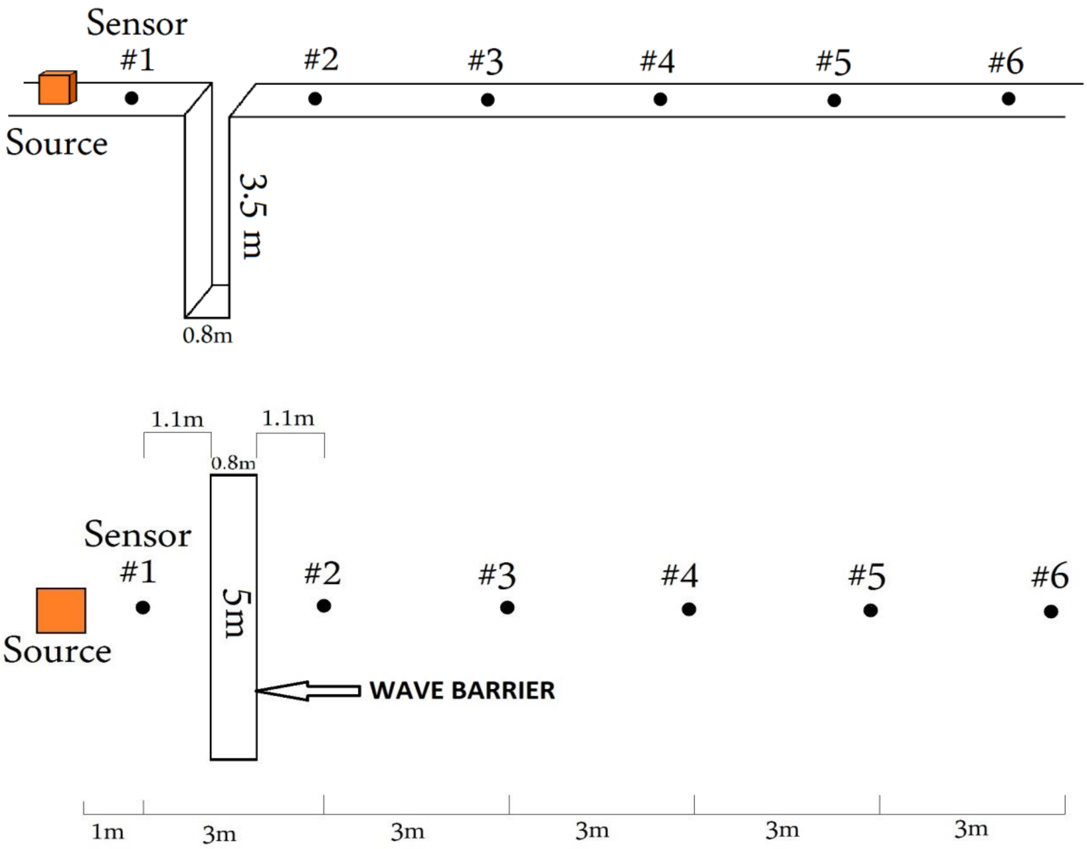


Figure 3.12. Three-dimensional and plan section charts for the location of vibration source and sensors

3.4.1. Open Trench

As a reference case, open trench wave barriers have always been a basic study to be compared with filled-in wave barriers for evaluating the screening efficiency of filled-in wave barriers.

Dimensions for the open trench are selected to be 3.5 m depth and 0.8 m width. It has been observed that for open trenches, the contribution of geometry –especially depth-on the vibration screening efficiency is big. Therefore, depth of trench is selected to be maximized. However, during to the high level of ground water table, the trench depth was selected to be 3.5 m. Regarding the width of the open trench, it is selected to be 0.8 m according to the excavator width, the trench length of earth was 5 m.

Considering the behaviour of the propagated vibrational waves, it was stated that they behave as surface waves (Rayleigh waves). Due to the sensitivity and variability of the Rayleigh wavelength with respect to generated vibration frequency, the geometry of the trench is normalized with Rayleigh wavelength λ_R.

Throughout experimentation, the compactor (Figure 3.15) and the M40 vibromotor were used as regular vibration sources (generators). The site surface was levelled and set (Figure 3.13), the six accelerometer sensors were located according to the plan chart (Figure 3.14), they were connected to the data acquisition system (Figure 3.16), and then the measurements were recorded during the function of the vibration sources.

The vibration sources (the compactor and vibromotor) were found to generate frequencies 32 Hz, 50 Hz, and 75 Hz. Each source has been functioned for each single case of free field (no trench) (Figure3.15), open trench (Figure 3.17), and rubber chip-filled trench (Figure 3.19) respectively.

Figure 3.13. Levelling the site location before starting the tests

Figure 3.14. Setting the alignment and spacings of the sensors and the vibration source

Figure 3.15. Experimentation for free field condition

Figure 3.16. Data acquisition logger connected to sensors

Figure 3.17. Excavated open trench

3.4.2. Rubber Chip-Filled Trench

Regarding the probability of soil failure in open trenches' sides in cases of cohesionless soils, filling an open trench by the rubber chips (tyres) would create more stability to the trench and will be able to provide a screening efficiency for the vibration waves which varies according to the filled-in material properties.

Rubber chips are the aggregates resulting from crushing of the waste tyres. Rubber chips are classified as an abundant material that can be obtained from the industrial wastes and scrap. They are soft, lightweight material with a density that varies in the range 400-600 Kg/m^3.

Figure 3.18. Rubber chip-filled trench

In the procedure of using rubber chips as fill-in material, the physical and dynamic properties of rubber chips are determined. Rubber chips have been placed in the excavated open trench (Figure 3.18) after finishing the open trench measurements. The rubber chips have been freely dropped into the open trench without any additional compaction or extra densification. However, the trench has been totally filled and levelled (Figure 3.18).

Figure 3.19. Rubber chip-filled trench setting out

Then the vibrations have been generated using the multi-intensity vibrators, and measurements of the acceleration amplitude have been recorded using the accelerometer sensors.

3.4.3. Calibration of Obtained Data and Filtering:

Vibrations propagated into soil have been measured in terms of voltage. Thus, the voltage unit readings were transformed into acceleration amplitudes in terms of gravity acceleration g. Since the six accelerometer sensors are identical, a scaling factor of 0.5 has been multiplied by all voltage values. Then, the six accelerometer sensors' amplitudes were extracted as acceleration-time history files.

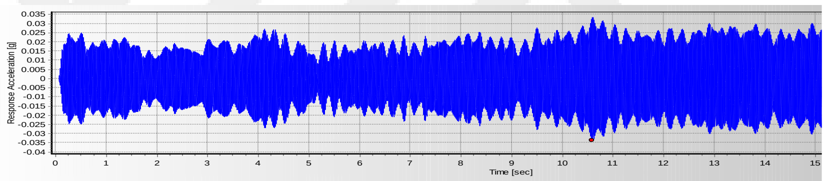
In order to screen out the undesired frequency content out of pass band, a filtering process for the obtained data has been conducted using SeismoSignal V5.1.0 software with a frequency range of ±5 Hz. SeismoSignal V5.1.0 program enables the user to filter the noise which is induced by surrounding nuisance. This noise has been included automatically in the measured signals.

4. RESULTS AND DISCUSSION

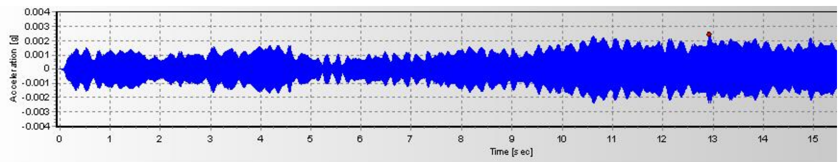
Vibrations were generated using the compactor and vibromotors in order to produce major vibrations having frequencies of 32 Hz, 50 Hz, and 75 Hz.

Produced vibrations were measured by the six accelerometers at specified locations in cases of no trench attenuation, open trench, and rubber chip-filled trench.

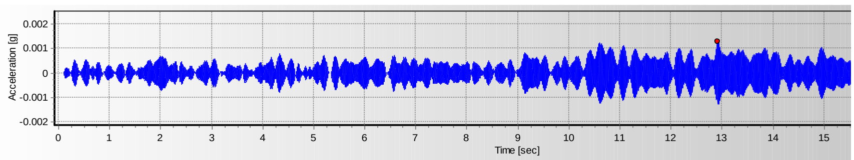
To understand the behaviour of the propagated waves in each case, an analysis based on measuring the peak particle acceleration on specified points was performed using SeismoSignal V5.1.0. Maximum acceleration values were captured in each case regarding all accelerometers as shown in figure 4.1.



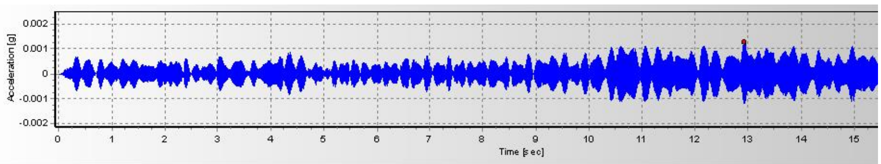
a) Sensor #1



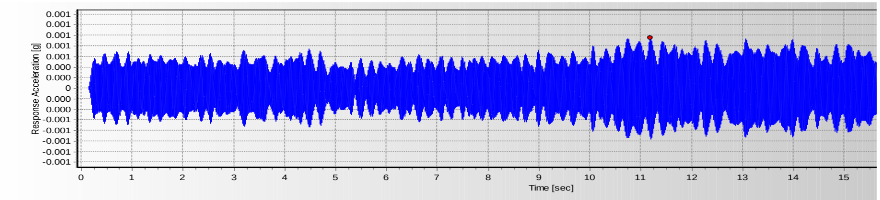
b) Sensor #2



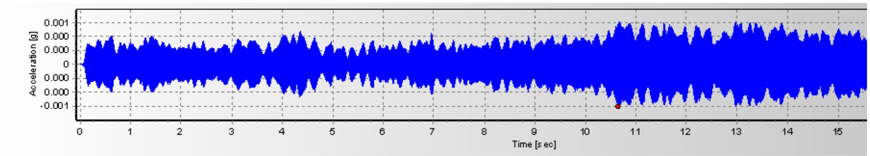
c) Sensor #3



d) Sensor #4



e) Sensor #5



f) Sensor #6

Figure 4.1. Peak particle acceleration from accelograms – case of no trench attenuation 50 Hz frequency.

