CHAPTER 1
INTRODUCTION

1.1. GENERAL

Other than earthquakes, ground vibrations are generated from a number of man-made sources like vibrating machineries, vehicular movement and traffic, and construction activities such as pile driving, deep dynamic compaction, blasting etc. Ground-borne vibrations propagate through the surrounding soil to adjacent structures. Undue ground vibrations are not desirable as they may cause malfunctioning of high-precision instruments or facilities housed in a building, fatigue of adjacent structures and sub-structures or even damage in extreme circumstances, while becoming a source of continuous annoyance to the residents. Apparently, vibration isolation has been drawing special attention, especially in thickly populated urban or semi-urban areas and for structures housing sensitive instruments and facilities. It should be mentioned that effect of vibration on human comfort and annoyance cannot be specified only in terms of magnitude of monitored vibrations alone.

Vibration mitigation schemes are commonly known as vibration isolation or screening which may be accomplished in general, by constructing barriers across the path of propagation of surface waves. Wave barrier isolation is based on the principles of reflection, scattering, and diffraction of wave energy by barriers (Jain and Soni, 2007). Placing a barrier means creating a finite geometric or material discontinuity in the wave-field of an otherwise undisturbed half-space which intercepts the incident waves and sufficiently reduces their amplitudes. In circumstances where other isolation techniques such as machine base isolation etc. are impractical, isolation by wave barriers often proves to be an effective alternative. These barriers may include trenches (open or in-filled), sheet piles, a row of solid or tubular piles, concrete walls, diaphragm walls, gas-cushion screen etc. Effectiveness of an isolation scheme is dependent on the type of barrier provided.

Selection of a particular barrier largely depends on the sub-soil characteristics, frequency of excitation, and the targeted amplitude reduction level. The construction and financial feasibility aspects must be taken into account prior to adopting an effective isolation measure. Among the various options, open and in-filled trenches are most widely used as they are easy to construct and capable of reducing ground vibration to a significant extent, if suitably designed. Open trench barriers provide good isolation effectiveness but possess side wall instability problem, water logging, and could entrap human beings or other living animals, if used in long run. To serve long-term needs and to avoid wall instability problem, in-filled trenches prove to be a better choice. The functional difference between these two types of barriers primarily lies in the ability of an in-filled trench to allow the passage of an incident wave. An open trench is, in fact, a point of material discontinuity in an otherwise undisturbed half-space which does not allow the incident waves to transmit through. In low frequency vibration cases, trench barrier may not be a feasible solution as it may require unrealistic depth. In such cases, pile wave barriers may be adopted as an alternate isolation measure.

Vibration screening schemes are basically classified into two distinct categories based on proximity of the barrier with respect to source of excitation. The isolation scheme is termed as active isolation/source isolation/near-field isolation if the barrier is located close to the source. On the other hand, when the barrier is placed remote from the source or in the vicinity of the target or site which is to be protected, the scheme is termed as passive isolation/target isolation/far-field isolation.

1.2. NEED FOR RESEARCH

Review of literature regarding open trench isolation shows that the effects of barrier cross-sectional features on vibration screening are mostly studied against a particular barrier location, i.e. either in active or passive cases. Effects of cross-sectional features may vary depending on the distance of barrier from source which is not extensively studied in the earlier works. Isolation of the horizontal vibration component also needs concern since wave screening by open trenches is studied, mostly in terms of the vertical vibration component. Another point of concern in the field is the lack of simplified design models. So far, there is only one regression model belonging to this class and scope of its application is also limited. Design models are of much significance from application point of view. Further research is, therefore, required in the field of open trench isolation to establish the effects cross-sectional features at changing barrier locations. There is also an excellent opportunity to constitute simplified regression models for designing open trenches in active and passive cases, taking both vertical and horizontal vibration components into account.

Unlike open trenches, screening efficiency of in-filled trenches largely depends on the backfill material characteristics. Review of literature concerning in-filled trench isolation shows that much emphasis is given on the use of stiffer backfilled (concrete-filled) trenches. There are few studies where some aspects softer barrier isolation is addressed in contrast to many such studies on open and concrete-filled trenches. Nevertheless, these literature do not have sufficient depth to provide an in-depth understanding on the use of softer backfilled trenches. This provides a scope of studying softer barrier isolation in terms of the effects of various participating parameters to frame some generalized design principles of such barriers.

The use of open or in-filled trenches is restricted to cases involving small and medium surface wavelengths. The alternate solution, although not equally effective, in longer wavelength case is the use of pile wave barriers. A wave barrier comprising of a pair of trenches can be studied in this context which would possibly require shallower depth than isolated trenches. Further research may be pursued on vibration isolation by paired open or in-filled trenches to establish the effects of key parameters of such barriers and to frame some design guidelines for their practical applications.

1.3. OBJECTIVES

To address the aforementioned needs, the fundamental theme of this research work is to numerically study the unexplored areas of vibration isolation by single and dual, open and in-filled trenches. The principal objective is to investigate the isolation effectiveness of these barriers in terms of the effects of the participating parameters. In case of isolated/dual open trench barriers, effects of the geometric parameters are to be investigated. In contrast, isolation responses of isolated/dual in-filled trench barriers need to be investigated against the variations in barrier geometric features and in-fill material parameters. The study aims at conducting a non-dimensional parametric study in order to frame some generalized design principles on these barriers. Detailed objectives and scope of this study are described in *Section 2.6*.

1.4. STRUCTURE OF THE THESIS

The thesis is organized into seven chapters followed by list of references, appendices, and list of publications. The break-up and sequence of the chapters are as follows:

- *Chapter 1* deals with an overview on wave barrier isolation, need for research, broad objectives of the study, and structure of the dissertation.

- *Chapter 2* deals with fundamentals of elastic wave propagation in semi-infinite media, characteristics and significance of different types of seismic waves, active and passive isolation, factors affecting barrier effectiveness, types of vibrations, comprehensive review of previous studies on the domain, and detailed objectives and scope of the study.

- *Chapter 3* presents the overall methodology adopted in the study including justification on the use of 2-D models, the key steps of finite element modelling approach in PLAXIS, method of estimating amplitude reduction by barriers, and an overview of non-dimensional approach.