4.1. Attenuation of Vibration

Vibrations were produced using two vibration sources: a compactor and a vibromotor. The vibromotor was placed and fixed to a steel base having the geometry 90 cm x 90 cm x 0.5 cm. This was performed in purpose of regulating the produced vibrations to keep the attained frequency constant. Nevertheless, there might be some slight differences in the input vibration frequencies due to some potential errors in fixing the vibration sources. Therefore, normalization for the peak particle accelerations of all points with respect to the first point’s was conducted.

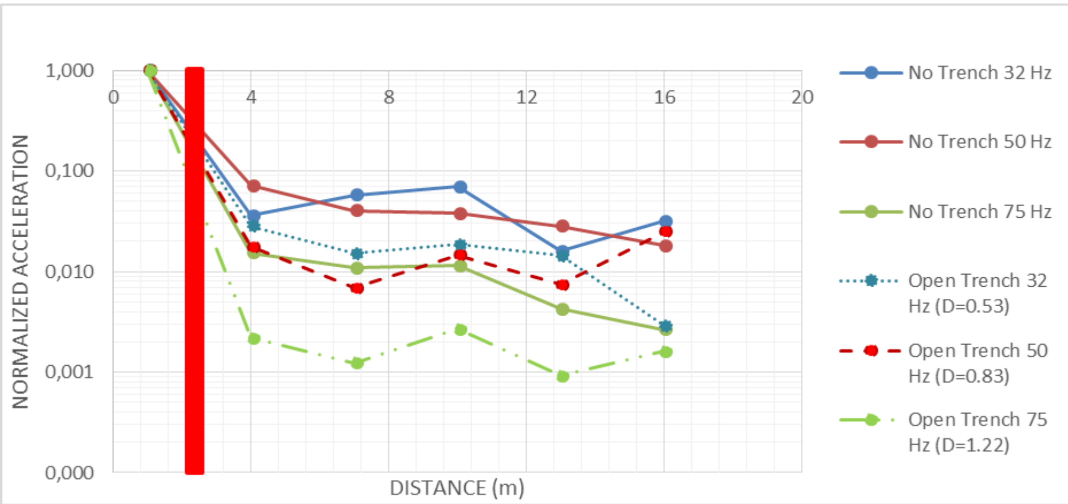


Figure 4.2. Variation of Normalized Accelerations for No Trench Case Compared with Open Trench Case

In the figure 4.2, the continuous lines indicate the normalized acceleration amplitudes attenuated by soil only (no trench case). However, the dashed lines represent the normalized acceleration amplitudes in case of presence of open trench wave barrier.

Since the first point attain the most of the produced vibration, and due to the normalization procedure of the acceleration amplitudes; it can be monitored that the normalized acceleration amplitudes for the sensors #2 to #6 are relatively small and having an exponential trend. From the changing rate of the normalized acceleration amplitudes it is stated that the obtained trend is expected to be overall decreasing with distance, however; variations in values of normalized acceleration are monitored. Due to non-homogeneity of soil particles and layering of soil profile, an effect of reflection and refraction of propagated waves is existed in the system, leading to variations in normalized acceleration amplitudes.

From the continuous trend lines expressing the no trench case, it can be stated that the normalized acceleration amplitudes 4 meters away of the vibration sources decrease more than 90% creating a graded reduction for the trend lines 50 Hz and 75 Hz. However, the trend line of 32 Hz is relatively fluctuated having a sub-peak at 10 m away of the vibration source.

From the figure 4.2, it is observed that least normalized acceleration amplitude is matched with the largest frequency (75 Hz) in case of free field attenuation (no trench) and in case of open trench wave barrier.

Figure 4.3. Variation of Normalized Accelerations for No Trench Case Compared with Rubber Chip-Filled Trench Case

In the figure 4.3, the continuous lines indicate the normalized acceleration amplitudes attenuated by soil only (no trench case). However, the dashed lines represent the normalized acceleration amplitudes in case of presence of Rubber Chip-filled trench wave barrier.

From figure 4.3, it is seen that for trend lines expressing open trench, more reduction in normalized acceleration amplitudes is found. Moreover, it is observed that least normalized acceleration amplitude is matched with the largest frequency (75 Hz), in case of free field attenuation (no trench) and in case of rubber chip-filled trench wave barrier.

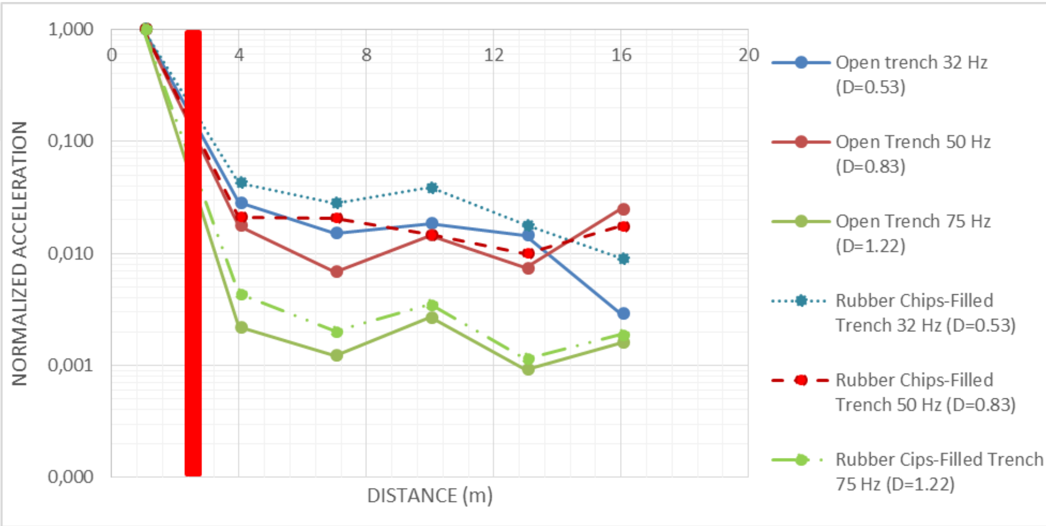
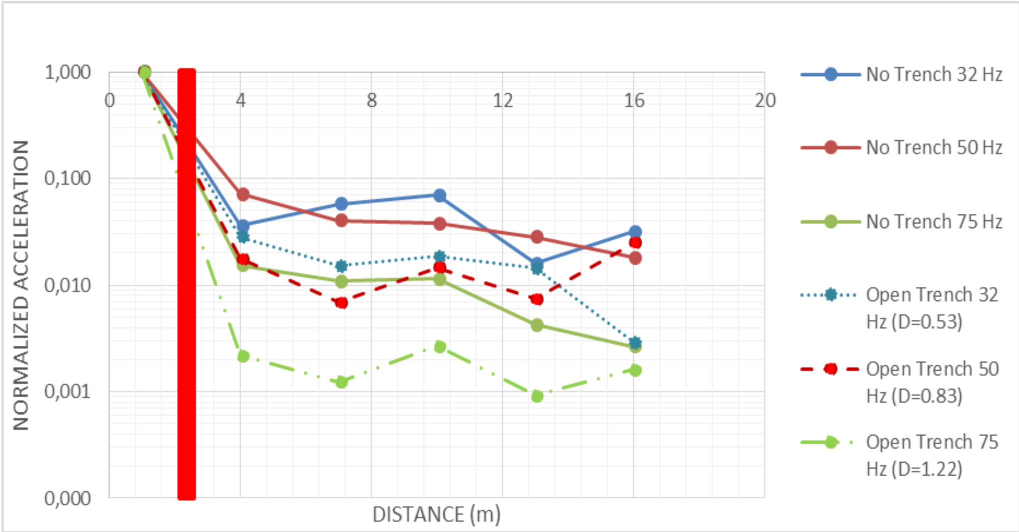


Figure 4.4. Variation of Normalized Accelerations for Open Trench Case Compared with Rubber Chip-Filled Trench Case

From the figure 4.4, it is found that whatever was the produced frequency, the obtained normalized acceleration amplitude regarding open trench is less than the rubber chip-filled trench counterpart. Although, the region from 5th to 6th sensors experiencing an overlapping in trend lines of open trench and rubber chip-filled trench at 50 Hz frequency.

4.2. Efficiency Criteria and Vibration Isolation by Wave Barriers

The figures which illustrate the normalized acceleration amplitude of different generated frequencies versus distance are shown as following.



a) Open Trench Case

b) Rubber Chip-Filled Trench Case

Figure 4.5. Variation of Normalized Accelerations for No Trench Case Compared with a) Open Trench Case. b) Rubber Chip-Filled Trench Case

In existence of a wave barrier, any of open trench and rubber chip-filled trench, it is found that the normalized acceleration amplitudes were overall less than the ones obtained in case of soil attenuation (no trench). Herein, it is acceptable to state that: fractional vibration isolation in existence of a wave barrier is expected to occur.

As aforementioned, (section 2.5.1) Efficiency Criteria is a manner suggested by researchers in purpose of evaluating the vibration screening effectiveness of a wave barrier. It comes in many terms as a ratio of displacements, velocities, or accelerations after and before placing the wave barrier, and termed as Amplitude Reduction Ratio.

In present study, an amplitude reduction ratio based of normalized acceleration amplitudes after and before placing the trench has been considered as a quantitative efficiency criteria.

$$A_R = \frac{A_{max-after\,Trench}}{A_{max-before\,Trench}} \qquad (4.1)$$

As an expression, the amplitude reduction ratios in this study were calculated through dividing the maximum normalized accelerations in existence of trench by those were obtained in absence of it. The procedure was applied for each of the six sensors.