- *Chapter 4* deals with the study on vibration isolation by open trenches. Introductory part of this chapter provides a discussion on the approach of study including parameter normalization, basic assumptions, and finite element modelling approach etc. Subsequent part contains parametric study on open trench isolation, results and discussion, simplified regression models with validation, discussion on their applicability, and summary of the salient findings.

- *Chapter 5* deals with vibration isolation using softer in-filled trenches. This chapter deals with discussion on the approach adopted for the study of in-filled trench isolation, parametric study on softer barrier isolation including non-dimensional design charts, results and discussion, validation of the design charts with some published results, and a brief summary of the crucial observations.

- *Chapter 6* deals with the study of vibration isolation by dual trenches; open and in-filled. This chapter includes the scheme of study, parametric study on dual open trench isolation with results and discussion, parametric study on dual in-filled trench isolation followed by results and discussion, justification on the usefulness of dual trench barriers over isolated trenches with examples, and brief summary of the crucial findings.

- *Chapter 7* presents an overall discussion on the conclusions drawn from the study and summarizes the salient findings of this work. It also highlights the novel contributions of this study and scope of future studies in the domain.

- References.

- Appendices.

- List of publications.

CHAPTER 2
BACKGROUND

This chapter provides an overall background study which is crucial in understanding vibration isolation by barriers and realizing the scope of previous studies in the domain. It deals with the fundamentals of elastic wave propagation in semi-infinite media, characteristics and significance of different types of seismic waves, types of vibrations generated by different sources, and a comprehensive review of previous studies in the domain.

2.1. FUNDAMENTALS OF WAVE PROPAGATION

A comprehensive understanding on the phenomena of wave propagation in an elastic medium is of fundamental importance in wave barrier isolation studies. In a semi-infinite body, vibratory energy propagates in the form of body waves (that travels in to the half-space) and surface waves (that travels exclusively along the surface).

2.1.1. Wave Propagation in Semi-Infinite Media

Two types of body waves propagate in an elastic medium causing respectively, instantaneous volumetric changes (contraction and dilatation) and distortion of the material. The body wave that causes volumetric changes is termed as compression or primary wave (P-wave). P-wave is the fastest kind of seismic wave that can travel through solids and liquids. The primary wave velocity (V_p) can be expressed in the following form (Das and Ramana, 2011):

$$V_p = \sqrt{\frac{\lambda + 2G}{\rho}} = \sqrt{\frac{(1-\nu)E}{\rho(1+\nu)(1-2\nu)}} \qquad (2.1)$$

The significance and mathematical expressions of the parameters involved in the equation are:

Lami's constant, $\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$

Shear modulus, $G = \frac{E}{2(1+\nu)}$

The elastic modulus, mass density, and Poisson's ratio of the material are denoted by *E*, ρ, and ν in the above expressions. P-waves are longitudinal in nature in which the particle motion is parallel to the direction of wave propagation.

The second kind of body waves are termed as S-waves that cause distortion of the material. They are characterized by velocities much slower than P-waves and travel only in solids. Velocity of S-wave (V_s) can be expressed as follows (Das and Ramana, 2011):

$$V_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\nu)\rho}} \tag{2.2}$$

S-waves are transverse in nature where the particle motion is perpendicular to the direction of propagation of waves. S-waves are further classified as SH and SV-waves depending whether the particle motion is confined to a horizontal (H) or vertical (V) plane. Comparing the velocities of P and S-waves from *Equations (2.1)* and *(2.2)*:

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \tag{2.3}$$

It is apparent from *Equation (2.3)* that the extent by which P-wave velocity exceeds that of S-wave is governed by Poisson's ratio of the material. Poisson's ratio of soil influences the wave propagation velocities in soil, the compression wave in particular. When Poisson's ratio approaches 0.5, V_p approaches infinity, so the ratio, $V_p/V_s \rightarrow \propto$ as well.

The free surface boundary conditions of earth allow additional solutions to the wave motion problem which are termed as surface waves. The first kind of surface wave is Rayleigh wave (R-wave) which is generated due to the interaction of P and S-waves at the surface. Rayleigh waves are also called ground rolls that make the ground to move up and down and side-to-side in the direction of wave propagation. The motion of a particle under the action of R-waves follows the trajectory of a retrograde ellipse.

The other type is termed as Love wave that requires a superficial layer of lower S-wave velocity than the underlying half-space (Richart *et al.*, 1970). Love waves primarily consist of reflected SH-waves trapped within the superficial layer. Particle motion consists of alternating transverse motions in a horizontal plane, implying that Love waves are transverse in nature. However, in a homogeneous half-space, Love waves do not exist and the only surface wave which is of importance is R-wave. The Rayleigh wave amplitude is much higher than body waves and associated with major tremors.

The mathematical expression relating velocities of P, S, and R-waves (Kramer, 1996) is given by:

$$K^6 - 8K^4 + \left(24 - 16\alpha^2\right)K^2 + 16\left(\alpha^2 - 1\right) = 0 \qquad (2.4)$$

Where, $K = V_R / V_s$ and $\alpha = V_s / V_p = \sqrt{\dfrac{1 - 2\nu}{2(1-\nu)}}$

Equation (2.4) allows evaluating the ratios of P-wave and R-wave velocities to that of S-waves (V_p/V_s and V_R/V_s) as functions of Poisson's ratio as shown in *Figure 2.1*. An approximate solution to this equation relating R-wave and S-wave velocity (Yang and Hung, 1997) is:

$$V_R = \left(\frac{0.87 + 1.12\nu}{1 + \nu}\right) V_s \qquad (2.5)$$

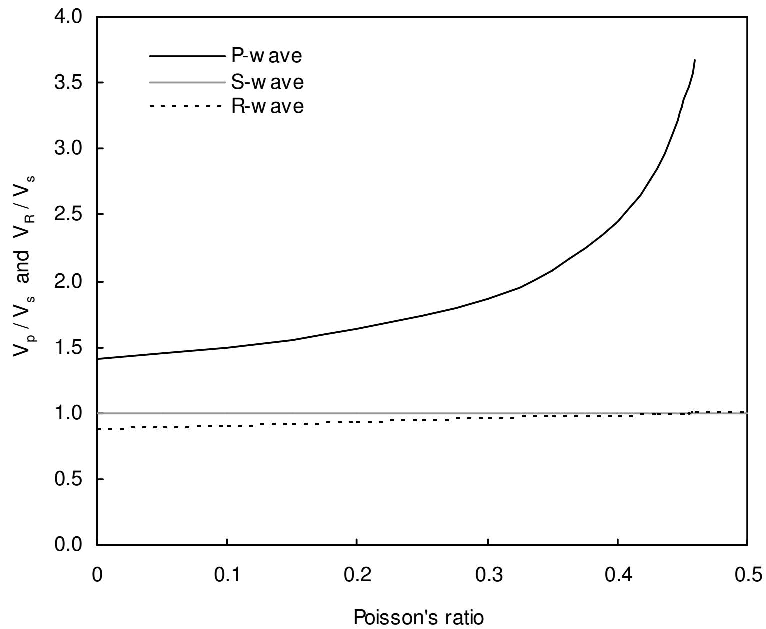

Figure 2.1: Variation of V_p/V_s and V_R/V_s against Poisson's ratio (redrawn after Kramer, 1996)

From the preceding expression, it is apparent that R-waves travel at a velocity, V_R which is slightly slower than V_s.

Components of R-wave decay exponentially with depth (Villaverde, 2009) with their amplitudes being the maximum at the surface. The amplitudes at a depth (z) expressed as fractions of surface amplitudes is plotted against dimensionless depth ($Z=z/L_R$) as shown in *Figure 2.2*.

The dimensionless depth is the actual depth normalized over Rayleigh wavelength (L_R). It is apparent from *Figure 2.2* that the dominant zone of R-wave propagation lies within a depth of nearly one Rayleigh wavelength from the surface. Nevertheless, the extent to which this zone prevails depends on Rayleigh wavelength of vibration in half-space. For a particular half-space, it may extend from few centimetres to several meters depending on the frequency of vibration. Low frequency vibration gives rise to higher wavelength and consequently, the dominate zone of R-wave propagation is larger.

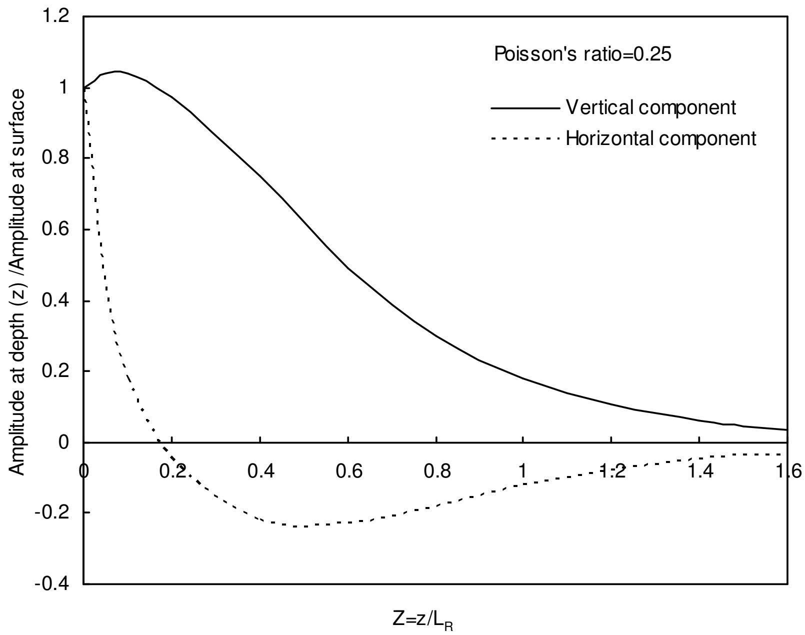

Figure 2.2: Variation of vertical and horizontal displacement components of R-wave with depth (redrawn after Das, 1990; Das and Ramana, 2011)

2.1.2. Radiation Damping

When seismic waves propagate away from source, they encounter an increasingly larger volume of soil medium causing the energy density to decrease with distance from source. The decrease in wave energy is termed as radiation damping or geometrical damping (Kramer, 1996). Body waves propagate in the form of hemispherical wave-fronts, whereas Rayleigh waves propagate radially outward in the form of cylindrical wave-fronts. In case of body waves, amplitude decreases with the inverse of distance from source of vibration (proportional to $1/r$). Along the surface of half-space, amplitude of body waves decreases at a higher rate (proportional to $1/r^2$). On the other hand, Rayleigh wave amplitude decreases with square root of distance from source (proportional to $1/\sqrt{r}$). This implies that surface waves attenuate geometrically at a rate much slower than body waves.

2.1.3. Material Damping

There is another type of damping that occurs due to wave absorption in real earth materials and is termed as material damping. It is an internal property of the material by virtue of which some energy, with each cycle of oscillation, is absorbed in the material as internal friction loss as the particles move against each other (Lidén, 2012). Material damping of geologic materials is often described in terms of a factor, β called absorption coefficient. Absorption coefficient values are higher for soft materials and lower for hard materials. The absorption coefficient is dependent on the frequency of excitation in a linear manner as follows:

$$\beta_2 = \beta_1 \frac{f_2}{f_1} \tag{2.6}$$

Here, β_1 is the known value of absorption coefficient at frequency f_1 and β_2 is unknown value at frequency f_2. It is apparent that absorption coefficient is less for low frequencies, implying that low frequency vibrations decay with distance at a slower rate than high frequency vibrations. *Table 2.1* presents some representative values of absorption coefficients for different soil types calculated against a frequency of 30 Hz.

Table 2.1: Absorption coefficients for different soil types (after Woods, 1997)

Absorption coefficient, β (m^{-1})	Soil type
0.06-0.195	Weak or soft soils: dry peat and muck, mud, loose beach sand, dune sand, recently ploughed ground, organic soil (shovel penetrates easily).
0.0195-0.06	Competent soils: sands, sandy clays, silty clays, gravel, silts, weathered rocks (can be dug with shovel)
0.00195-0.0195	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rocks (cannot be dug with shovel)
Less than 0.00195	Hard competent rock: bedrock, freshly exposed hard rock (difficult to break with hammer)

Effect of material damping on wave attenuation is usually less than radiation damping but it may be significant in case of vibrations propagating through soft soils.