The obtained amplitude reduction ratios were set in graphs with distance to the source in order to understand the behaviour of wave propagation within the soil medium at different frequencies. Amplitude reduction ratios were also analysed against the normalized trench depth. Since the produced vibrations were in the range 32-75 Hz, the corresponding surface wavelength (Rayleigh wavelength) was within the interval 2.86- 6.62 m. consequently, the corresponding normalized depth was varying between 0.5 - 1.25. Whichever, analysing amplitude reduction ratio taking into consideration normalized depth helps to include the effect of changed frequency in addition to trench depth effect in assessing the vibration screening efficiency of the wave barrier.

4.2.1. Screening Efficiency of Open Trench

In purpose to evaluate the vibration isolation screening efficiency of open trench, the relevant amplitude reduction ratios were calculated basing on normalized acceleration amplitudes. Thereafter, variation of the obtained amplitude reduction ratios with distance is shown in figure 4.6.

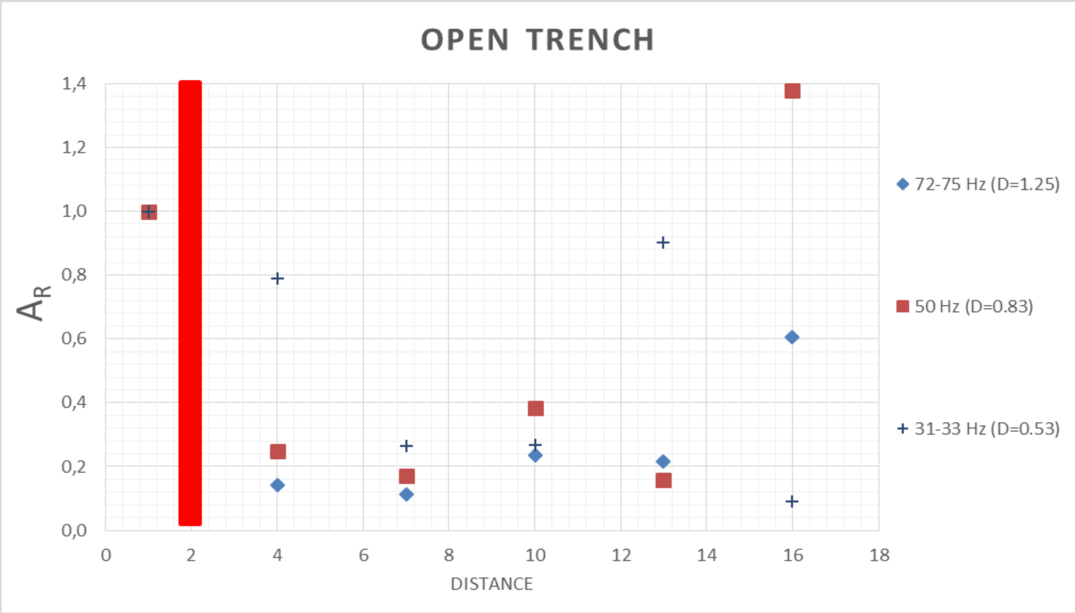


Figure 4.6. Variation of A_R with Distance for Open Trench

From Figure 4.6, it is observed that for a normalized depth of 0.53 (corresponds to frequency of 32 Hz), an average amplitude reduction ratio of 50% is attained. In other words, a vibration isolation less than 50% is achieved. Although first point after the trench experiences an amplification in amplitude reduction ratio with a value of 0.8. However, points #3 and #4 (4.1 and 7.1 m away from trench) encounter an amplitude reduction ratio of 0.25, which means an isolation reaches 75% is achieved at that region. Furthermore, at point #5 (10.1 m away from trench) the amplitude reduction ratio became 0.85, which expresses an isolation efficiency of 15%.

Moreover, at an excitation frequency of 50 Hz (matches a normalized depth of 0.83) it is found that more isolation efficiency is provided. At least 60% vibration isolation is provided for the third point after trench (#4). Yet, screening efficiency increases up to 80% with the decrease in amplitude reduction ratio for points #2, #3, and #5.

Likewise, when the excitation frequency increases to 75 Hz (D=1.25), vibration isolation efficacy maximized up to the range 80-90% for the after trench region wherever was the considered point. However, regarding the furthest accelerometer sensor (at point #6) amplitude reduction ratios of 0.1, 1.4, and 0.6 are captured for the produced frequencies 32 Hz, 50 Hz, and 75 Hz respectively. This invalidity in the obtained amplitude reduction ratios is justified through the lack of domination of the produced frequencies' accelerations when comparing to the noise of the site. In other words, acceleration amplitudes at point #6 were of the digit 10^{-4} g, which is low in comparison with the noise level existed on site. Thus, attenuations and amplifications are expected to be observed.

Hence, disregarding the obtained measurement at accelerometer sensor #6, average amplitude reduction ratios at normalized depths of 0.53, 0.83, and 1.25 were calculated as 0.56, 0.24, and 0.18 respectively. In result, in order to gain a significant amount of vibration isolation of soil using an open trench wave barrier, it is recommended to start with an open trench with a depth $d \geq 0.83\ \lambda_R$. This –somehow- agrees with the recommendation of woods (1968) who implies the amplitude reduction ratio to be 0.25 to obtain an effective wave barrier.

4.2.2. Screening Efficiency of Rubber Chip-Filled Trench

The open trench was filled with rubber chips (shredded tyres) achieving a bulk density about $\rho_{bulk} = 400\ {}^{kg}/_{m^3}$. Then, amplitude reduction ratios were calculated basing on normalized acceleration amplitudes. Thereafter, variation of the obtained amplitude reduction ratios of filled-in rubber chip trench with distance are shown in figure 4.7.

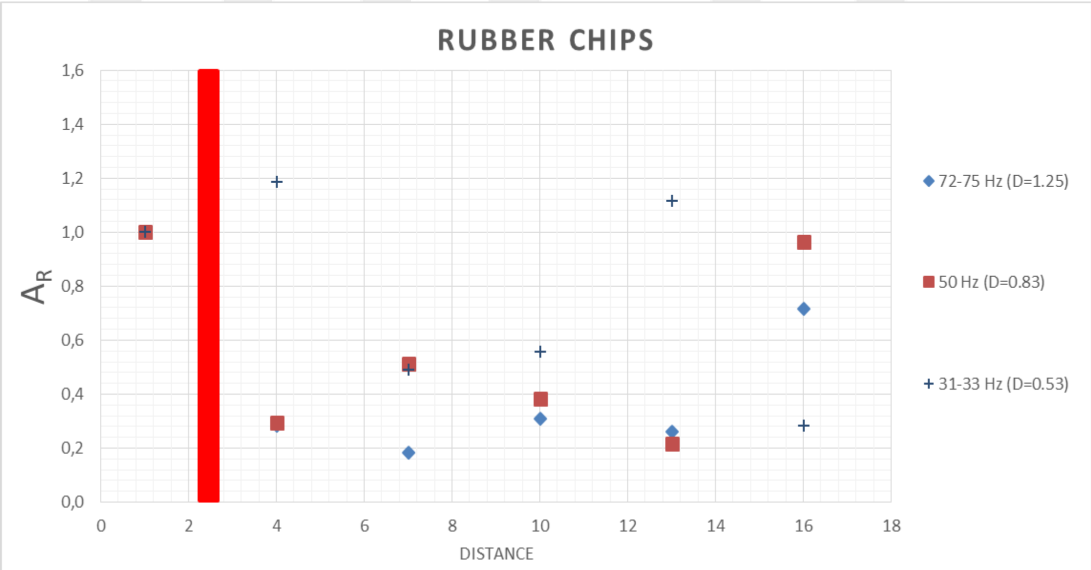


Figure 4.7. Variation of A_R with distance for rubber chip-filled trench

From figure 4.7, it is observed that for a normalized depth of 0.53 (corresponds to frequency of 32 Hz), an average amplitude reduction ratio of 80% is attained. In other words, a vibration isolation about 20% is provided. However, first point after the trench (Point #2) experiences an amplification in amplitude reduction ratio reaching a value of 1.2. Noting that, at points #3 and #4 (region 4.1 - 7.1 m away from trench) they encounter an amplitude reduction ratio of 0.5, which means an isolation reaches 50% is achieved. Furthermore, at point #5 (10.1 m away from trench) the amplitude reduction ratio increases dramatically to 1.1, which expresses an amplifying in the propagated vibration wave. In other words, no vibration isolation is attained at that point at the normalized depth D=0.53.On the other hand, at an excitation frequency of 50 Hz (matches a normalized depth of D=0.83) it is found that more isolation efficiency is provided. From the figure, 60% vibration isolation is provided for the third point after trench (#4). Yet, screening efficiency varies within the range 50%-70% for the after trench region (points #2, #3, #4, and #5) having an average screening efficiency of vibrations exceeds 65%.

Likewise, as the excitation frequency increases to 75 Hz (D = 1.25), vibration isolation efficacy maximized up to the range 70-80% for the after trench region wherever was the considered point. However, regarding the furthest accelerometer sensor (at point #6) amplitude reduction ratios of 0.28, 0.96, and 0.71 are captured for the produced frequencies 32 Hz, 50 Hz, and 75 Hz respectively. This invalidity in the obtained amplitude reduction ratios is justified through the lack of domination of the produced frequencies' accelerations when comparing to the noise of the site. In other words, acceleration amplitudes at point #6 were of the digit 10^{-4} g, which is low in comparison with the noise level existed on site. Thus, attenuations and amplifications are expected to be observed.

Hence, disregarding the obtained measurement at accelerometer sensor #6, average amplitude reduction ratios at normalized depths of 0.53, 0.83, and 1.25 were calculated as 0.84, 0.36, and 0.25 respectively. In result, in order to gain a significant amount of vibration isolation of soil using a rubber chip-filled trench wave barrier, at least a trench of a depth $d \geq 1.25\ \lambda_R$ is required. This is basing on the efficiency judgment criteria suggested by woods (1968) who implied the amplitude reduction ratio to be 0.25 to obtain an effective wave barrier.