2.1.4. Attenuation of Seismic Waves with Distance

The attenuation of seismic waves with distance from source is governed by both radiation damping and material damping. Taking both forms of damping into account, the total damping effect on wave amplitude is expressed in the following form (Woods, 1997):

$$A_2 = A_1\left(\frac{r_1}{r_2}\right)^n \exp\left[-\beta\left(r_2 - r_1\right)\right] \tag{2.7}$$

Where,

A_1 = Amplitude at distance r_1 from source

A_2 = Amplitude at distance r_2 from source

β = Absorption coefficient

n = 1/2 (for Rayleigh waves)

= 1 (for body waves)

= 2 (for body waves along the surface)

2.1.5. Significance of Rayleigh Waves

Rayleigh waves are largely responsible for vibration induced damages and distresses of structures and sub-structures since wave of this kind travels within a narrow zone close to the surface. Vibratory energy is transmitted in the half-space by a combination of compression, shear, and Rayleigh waves. The distribution of wave energy among these waves was computed by Miller and Pursey (1955) in case of an elastic half-space of Poisson’s ratio, 0.25 subjected to a vertical oscillation. It was observed that R-wave alone carries 67% of the wave energy followed by S-waves (26%) and P-waves (7%). The principal characteristics of body waves and Rayleigh waves are summarized in *Table 2.2*.

Table 2.2: Characteristics of body waves (P and S-waves) and R-waves

Characteristics	Body waves	Rayleigh waves
Percentage energy distribution	33%	67%
Geometrical damping	$1/r$ (except along the surface; for which it is $1/r^2$).	$1/\sqrt{r}$
Propagation	To the interior of earth.	Zone of propagation is confined within a depth roughly equal to one Rayleigh wavelength measured from surface.
Amplitude	Less	Highest
Remarks	Causes minor tremor.	Causes major tremor.

Apparently, a bulk portion of wave energy is transmitted in the form of Rayleigh waves that propagates exclusively along the surface with the largest amplitude. Moreover, it decays with distance at a rate much slower than body waves, signifying that Rayleigh wave is of primary concern in vibration isolation studies.

2.2. ACTIVE AND PASSIVE ISOLATION SCHEMES

As already stated, vibration isolation schemes can be active or passive type depending on whether the barrier is placed close to the source or far-off. Choice of a particular scheme is problem dependant. For instance, active isolation is typically practised in case of machine foundations, while for shielding residential buildings from traffic-induced vibrations; passive isolation scheme is usually adopted. 2-D schematic of active and passive isolation schemes are depicted in *Figures 2.3(a)* and *2.3(b)*.

Closer to the source of vibration, influence of body waves (compression and shear waves) is significant. At distances remote from the source, surface waves predominate body waves as the latter decays to an insignificant extent owing to the fact that body waves attenuate at a much higher rate (along the surface, in particular) than surface waves. This signifies that active isolation or source isolation is associated with body waves and surface waves, whereas passive isolation or target isolation principally consists of surface wave screening.

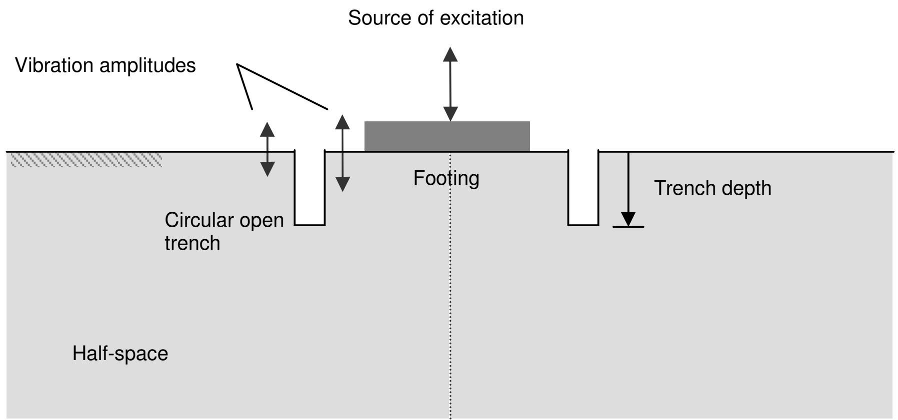

Figure 2.3(a): Active isolation by a circular trench (redrawn after Woods, 1968a)

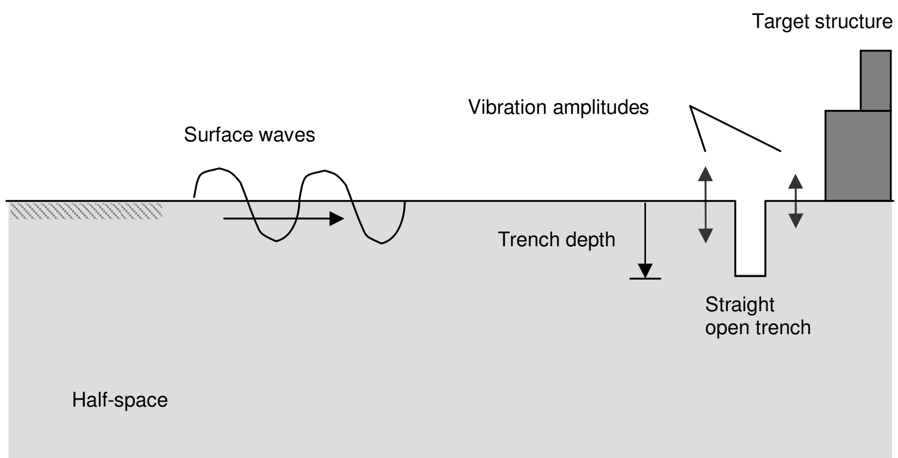

Figure 2.3(b): Passive isolation by a straight trench (redrawn after Woods, 1968a)

2.3. FACTORS GOVERNING SCREENING EFFECTIVENESS OF TRENCH BARRIERS

Parameters that govern the vibration isolation effectiveness of a trench are the barrier features, material parameters of soil, and frequency of excitation.

Barrier features of an open trench include the geometric parameters. Depth, width, and distance of barrier from source are the geometric parameters of a trench barrier that govern its isolation effectiveness. The effect of barrier distance from source could be attributed to attenuation of seismic waves with distance.

In case of an in-filled trench, the isolation efficiency is governed by its backfill material parameters in conjunction with the geometric features. Choosing a proper backfill, in fact, is equally important as selecting the geometric features. The materials that are widely used in trench filling are concrete, bentonite slurry, geofoam etc. The stiffness of trench backfill is an important factor affecting the isolation effectiveness of barrier.

Material parameters of soil and frequency of excitation are the external parameters that govern the Rayleigh wavelength of vibration which, in turn, governs the isolation efficiency of a barrier. Rayleigh wavelength is the ratio between Rayleigh wave velocity and frequency of excitation. Under a particular frequency of excitation, soil of higher Rayleigh wave velocity will have higher Rayleigh wavelength. On the other hand, in a particular soil, sources emitting high frequency vibrations result in shorter surface wavelengths and vice-versa. This implies that screening effectiveness of a particular trench will vary according to the excitation frequency and sub-soil parameters. Alternately, for a given sub-soil and frequency of excitation, screening effectiveness will differ depending on the barrier features.

2.4. TYPES OF VIBRATIONS

The nature of ground-borne vibration depends on the source of excitation. The vibration may be periodic, transient or random depending on the type of excitation. The periodic loadings are repetitive loads which exhibit the same variation with time for a large number of cycles. The most common example is the rotating type or reciprocating machine that induces steady-state vibrations. Machines that generate transient vibrations are forge hammers, crushers, and mills. This type of vibration can also be termed as impulse load or shock as the excitation force is of short duration. Transient vibrations are often approximated as declining periodic vibrations. The dynamic responses induced by a moving train, blasting etc. are few more examples of transient vibrations. On the other hand, random vibrations are characterized by wave patterns that never repeat themselves.

2.5. REVIEW OF LITERATURE

A good deal of research has been carried out in the last few decades to study isolation of ground-borne vibrations using wave barriers. The first experimental study on open and in-filled trench wave barriers was carried out by Barkan (1962). This study shows that the screening efficiency of a barrier increases with its depth and distance from the source of excitation. Woods (1968) conducted a series of field experiments on active and passive isolation by open trenches and found the parameter that mostly governs the screening efficiency is the ratio between depth of barrier and wavelength of surface wave, whereas the width participates little in isolation process. This was also observed that deeper trenches are required at greater distances from source to accomplish a given amplitude reduction. Based on the experimental findings, this study proposes some guidelines for designing open trenches that can achieve amplitude reduction up to 75% or more. Haupt (1981) investigated vibration screening effectiveness of different barriers (concrete wall, open trenches, and a row of boreholes) using small-scale laboratory tests. In case of stiffer barriers, amplitude reduction is found to be governed by the cross-sectional area of the barrier rather than its actual shape, whereas for softer barriers it depends on the shape.

In barrier isolation studies, much emphasis is given on the use of numerical methods rather than full-scale or small-scale experimentation. Full-scale experimentation is certainly a more convincing approach but it inherits the sub-soil stratification problem which makes it difficult to draw generalized conclusions. Moreover, the number of cases that can be investigated with a numerical approach is almost impractical with full-scale experiments. Likewise, in a small scale model test, it is difficult to extrapolate the half-space (semi-infinite) condition. A numerical method, on the other hand, proves to be a competent approach to investigate barrier isolation problems. In view of this, majority of the barrier isolation studies are performed using numerical methods, such as boundary element method (BEM) and finite element method (FEM) in contrast to fewer experimental studies in the domain. The BEM has extensively been used to study such problems since it requires discretization of only the surface layer and automatically satisfies the infinite boundary condition. The FEM is usually used in conjunction with special non-reflecting boundaries.

Wass (1972) was probably the first to investigate isolation effectiveness of trenches using FEM with special elements accounting for wave radiation at boundaries. Haupt (1977) employed FEM in investigating the screening response of concrete barriers and later validated some results in his subsequent small-scale experimental study (Haupt, 1981). Segol *et al.* (1978) used FEM for studying vibration screening by open and in-filled trenches in layered soils. Their findings for open trenches showed qualitative agreement with Wood's (1968) experimental results. May and Bolt (1982) performed a plane strain FEM study on vibration screening effectiveness of open trenches in a two-layered soil profile. Fuyuki and Matsumoto (1980), using a finite difference scheme with an advanced treatment of corners and absorbing boundary conditions, studied wave scattering by rectangular open trenches and found that in addition to trench depth, the effect of width could be significant for shallow open trenches.

Emad and Manolis (1985) employed BEM in a 2-D context in investigating surface wave isolation by shallow trenches. Widespread application of BEM to wave barrier isolation studies started with the 2-D BEM investigation of Beskos *et al.* (1986) on the effectiveness of open and filled trenches in screening ground-borne vibrations in an elastic and homogeneous half-space. This literature presents some guidelines on optimal dimensioning of open and concrete-filled trenches and concludes, in general, that open trenches provide better screening effect than concrete-filled trenches. The isolation response of open and concrete-filled trenches in a 3-D context was later investigated in the BEM study of Dasgupta *et al.* (1990). This is an extension of the methodology of Beskos *et al.* (1986) to wave scattering problems in three dimensions. Results of 3-D analyses are found in good agreement with previous study of Beskos *et al.* (1986). A further study on the screening efficiencies of open and concrete-filled trenches in a 2-D layered half-space (considering the effect of non-homogeneity of sub-soil with a few specific layered cases) was performed by

Leung *et al.* (1990) in continuation with previous works of Beskos *et al.* (1986) and Dasgupta *et al.* (1990). It leads to the conclusion that in case of softer layers underlain by stronger layers, deeper trenches are required to achieve the same degree of isolation as in homogeneous soils, with this trend being more pronounced for concrete-filled trenches.