4.3. Screening Efficiency and Isolation Behaviour

The vibration isolation ability of open trench and filled-in rubber chips wave barriers were evaluated through amplitude reduction ratios. As evaluation criteria, amplitude reduction ratio was obtained basing on normalizing maximum acceleration amplitudes with respect to the first sensor's measurement. However, other factors like distance to the trench, depth of trench, and properties of fill-in material may effect on the screening efficiency of the wave barrier. Therefore, all obtained amplitude reduction ratios for open and filled-in trench were tabulated with their related points (Tables 4.1 and 4.2).

Table 4.1. Obtained amplitude reduction ratios in case of open trench

AMPLITUDE REDUCTION RATIO (A_R)						
OPEN TRENCH						
	Sensor #2	Sensor #3	Sensor #4	Sensor #5	Sensor #6	Average
D≈0.53 (32 Hz)	0.79	0.26	0.27	0.9	0.09	0.56
D≈0.83 (50 Hz)	0.25	0.17	0.38	0.16	1.38	0.24
D≈1.25 (75 Hz)	0.14	0.11	0.24	0.22	0.61	0.18

Table 4.2. Obtained amplitude reduction ratios in case of rubber chip-filled trench

AMPLITUDE REDUCTION RATIO (A_R)						
RUBBER CHIP-FILLED TRENCH						
	Sensor #2	Sensor #3	Sensor #4	Sensor #5	Sensor #6	Average
D≈0.53 (32 Hz)	1.19	0.49	0.56	1.12	0.28	0.84
D≈0.83 (50 Hz)	0.3	0.51	0.38	0.22	0.96	0.35
D≈1.25 (75 Hz)	0.28	0.19	0.31	0.27	0.72	0.25

Finding the average amplitude reduction ratios for the after trench sensors –excluding the sensor at point #6- for each trenching case and excitation frequency, gives the upcoming derivations (Figure 4.8).

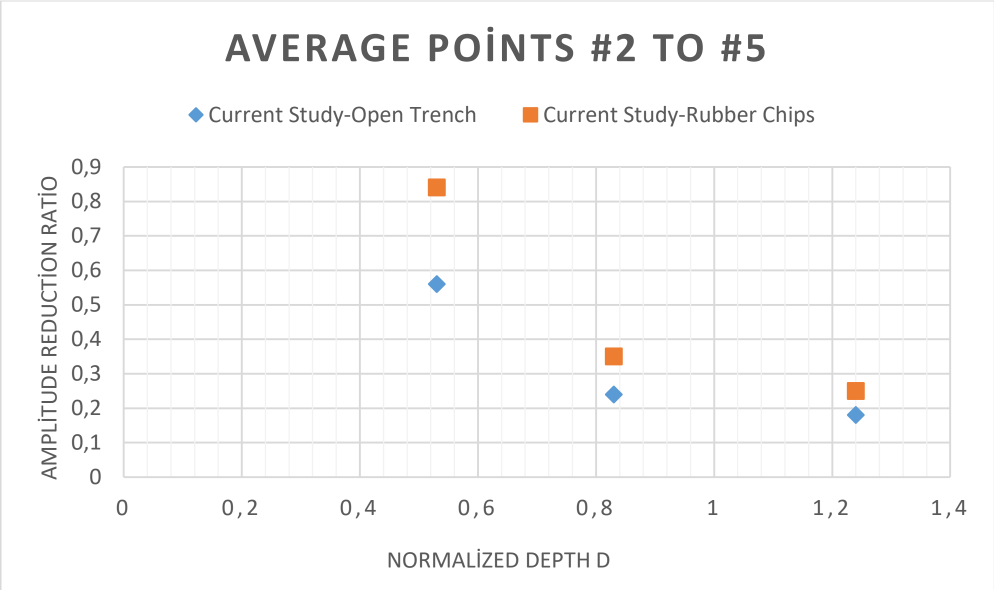


Figure 4.8. Comparison in the isolation efficiency of open trench and rubber chip-filled trench

For an open trench and for the sake of obtaining a sufficient vibration isolation, a trench of a depth at least of d = 0.83 λ_R is required. Nevertheless, more screening efficiency is provided when increasing normalized depth D to 1.25. In other words, whenever depth of an open trench gets d = 1.25 λ_R the average screening efficiency reaches 80%. However, for low open trench depths (d = 0.53 λ_R) a minimal average vibration isolation efficiency about 40% is resulting.

Considering rubber chips barriers, the sufficient screening efficiency (75% vibration isolation) is only achieved for a trench depth d = 1.25 λ_R However, a vibration isolation of 65% is provided when the filled trench depth decreases to 0.83λ_R. This can be considered as relatively valid isolation. Except for lower filled trench depths almost no vibrational isolation is monitored. Numerically, 16% vibration screening is attained for a rubber chip-filled trench of depth d = 0.53 λ_R.

Regarding the individual amplitude reduction ratios, it is observed that for the first point after trench (point #2) which is located at a distance 1.1 m from trench, the amplitude reduction ratios vary within a small range less or more than the obtained average amplitude reduction ratios. This observation is valid only for moderate and relatively high frequencies (50 Hz and 75 Hz), that corresponds to normalized depths of 0.83 and 1.25 respectively. However, for lower normalized depths (D = 0.53), the difference between the amplitude reduction ratio of point #2 and the average amplitude reduction ratio became 41% in favour of the premier, whatever was the type of trench, open or rubber chip-filled trench.

From the tables 4.1 and 4.2, and by looking to the individual amplitude reduction ratios of the sensors of the points (#3, #4, and #5), it is found that the effective vibration isolation region lies in the first 10 m from the trench. However, vibration isolation efficiency decreases with distance from the trench after the aforementioned effective region. This can be justified by the soil transmissibility to the propagated vibrational waves into it, effect of noise to the sensors located far away of the trench, and due to the reflection and refraction of waves after the trench region which may lead to extra amplifications induced by the superposition of waves.

Herein, the general behaviour of open and rubber chip-filled trenches is similar in wave propagation, effective isolated region, and in the differentiations in the individual values of the amplitude reduction ratio. However, vibration screening efficiency of open trench for all normalized depth and regions was more than the ones that obtained in rubber chip-filled trench.

4.4. Comparison of Current Study with Published Studies

So far, from the obtained efficiency charts and figures, it is found that isolation performance of wave barriers is mainly influenced by the normalized depth (D) of the wave barrier. Thus, the obtained results in current study were comparable with those published in literature. Comparison is needed in order to evaluate the accuracy and consistency of current study with the previous ones. Basically, since there is no experimental studies about screening efficiency of rubber chips barriers were conducted, the comparison has been made for open trench wave barriers only.

4.4.1. Experimental Studies Published in Literature

Woods (1968) performed a series of field experiments on vibration screening efficiency of a circular open trench. Haupt (1981) conducted a series of scaled laboratory experiments on open trenches in 10m x10m rectangular bin filled with dense sand. Later, Alzawi and El Naggar (2011a) made a full scale field experiments series using open trench excavated 5 m away from the vibration source. Recently, Toygar (2015) has performed an experimental study on vibration screening efficiency of open trenches, building his study on two source-trench distance to examine the active and the passive isolation of open trenches.

The current study has been compared with all aforementioned studies considering the change of amplitude reduction ratio with the normalized depth, taking into account dividing the after trench region (the isolated region) to close and far region in order to assess the effect of distance. In current study, points #2 and #3 (at distances from trench 1.1 and 4.1 m respectively) were assumed to be the close region to the trench, whereas, points #4 and #5 (at distances from trench 7.1 and 10.1 m respectively) were assumed to represent the far region to the trench. This was in accordance of Haupt (1981) reported results of near-to-trench screening efficiency of open trench.

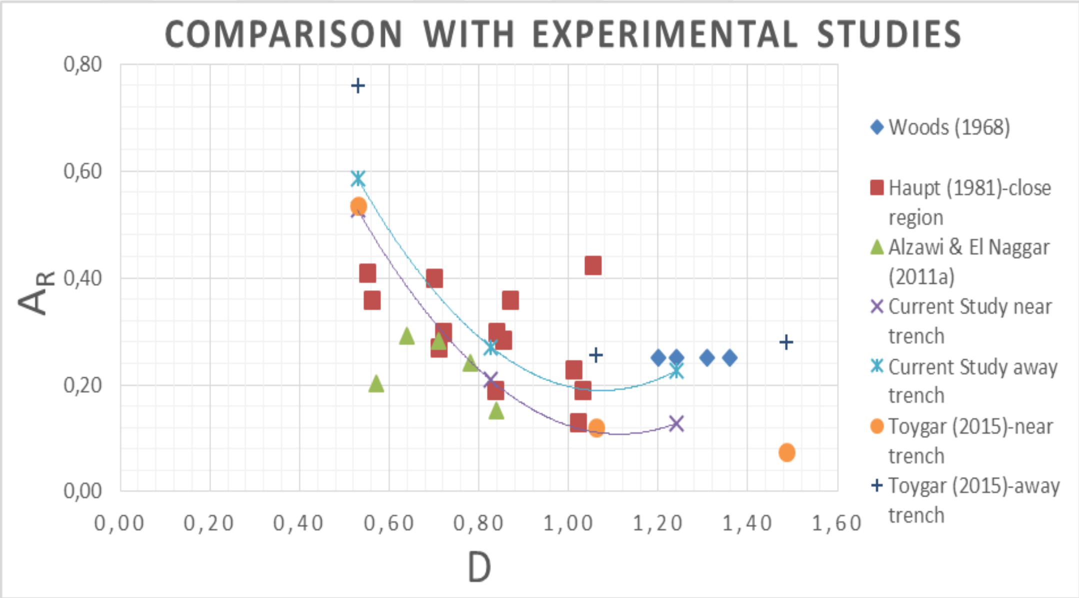


Figure 4.9. Comparison of current study with experimental published studies

From figure 4.9, the results of vibration isolation efficiency of the current study is found to be consistent with the experimental counterpart studies published in literature. Although the present study covers a relatively narrow range of normalized depth ($0.53 \leq D \leq 1.25$), a good level of harmonization is resulted.