Subsequent 2-D BEM investigation of Ahmad and Al-Hussaini (1991) on screening effectiveness of open and concrete-filled trenches provides a deeper insight into the domain. Various geometric and material parameters governing the screening effectiveness of such barriers are identified and simplified design models are developed incorporating the effects of these parameters. Some layered cases are also studied and important aspects of soil layering on barrier performance are outlined. Al-Hussaini and Ahmad (1991) carried out a further study on rectangular wave barriers (solid obstacles) in screening horizontal surface vibrations using a rigorous BEM algorithm. Ahmad *et al.* (1996) performed another extensive study on active isolation of machine foundations by open trenches in a 3-D context using BEM. In continuation, active isolation of machine foundations with in-filled trench barriers was investigated by Al-Hussaini and Ahmad (1996). Although, this work primarily focuses on concrete-filled trenches, some aspects of softer barriers are also studied. The key geometric features and in-fill material parameters that govern the performance in-filled trenches are identified and some design guidelines are proposed. The experimental studies and the series of numerical investigations discussed so far provide a good understanding on the subject and in fact, made the framework of subsequent studies in the domain.

Klein *et al.* (1997) studied screening effectiveness of open trenches in a homogeneous and elastic half-space adopting a 3-D BEM code and found reasonable agreement between numerical simulation and experimental data. Shrivastava and Rao (2002) conducted a 3-D FEM study on open and concrete-filled trenches in reducing pulse-induced vibration. This study shows that open trenches are more effective than concrete-filled trenches and isolation efficiency is primarily governed by the depth of a trench.

Yang and Hung (1997) extensively studied active isolation of train-induced vibration by the use of open trench, in-filled trench, and elastic foundation using a finite/infinite element scheme (2-D finite element scheme with infinite elements at boundaries to allow for wave absorption). The isolation responses of the barriers are investigated with respect to different geometrical and material parameters and conclusions are made regarding the selection of optimal parameters. This literature concludes, in general, that these wave barriers are suitable only for screening high frequency vibrations. In continuation, Hung *et al.* (2004) investigated the effectiveness open trenches, in-filled (concrete-filled) trenches, and wave impeding blocks in isolating ground vibrations induced by trains moving at sub-critical and super-critical speeds using the previously developed finite/infinite element scheme. It is noted that efficiency of open and in-filled trenches increases with increase in excitation frequency. The wave impending block is effective only in isolating vibrations of wavelength comparable to the wave impending block itself. In the context of train-induced vibration reduction, 3-D FEM study of Ju (2004) on open trenches, in-filled trenches, and ground improvement methods, 3-D FEM study of Ju and Lin (2004) on soil improvement and a concrete slab barrier, Celebi and Schmid (2005) on open trenches employing a thin layer method/flexible volume method and BEM in a 3-D context can be referred to. Study of Ju (2004) summarizes that low frequency vibrations caused by trains running at speeds of 300 km/hour or more require deeper trenches which are not feasible. Soil improvement schemes are found to contribute little to vibration reduction, especially vertical vibration. Ju and Lin (2004) points out that soil improvement method and concrete slab barrier are effective only when the train speed is more than that of Rayleigh wave. Celebi and Schmid (2005) points out that open rectangular trenches with optimum depth are very effective in reducing both horizontal and vertical components of ground vibration. Adam and Estorff (2005), on the other hand, investigated reduction of train-induced building vibrations by open and filled trenches with a coupled boundary element-finite element algorithm in a 2-D context. Results indicate that a properly designed trench barrier can reduce up to 80% of the building vibrations and internal forces. Increasing the depth or width of a trench and use of softer backfill materials result in better isolation effect. Out of these, the most relevant literature in the current context is Yang and Hung (1997). The other few (Hung *et al.*, 2004; Ju, 2004; Ju and Lin, 2004; Celebi and Schmid, 2005; Adam and Estorff, 2005) viewed the problem from different perspectives and do not have one-to-one relevance with the present study. The usefulness of softer barriers as indicated by Adam and Estorff (2005), however, provides a scope of future investigations on such barriers.

Literatures of Di Mino *et al.* (2009) on the use of open trench barriers, Younesian and Sadri (2012) on using open trench barriers, Leonardi and Buonsanti (2014) on the use of concrete trenches and compacted soil barrier, Hasheminezhad (2014) on using trenches filled with pipes, are few other studies in the context of train-induced vibration isolation. The 2-D FEM study of Di Mino *et al.* (2009) is informative but its scope is limited to the case of a soil layer of finite thickness underlain by rigid bedrock. This work adopts the artificial neural network for quantifying the relative contribution of various parameters. The depth of a trench is found to be the most significant geometric parameter. However, its effect must be evaluated in terms of the thickness of soil layer under study. In two recent FEM studies, effectiveness of V-shaped open trench (Esmaeili *et al.*, 2014) and that of step-shaped open and in-filled trenches (Zakeri *et al.*, 2014) against reducing train-induced vibrations are investigated and observed that such trenches are more effective than common rectangular trenches.

El Naggar and Chehab (2005) conducted a 2-D FEM study on soft and stiff barriers in isolating vibrations caused by shock-producing equipments resting on an elastic half-space or a layer of limited thickness underlain by rigid bedrock. Results indicate that wave barriers are suitable for isolating shock-induced vibration if the soil layer under study is of finite thickness and underlain by rigid bedrock. The efficiency increases with depth of trench relative to the soil layer under study. Soft wave barriers (gas cushion, empty trenches, bentonite- filled trenches) are shown to be more effective than stiff barriers, i.e. concrete-filled trenches which is a crucial observation of this study. Similar observation that softer barriers provide better isolation effect than stiffer ones was made in the experimental study of Celebi *et al.* (2009) on open and in-filled trench isolation and 3-D FEM study of Rahman and Orr (2006) on reducing vibration induced by tunnel boring machines using in-filled trenches. Recent 2-D FEM study of Bo *et al.* (2014) can be referred in this context that too shows that use of softer barriers provide better isolation effectiveness than stiffer barriers. Effects of various features of in-filled wave barriers are extensively investigated in this work and an optimized design methodology is proposed.

A different approach of wave isolation using multiple shallow open trenches in the context of ground vibration caused by dynamic compaction is investigated by Hwang and Tu (2006). This experimental study shows that shallow trenches have nearly no isolation effect in such cases. However, this study provides a scope of future investigations on the use of multiple trenches as wave barriers. From application standpoint, open trenches with wall sidings are more feasible solutions as they do not posses the problem of side wall instability. This perspective is investigated in the 2-D BEM study of Tsai and Chang (2009) on the effectiveness open trenches with sidings (with sheet piles and diaphragm walls on both sides of an open trench). Open trenches with diaphragm walls or sheet pile sidings are found less effective than open trenches without sidings. This is an informative non-dimensional study and the cases of open trenches without sidings provide a good basis for comparison; although, it seems to have little relevance in the current context.