As reported before, it is clear that for the same site and experiment conditions, close regions provide more vibration isolation than the far ones. This is observed for Toygar (2015) experimental study in addition to the current study.

5. MODELLING AND NUMERICAL ANALYSIS

5.1. Purpose of Numerical Analysis

Numerical analysis is the study of algorithms that use numerical approximation for the problems in order to find applications in all fields of engineering and the physical sciences. The aim of analysing a system numerically is to study and visualize the changes occurring to that system under a specific case of motion or forces.

In this study, a series of numerical analyses for the vibration-to-trench system has been performed using Quake/W software. The analyses are done considering open trenches and filled-in rubber chips wave barriers. However, Quake/W is a product of GEOSTUDIO/GEOSLOPE that enables to run an elastic dynamic analysis for vibrations.

The main goal of performing this analysis was to make an initial evaluation for the benefit of conducting such experiments using a rarely-used material in field which are rubber chips. Moreover, this numerical analysis provides an opportunity for the researcher to realize the most affecting parameters in the study after experiencing their variations and changings easily during analysis.

5.2. Analysis Validation and Procedure

In favour of verifying and validating the numerical analysis of results, series of analyses have been performed regarding the case of open trench. The obtained results were compared with the results of the experimental study of Toygar (2015). The Quake/W numerical analysis results were drawn in graphs with respect to the major affecting parameters. The drawn curves were found consistent with the realistic premeasured curves by Ulgen and Toygar (2016).

The procedure of modelling started with defining two systems of definition; first system simulates the static case of the profile, which means before starting motion, and the second defining system expresses the dynamic case after starting the vibration motion. The soil geometry and profile were drawn considering the real layering of the profile in addition to thicknesses of each layer, the trench and 6 studied nodes were located on the profile surface, and the boundary fixities were assigned. Then, materials have been defined in each of the static and dynamic stage, and the input motion functions which have been defined in terms of vibration frequency.

Mesh was modelled to be rectangular as 105 m × 49.5 m, mesh size was selected to be 0.4 m, which satisfies the criteria suggested by Lysmer et al (1975). This produced 32617 elements and 33004 nodes in the mesh. Then, soil profile was divided to layers, soil characteristics of each layer have been defined in accordance with the real soil investigation results. Ground water table was assigned to be 3.5 m deep from ground surface.

Thereafter, the analysis started for each frequency separately, starting by 30 Hz, 50, and 70 Hz. First running is done for the case of no trench (attenuation). Then, running is done considering the case of open trench. Obtained results were recorded and exported to Excel files in terms of instant acceleration for the regarded points.

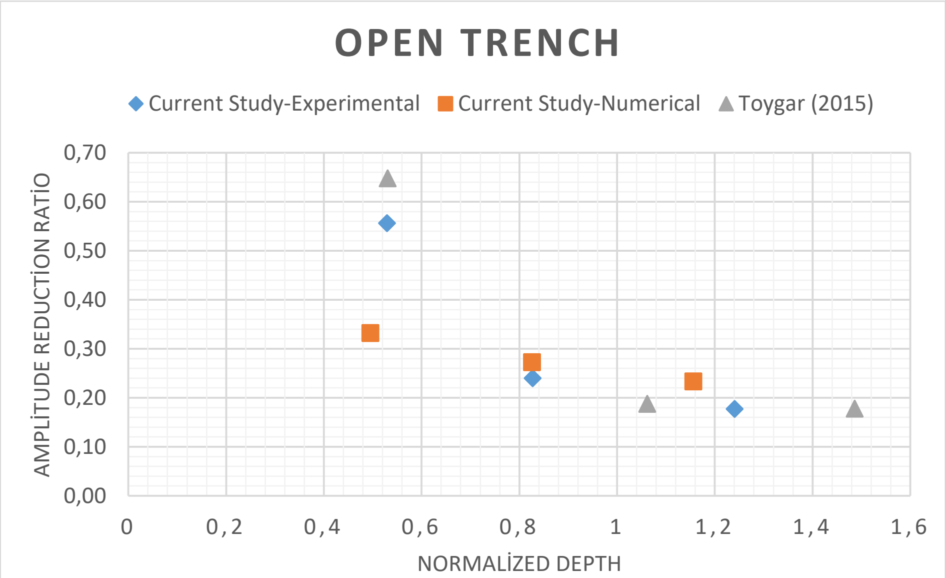


Figure 5.1. Comparison between experimental and numerical results of open trench case

From figure 5.1, the obtained results via the numerical analysis of Quake/W were found to be consistent with those obtained experimentally on site. Precisely, the amplitude reduction ratios resulting from the numerical analysis are closer to the ones obtained experimentally for high ranges of normalized depth of trench (for D ≥ 0.8). Herein, frequency enlarged-range of open trench vibration isolation is carried out. Consequently, another series of analyses regarding the rubber chip-filled trench is constructed.

Furthermore, detailed comparisons between the numerically obtained results -by Quake/W- with those obtained experimentally were established for different regions (Figures 5.2, 5.3, and 5.4). This was in order to assess the isolation behaviour of open trench at different frequency levels. The comparisons were built regarding the average amplitude reduction ratios of the after trench regions and the normalized depths of trenches. Accuracy and consistency in experimental and numerical results were analysed in each case of trenching (open and rubber chip-filling).

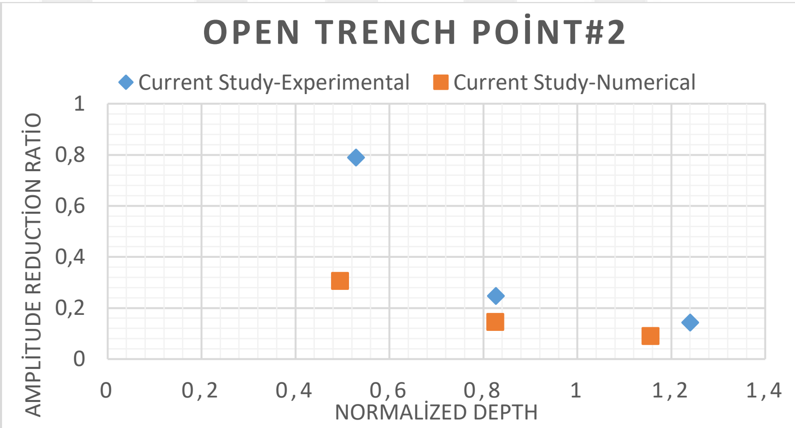


Figure 5.2. Comparison between experimental and numerical results of open trench case at point #2

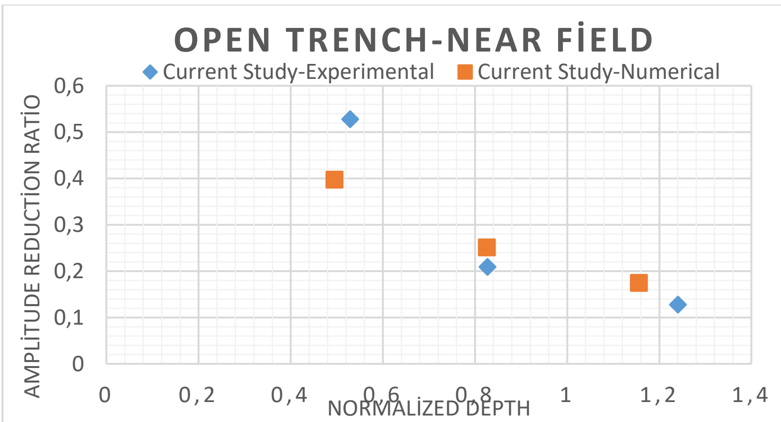


Figure 5.3. Comparison between experimental and numerical results of open trench case at near field condition

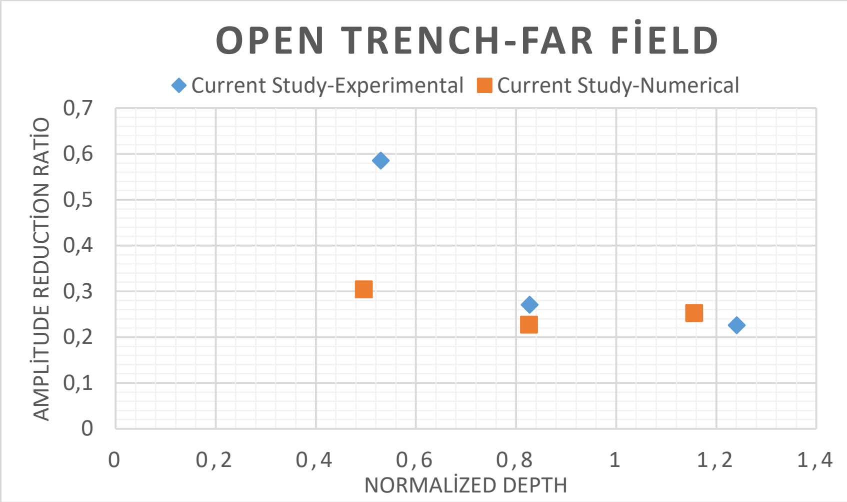


Figure 5.4. Comparison between experimental and numerical results of open trench case at far field condition

From figures 5.2, 5.3, and 5.4, comparing the trends resulting from the numerical and experimental approaches of open trench isolation efficiency chart, good levels of agreement is reported. It is observed that the isolation efficiency of open trench obtained by numerical approach is uniform and gradually changing as the normalized depth changes. However, and regarding the experimental approach, the changing rate in the amplitude reduction ratios is observed to be higher.

It is also reported that for lower normalized depths, there are gaps in the relevant amplitude reduction ratios between the numerical and experimental approaches. Furthermore, it is found that, for a trench depth d $\geq 0.83\ \lambda_R$ the isolation efficiency obtained experimentally exceeds the one obtained numerically.

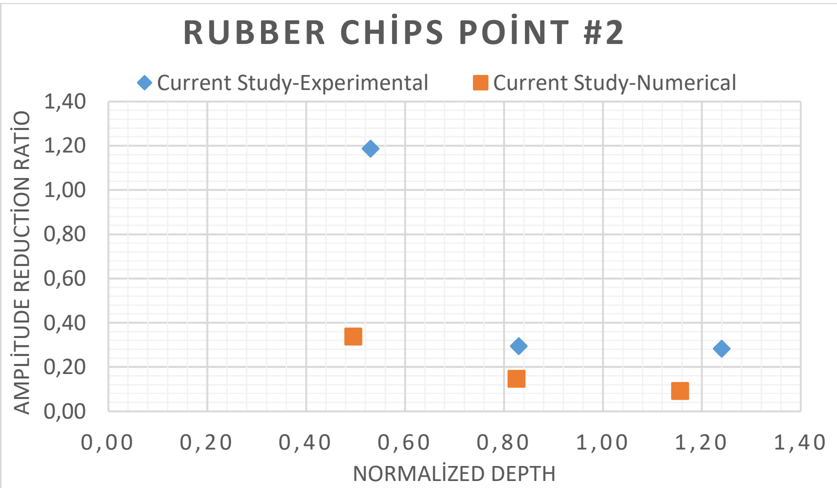


Figure 5.5. Comparison between experimental and numerical results of rubber chip-filled trench case at point #2

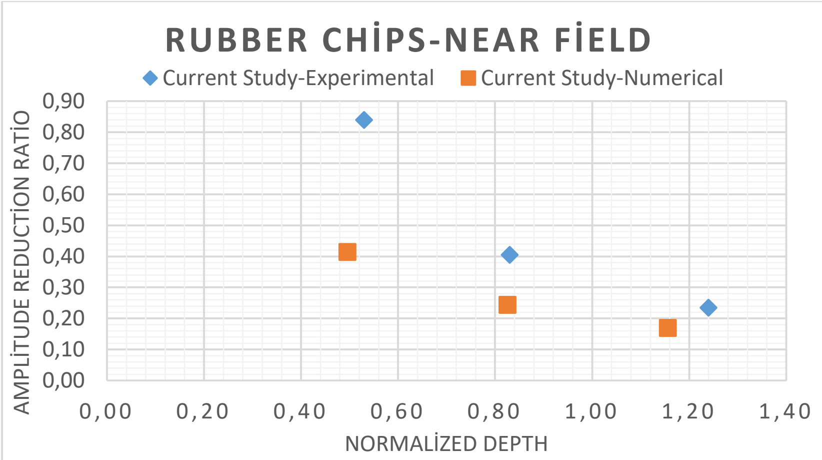


Figure 5.6. Comparison between experimental and numerical results of rubber chip-filled trench case at near field condition

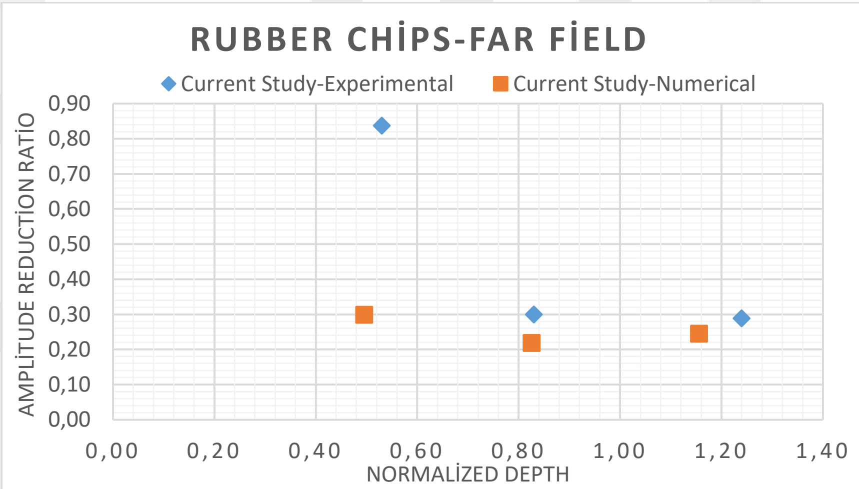


Figure 5.7. Comparison between experimental and numerical results of rubber chip-filled trench case at far field condition

From figure 5.5, 5.6, and 5.7, and by comparing the trend curves resulting from the numerical and experimental approaches of rubber chip-filled trench isolation efficiency charts. Acceptable levels of matching are reported. It is observed that the isolation efficiency of rubber chip-filled trench obtained by numerical approach is more uniform and gradually changing with changing of normalized depth. However, and regarding the experimental approach, the changing rate in the amplitude reduction ratios is observed to be higher.

It is also found that, whatever was the normalized trench depth D, the isolation efficiency obtained numerically exceeds the one obtained experimentally.

5.3. Numerical Model

As aforementioned, mesh was modelled to be rectangular as 105 m × 49.5 m (Figure 5.8); which is relatively large in order to avoid boundaries' reflection of propagated waves. Mesh size was selected to be 0.4 m, which satisfies the criteria suggested by Lysmer et al (1975) that specified the element size limitations in order to reach a reliable model to be controlled by the shear wavelength L as shown in equation:

$$l_{max} = \left(\frac{1}{8} \sim \frac{1}{5}\right) L_s \tag{5.1}$$

This helps in increasing the analysis accuracy by capturing the wave in larger number of elements and nodes. Consequently, the mesh had 32617 elements and 33004 nodes.

The soil profile was divided to layers, soil characteristics of each layer have been defined in accordance with the real soil investigation results. Ground water table was assigned to be 3.5 m deep from ground surface (Figure 5.9).

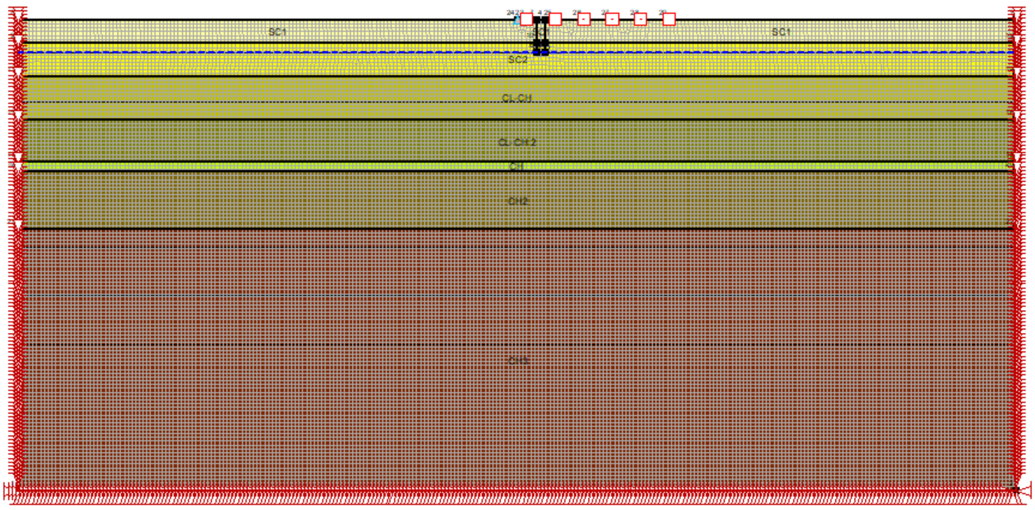


Figure 5.8. The modelled soil profile and fixities on Quake/W

In the case of no trench (attenuation), the trench void was filled with materials identical in properties to the soil surrounding it. However, regarding the case of filled-with rubber chip trench, the used material properties of rubber chips were defined.

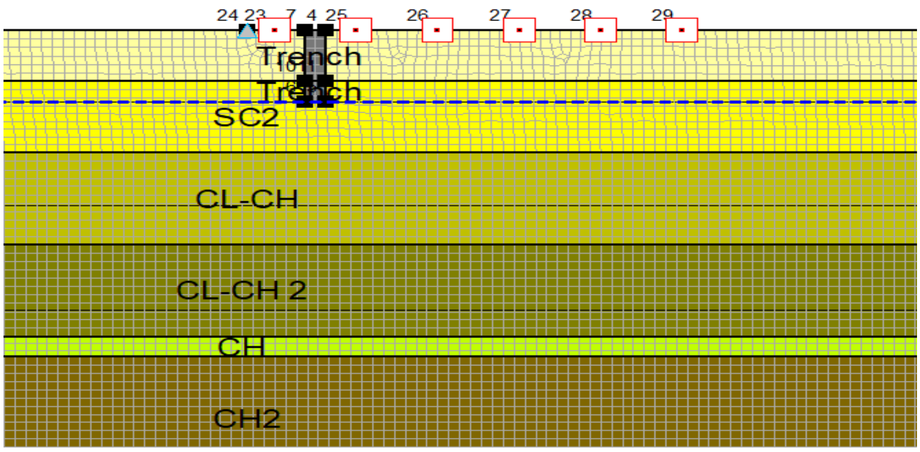


Figure 5.9. Locating of trench and nodes on Quake/W

5.4. Material Properties

According to the known properties of the in-field used rubber chips, and relying on Edeskar (2004), the required characteristics of the defined rubber chips are shown in the following table in addition to the properties of the defined soil layers.

Table 5.1. Properties and characteristics of soil profile

Material	Unit Weight γ (kN/m^3)	Poisson's ratio ν	Damping Ratio	Shear Modulus G_{max}(kPa)	Geometry
SC1	18	0.25	0.04	97.920	2.5 m
SC2	18	0.25	0.04	97.920	3.5 m
CL-CH1	18	0.25	0.04	245.000	4.5 m
CL-CH2	18	0.25	0.04	408.000	4.5 m
CH1	19	0.25	0.04	408.000	1 m
CH2	19	0.25	0.04	590.000	6.5 m
CH3	19	0.25	0.04	800.000	27.5 m
Rubber Chips	4	0.29	0.01	310.08	3.5 m × 0.8 m

5.5. Results

Initial static and dynamic analyses have been conducted in a 2D plain strain condition using finite element based software Quake/W. The motion output data resulted from 6 history points were recorded and exported in terms of acceleration. A normalization procedure was done for all accelerations with respect to the first point (most near point to trench). Purpose of normalization was to evaluate the changes in acceleration values for the successive points.