Application of geofoam-filled trenches as wave isolation measures is emphasized in few recent literatures. Wang *et al.* (2009) investigated active isolation of blast induced vibrations using 3-D FEM with open trench, inundated water trench, geofoam wall, and concrete wall. This study shows open trench and geofoam wall can sufficiently reduce blast induced stress waves, whereas inundated water trench and concrete wall have nearly no isolation effect. Murillo *et al.* (2009) conducted a parametric study on geofoam wave barriers with a small-scale centrifuge model test and framed some guidelines regarding the barrier width, depth, and its distance from source for its optimum efficiency. Alzawi and El Naggar (2009) numerically investigated active and passive isolation effectiveness of geofoam barriers of different configurations. Results showed that such barriers perform well in reducing surface waves. Alzawi and El Naggar (2011) carried out a full-scale experimental investigation on the effectiveness of open and geofoam-filled trenches in scattering steady-state vibrations induced by machine foundations. The experimental results are compared with 2-D FEM results and good agreement is obtained. Effects of the key barrier features on screening effectiveness of open and geofoam-filled trenches are summarized in this study. FEM study Ekanayake *et al.* (2014) on water-filled and geofoam trench isolation is a recent literature which shows that such barriers exhibits isolation effectiveness comparable to open trenches.

Madheswaran *et al.* (2009) conducted an experimental study supported by 2-D FEM analysis on open and concrete-filled trenches in reducing vibrations caused by pile driving. Babu *et al.* (2011) carried out a field vibration test followed by 2-D numerical analysis using a finite difference tool to suggest effective isolation measures for a site-specific case. Ju and Li (2011) performed a 3-D FEM study on vibration isolation by water-filled trenches and shows that water-filled trenches are comparable to open trenches in reducing the vertical and transverse vibration components. Jesmani *et al.* (2012) conducted a study on passive isolation by open trench barriers (in the form of a circular arc) using 3-D FEM and highlighted the contribution of different parameters. Nam *et al.* (2013) contributed a comprehensive review on current practices of vibration mitigation by wave barriers. Literature of Connolly *et al.* (2013) on mitigation of train-induced vibration with low acoustic impedance backfilled trenches using 3-D FEM is another contemporary study. Reliability of numerical result is first validated with an experimental program and open trench condition is used to simulate low acoustic impedance material in the numerical computations. The depth of trench is found to be the most significant factor; whereas its width shows little effect in vibration screening.

Use of trenches as wave barriers is limited to cases involving small to medium surface wavelengths as construction of deep trenches required in cases of long surface wavelengths is almost impractical. Trenches of too large a depth also inherit side wall instability problems. The only practical wave barrier in such cases is a row of closely spaced piles. The major advantage of pile wave barriers is their ability to be driven deep into the ground. The isolation response of pile wave barriers is also investigated in several literatures. Kattis *et al.* (1999a) studied vibration isolation by a row of piles, replacing the pile row by an equivalent trench using BEM in a 3-D context. It is noted that open trenches and tubular piles are more effective than concrete-filled trench and solid concrete piles. In continuation with this work, screening effectiveness of a row of piles was investigated in a 3-D context with the aid of an advanced BEM code (Kattis *et al.*, 1999b). This work investigates screening effectiveness of tubular and solid concrete piles of square and circular cross-sections in contrast to open and in-filled trenches. It is reported that isolation response of a pile wave barrier is almost independent of pile cross-sections and tubular piles provide better isolation that solid concrete piles. The general wave scattering pattern of piles is found similar to that of trenches with the latter being always more effective than pile wave barriers. Piles are useful wave barriers where deeper trenches are not feasible for surface waves of longer wavelengths. Length, depth, and width of piles influence the screening effectiveness in a manner analogous to trenches. The isolation efficiency of a row of piles was found to increase with decreasing spacing.

Zhang *et al.* (2008) investigated isolation effectiveness of cast-in-place concrete pipe piles using 3-D FEM and observed good isolation effect within a distance of four times the Rayleigh wavelength behind the barrier. Tsai *et al.* (2008) performed a 3-D BEM study on screening response of a row of circular piles for the case of a massless footing subjected to harmonic vertical excitation. The parametric study includes four different types of piles; steel pipe piles, concrete hollow piles, concrete solid piles, and timber piles. Isolation performance of steel pipe piles is found better than that of solid piles and concrete hollow piles. The influence of pile length is more significant than pile spacing and distance of barrier from source of excitation. The screening efficiency of pile barrier is found insensitive to the frequency of vibration. Xu *et al.* (2010) conducted another numerical study on isolation of vibration induced by vertical harmonic load using a row of piles as wave barriers. Stiffer piles are shown to provide better isolation effect than flexible piles. Moreover, the screening efficiency increases with increase in pile depth and decrease in spacing between adjacent piles. Multiple pile rows lead to a better screening effect. However, the spacing between two adjacent rows (in case of multiple pile rows) does not have much effect on the screening effectiveness. The effectiveness of inclined secant micro-pile walls has recently been studied as an active isolation measure in a 3-D half-space using FEM (Turan *et al.*, 2013).

2.5.1. Summary of Literature Review

A crucial aspect of wave barrier isolation is the location of barrier from the source of excitation. In the earlier studies concerning open trench isolation, effort is mostly made to study the effects of cross-sectional features of open trenches against a particular location, i.e. either in active or passive cases which does not reflect variations in the effects of these parameters at varying locations. A specific case of Yang and Hung (1997), few cases by Beskos *et al.* (1986), and few experimental results of Alzawi and El Naggar (2011) do not provide a deep insight into the problem. Di Mino *et al.* (2009) studied a few such cases but this study has got no relevance to a half-space context. This pin-points the area where further study is required to establish the effect of barrier locations on the effectiveness of an open trench of different configurations and how the isolation scheme changes from an active to a passive case. The horizontal vibration screening also is of concern since the earlier studies primarily focus on the isolation of vertical vibration component by open trenches. In the study of Yang and Hung (1997) on active isolation of train-induced vibrations by open and in-filled trenches, a specific case of vertical and horizontal vibration screening was investigated at varying trench locations. This work, however, does not cover the detailed aspects of cross-sectional features of an open trench and their effects on reducing the horizontal component of vibration. Di Mino *et al.* (2009) investigated a number of such cases in their 2-D FEM study on reducing train-induced displacements and velocities by open trenches assuming a soil layer of finite thickness underlain by rigid bedrock which is not applicable to a semi-infinite scenario. Horizontal vibration screening by open trenches is partly addressed in few other literatures (Ju, 2004; Celebi and Schmid, 2005). However, these studies do not cover the detailed aspects of barriers features and are based on different approaches which cannot be considered within the scope of this study. The horizontal component of vibration attenuates in an entirely different pattern with respect to the variations in either trench location or its cross-sectional features. Therefore, the conclusions drawn on vertical vibrations do not apply in case of horizontal vibrations.