In purpose of investigating the isolation performance of rubber chip-filled trench type wave barriers, a series of numerical dynamic analyses are conducted. However, in order to evaluate the screening efficiency of rubber chips wave barriers, amplitude reduction ratio was considered as efficiency criteria. However, normalized depth was considered for the variations in Rayleigh wavelengths with respect to frequencies (Figures 5.10 and 5.11).

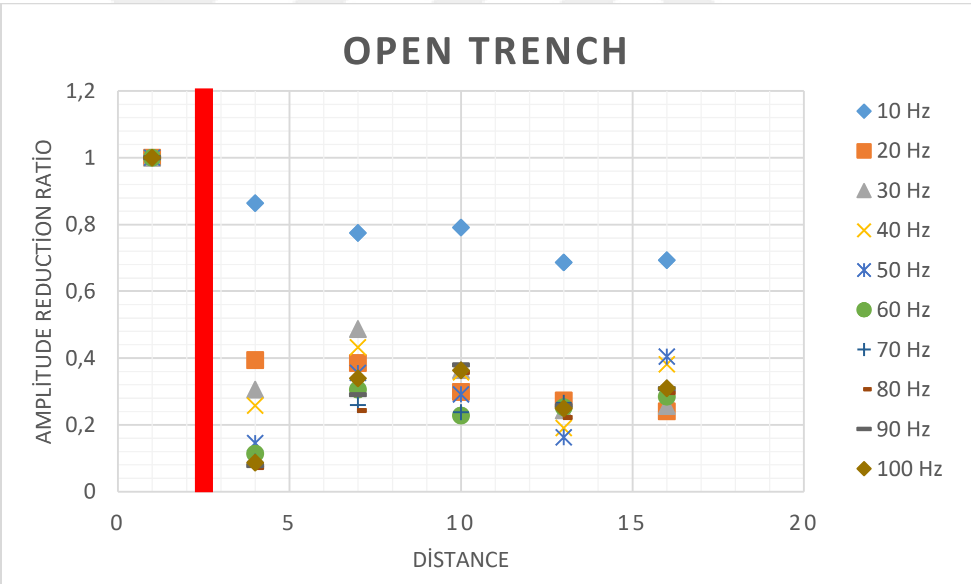


Figure 5.10. Vibration isolation efficiency chart of the open trench modelling case

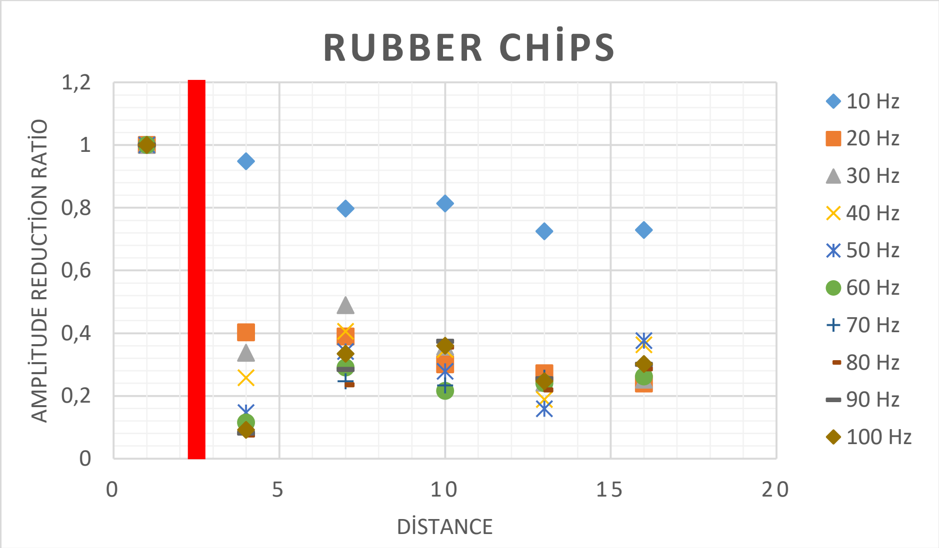


Figure 5.11. Vibration isolation efficiency chart of the rubber chip-filled trench modelling case

From figures 5.10 and 5.11, it is observed that vibration isolation efficiencies of open trench and rubber chip-filled trench vary with respect to excitation frequency and distance. Specifically, the amplitude reduction ratios for frequencies 10 Hz- 30 Hz is significantly less than those obtained for higher excitation frequencies. In addition, good levels of isolation efficiency are majorly occurred in the close region to the trench in comparison with the far region from the trench.

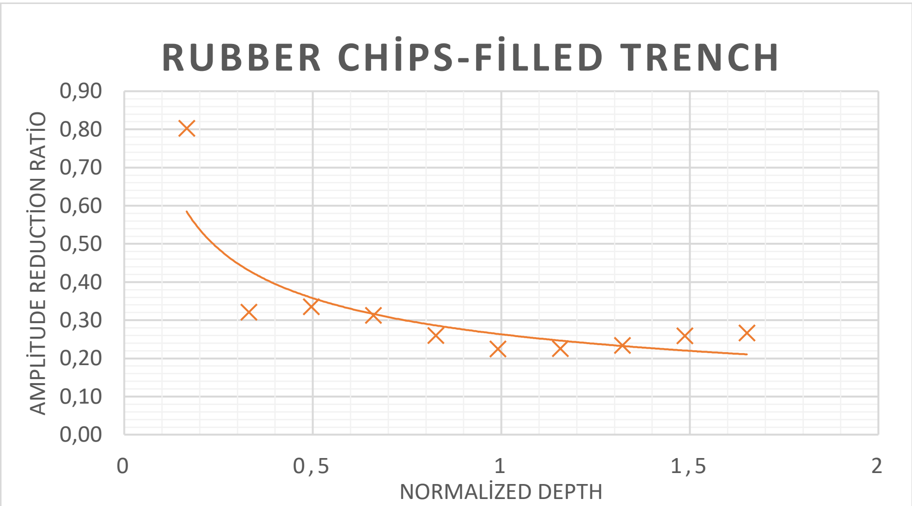


Figure 5.12. Vibration isolation efficiency chart of the rubber chip-filled trench

From figures 5.10 and 5.11, it is illustrated that better isolation efficiency is attained as the excitation frequency increases. In other words, and in accordance to the obtained curve in figüre 5.12, as the normalized depth increases the amplitude reduction ratio decreases, this means that the isolation efficiency is being maximized for the rubber chip-filled trench. The curve expressing this change has the following expenential equation

$$A_R = 0.26\ D^{0.45}\ ; \quad \text{whenever normalized depth D: } 0.15 \leq D \leq 1.5 \qquad (5.2)$$

Furthermore, from figüre 5.12 it is reported that whenever the trench depth belonged to the range 0.75 $\lambda_R \leq d \leq 1.5\ \lambda_R$, the amplitude reduction ratio will vary within the interval 0.3 – 0.2 respectively. This –numerically- corresponds to a screening efficiency of 70% - 80%.

Table 5.2. Obtained results of Quake/W for open trench case

AMPLITUDE REDUCTION PERCENTAGE (A_R)							
OPEN TRENCH							
	Sensor#2	Sensor#3	Sensor#4	Sensor#5	Sensor#6	Average	
						Near trench	Far Trench
D≈0.50 (30 Hz)	31%	49%	36%	24%	26%	40%	28.7%
D≈0.83 (50 Hz)	15%	36%	30%	16%	41%	26%	29%
D≈1.15 (70 Hz)	9%	26%	24%	27%	31%	18%	27.3%

Table 5.3. Obtained results of Quake/W for Rubber chip-filled trench case

AMPLITUDE REDUCTION PERCENTAGE (A_R)							
RUBBER CHIP-FILLED TRENCH							
	Sensor#2	Sensor#3	Sensor#4	Sensor#5	Sensor#6	Average	
						Near trench	Far Trench
D≈0.50 (30 Hz)	34%	49%	36%	24%	25%	42%	28.3%
D≈0.83 (50 Hz)	15%	34%	28%	16%	38%	24.5%	27.3%
D≈1.15 (70 Hz)	9%	25%	23%	26%	30%	17%	26.3%

From tables 5.2 and 5.3, and basing on obtained amplitude reduction ratios, it is found that both open trench and rubber chip-filled trench provide good levels of vibration isolation majorly. Moreover, it is observed that the singular amplitude reduction ratios for points decrease as the excitation frequency increases. Moreover, the average amplitude reduction ratios for the near trench region are mostly less than the ones obtained for the far from trench region. Unless, for frequency 30 Hz (normalized depth D = 0.5) isolation is optimized for the far region from trench. This can be justified through the wave behaviour in reflection by soil layers and refraction by trench while crossing the trench medium.

5.6. Comparison between Results of Current Study and the Published Studies

The obtained results in current study were compared with those published in literature. Comparison is needed in order to evaluate the accuracy and consistency of current study with the previous ones. Basically, since there is no experimental or numerical studies about screening efficiency of rubber chips wave barriers were conducted, the comparison has been made for open trench wave barriers only.

5.6.1. Numerical Studies Published in Literature

The numerical results of this study are compared with the studies of Beskos et al (1986), Al Hussaini (1992), Tsai and Chang (2009), Dolling (1965), and Saikia and Das (2014) who used other numerical approaches in order to examine the isolation efficiency of open trenches. The comparison is illustrated in figure 5.13.

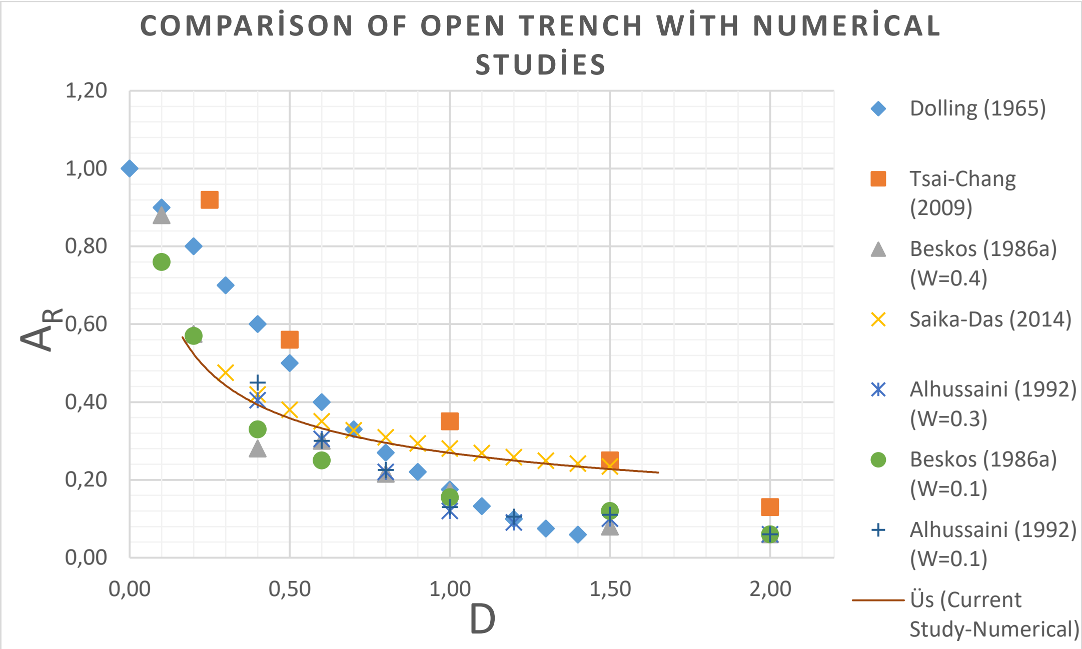


Figure 5.13. Comparison between numerical results of current study-open trench case with other numerical results published in literature

Throughout comparing trends in figure 5.13, it is stated that the results of vibration isolation efficiency of the current study is found to be consistent with the numerical counterpart studies published in literature. Precisely, Saikia and Das (2014) is found to be very close –almost coincided with- to the current study's trend line.

5.6.2. Experimental Studies Published in Literature:

As aforementioned (section 4.4.1), relying on Woods (1968), Haupt (1981), Alzawi and El Naggar (2011a), and Toygar (2015), the gained results of the current study have been compared with considering the change of amplitude reduction ratio with the normalized depth (Figure 5.14).

Through comparing trends, it is stated that the results of vibration isolation efficiency of the current study is found to be consistent with the experimental counterpart studies published in literature.

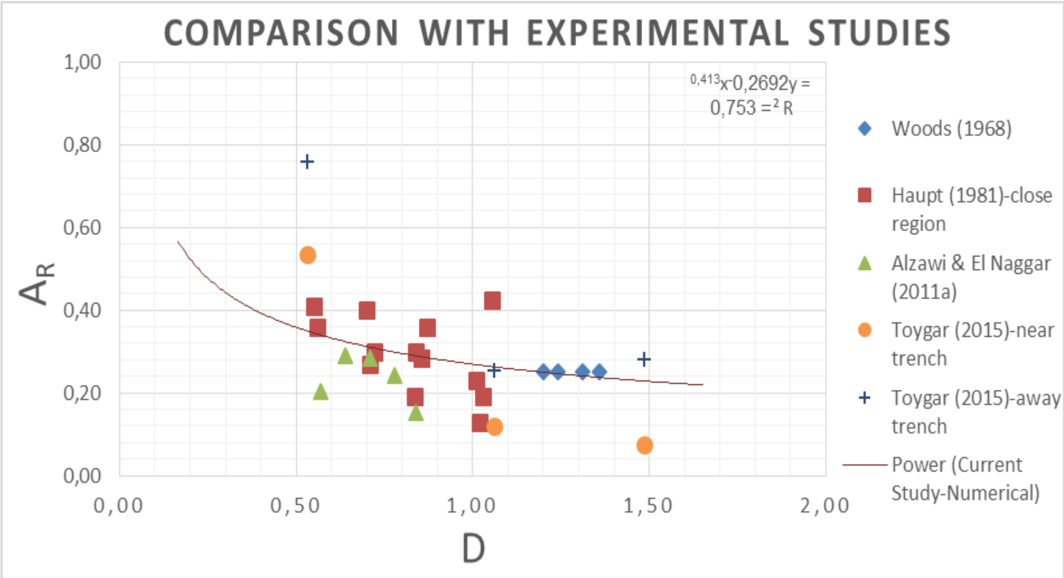


Figure 5.14. Comparison between numerical results of current study-open trench case with other experimental results published in literature

From the figure, it is observed that averagely good isolation efficiency is attained about D=1. Therefore, it is considered as a preliminary design value for designing the depth of an open trench wave barrier.

6. CONCLUSION

The purpose of the current study is to investigate –experimentally- the efficiency of rubber chips (shredded tyres) as vibration isolation fill-in material for wave barriers. Besides, the study targeted evaluating the vibrational screening efficiency of open trench wave barriers.

In the field, vibrations have been generated using two means; a soil compactor and a vibromotor. They both were used at different levels of intensity in order to generate multi frequencies around 32 Hz, 50 Hz, and 75 Hz. This range is repeatedly produced by highway traffic, railways, and construction activities (piling, excavating, etc.).

Trench was excavated on site, had a depth of 3.5 m depth, 0.8 m width, and 5 m length. Six measuring points were assigned as data recording points where the accelerometer sensors were placed. Tests were carried out for no trench case, open trench case, and filled-in rubber chip trench case. These all were performed to for estimating the vibration isolation efficiency of the open trench and the rubber chip-filled trench. Attenuation of vibration waves by soil damping has been measured by accelerometer sensors. To comprehend the vibrational screening efficiency of wave barriers from quantitative point of view, the term "amplitude reduction ratio" was defined, calculated basing on maximum normalized acceleration amplitude, and considered as an efficiency criteria for the behaviour of open and filled-in trenches. Depending on the normalized depth of barriers, the obtained results of current study relevant with screening efficiency of open trench have been compared with some of the experimental and numerical studies that published in literature.

This was an experimental study on reducing the ground borne vibrations using rubber chip-filled trench as a wave barrier. Among this study, the followings were concluded:

1) An attenuation to the ground-borne vibration waves was attained in case of no-trench. It was observed that normalized acceleration amplitudes tend to decrease as the distance to the source increases. Although there were fluctuations in the normalized

acceleration amplitude for low excited frequencies (32 Hz), however; more gradual decreases in normalized acceleration amplitudes are observed with increase of distance to the source. The aforementioned fluctuating is expected to happen due to reflecting and refracting of the elastic surface waves that might occur at boundaries of the layered soil profile.

2) Considering assessment of the screening efficiency of wave barriers, parameters were normalized with respect to Rayleigh wavelength so the evaluation of vibration isolation efficiency can be generalized and compared with other studies.

3) It is found that the normalized depth of trench D does have a major effect on vibration isolation efficiency of a wave barrier.

4) The average screening efficiency of open trench at a trench depth of 0.53 λ_R is 50%. However, an increase in the average screening efficiency up to 76% when trench depth reaches 0.83 λ_R. Furthermore, screening efficiency is maximized when trench depth comes closer to 1.25 λ_R.

5) Experimentally, the average amplitude reduction ratio of a rubber chip-filled trench varies within the range 0.25-0.35 whenever the trench depth changes within the interval 0.83 λ_R – 1.25 λ_R. In other words, this means that a rubber chip-filled trench is able to achieve 65% - 75% vibration isolation. However, decreasing the trench depth to values about 0.5 λ_R leads to vibration screening efficiencies do not exceed 15%.

6) The screening efficiency for open trench was better than the one obtained by the rubber chip-filled trench. Precisely, for lower trench depth $d < 0.8\ \lambda_R$, big differences in the isolation efficiency performance of open trench and rubber chip-filled trench are monitored in favour of open trench. However, more adjacency in amplitude reduction ratios is captured at trench depths $0.83\ \lambda_R \leq d \leq 1.25\ \lambda_R$. This indicates that the vibration isolation performance of rubber chip-filled trench is close to the isolation performance of open trench.

7) Experimentally, in order to obtain an idealized vibration isolation of soil using a rubber chip-filled wave barrier, the optimum trench depth must be selected to be $0.83\ \lambda_R \leq d \leq 1.25\ \lambda_R$. On the other hand, numerical analysis results have determined that an ideal screening efficiency using a rubber chip-filled trench starts at a trench depth $d = 1\ \lambda_R$.

8) Vibration isolation performance of open trench and rubber chip-filled trench decreases with distance of trench. Consequently, major isolation efficiency is found to be in the close-to-trench region. Whilst, less screening efficiency is observed in the far region, this is understandable in a layered soil profile where reflection and refraction of waves lead to a case of superposition of surface waves.

9) The amplitude reduction ratios obtained from the case of open trench have had a good consistency with the published experimental and numerical studies. However, there were no studies relevant to using rubber chips as trench fill-in material in literature, thus; no evaluation for the obtained amplitude reduction ratios of rubber chips barriers can be carried out.

In conclusion, rubber chips are cheap, light weight, and loose material that can form practical alternative to be filled-in trenches. They are being collected from disposal of industries and factories, and they are classified as environmentally friendly material due to their recyclability. From technical point of view, rubber chips provide good vibration isolation for trench depths of $0.83\ \lambda_R \leq d \leq 1.25\ \lambda_R$. They are abundant, easy to handle, sustainable, and effective isolator when filled-in trenches for the sake of isolating soil mediums against vibrations.

Recommendations for future studies:

1) In purpose of understanding the real influence of soil layering on vibration isolation of soil, further experimental studies should take place on different sites and soil profiles.

2) The present study targeted the average frequencies (30 Hz - 75 Hz) that induced by highway traffic, railway passage, and construction activities. However, to visualize isolation performance in other frequency levels further studies are recommended.

3) Rubber chips (shredded tyres) have been used newly as trench fill-in material. Thus, in order to realize the efficiency of them as fill-in material further investigations should be performed considering the variations in their sizes and textures.

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