Another scarcity in the field of open trench isolation is simplified design models which are of much significance from application standpoint. Although, significant contribution is made in the field, none of the previous studies, other than Ahmad and Al-Hussaini (1991), made an attempt to develop simplified design models. Application of the so far available model is, however, restricted to vertical vibration isolation in passive cases. Further investigation may be carried out on vibration screening by open trenches to establish the effects cross-sectional parameters with respect to change in barrier locations. The isolation effectiveness of such barriers may be investigated in terms of reduction of vertical and horizontal components of vibrations. Developing simplified regression models for designing open trenches in active and passive cases, taking both vertical and horizontal vibration components into account, can be taken as a lateral perspective of such study.

So far as the in-filled trench isolation is concerned, the previous works mostly focused on stiffer backfilled (concrete-filled) trenches. Al-Hussaini and Ahmad (1996) made an effort to study some aspects of softer barriers in their study on active isolation of machine foundations by in-filled trenches. The scope of this study is limited to vertical vibration isolation in active case and consequently, do not provide a comprehensive understanding on softer barrier isolation. In the study of Bo *et al.* (2014), it is reported that softer wave barriers can effectively reduce vertical and horizontal vibrations; whereas stiffer barriers contribute little to vibration reduction. However, the optimized design methodology proposed in this literature requires a lot of computational time and programming skill. On the other hand, much simpler guidelines can be contributed in the form of design charts. Studies of Adam and Estorff (2005), Celebi *et al.* (2009), El Naggar and Chehab (2005), Rahman and Orr (2006), Yang and Hung (1997) etc. are some literatures where few aspects of softer backfilled trenches are addressed to. Although, it has been manifested that softer barriers perform better than stiffer ones, no extensive study is conducted addressing isolation effectiveness of softer barriers in contrast to several such literatures on open and concrete-filled trenches. These pin-points the necessity of a further study to improve upon the understanding on vibration isolation by trenches, in-filled with softer material to identify the key aspects and to frame some generalized design principles.

Although, pile barriers can be used as alternatives of open and in-filled trenches when larger surface wavelengths are encountered, their effectiveness is found always less than open and in-filled trenches (Kattis *et al.*, 1999a, 1999b). This could be attributed to the spacing between adjacent piles which still allows the propagation of incident waves. Efficiency of pile barriers can be increased by the use of hollow piles, decreasing spacing between adjacent piles, or using multiple pile rows (Kattis *et al.*, 1999a; Kattis *et al.*, 1999b; Xu *et al.*, 2010). However, driving piles at very closer spacing is practically difficult and use of multiple pile rows may not be an economically viable solution. In this context, an alternate isolation scheme may be devised by constructing a pair of trenches across the line of propagation of surface waves. A barrier comprising of two trenches in succession would require lesser depth than isolated trenches and may be used in circumstances where the latter requires unrealistic depth. Although, relevant literatures on trench barrier isolation are plenty in numbers, the case of an isolation scheme comprising of a pair of trenches is not addressed in any of the literatures. Study of Hwang and Tu (2006) can be referred to in this context where an effort was made to study the effectiveness of multiple shallow open trenches in reducing dynamic compaction induced vibrations. These pin-point the area where further study is required to improve upon the art of vibration isolation by trenches. This provides a scope of studying paired open and in-filled trenches as vibration barriers and identifying the effects of the participating parameters to frame some design guidelines for their practical applications.

2.6. OBJECTIVES AND SCOPE OF THE STUDY

Although, the broad objectives have already been defined, it is necessary to narrate the objectives and the scope of the study in a more specific manner. The detailed objectives are as follows:

- To numerically investigate vibration isolation by open trench barriers in terms of the effects of barrier geometric features. Geometric features include barrier depth, width, and its location with respect to the source of excitation. To establish the effects of barrier cross-sectional features in active and passive cases. To develop regression models for simplified design of open trenches in active and passive cases.

- Conducting numerical study on screening effectiveness of softer in-filled trenches considering the effects of barrier geometric features (depth, width, and location with respect to the source) and in-fill material parameters. To establish the effects of various parameters, identifying the key parameters, and to frame some generalized design principles on softer barrier isolation.

- To numerically investigate the vibration isolation effectiveness of dual open trench barriers (a barrier comprising of two open trenches in succession). To study the effects of depths, widths, and barrier locations from the source of excitation with the objective of identifying the key parameters and to frame some design principles on such barriers.

- To conduct numerical study on isolation efficiency of a barrier comprising of a pair of softer backfilled trenches considering the effects of barrier location, depths, widths, and characteristics of in-fill material. The primary objective is to establish the effects of these features and to frame some design guidelines.

To achieve the stated objectives, screening effectiveness of these barriers is investigated with respect to various barrier features using a non-dimensional approach. The scope of the study is wide-ranging and can be briefed as follows:

- Extensive numerical investigation on the effectiveness of open trenches in terms of the effects of barrier geometric features. Non-dimensional design charts relating overall amplitude reduction with barrier features. Crucial observations regarding the effects of various features on amplitude attenuation by such barriers. Simplified regression models including all possible cases of open trench isolation.

- Justification on the usefulness of softer barriers over stiffer ones. Extensive investigation on barrier geometric features and in-fill material parameters. Non-dimensional design charts for practical application of such barriers in active and passive cases. Important observations on the effects of the participating parameters and recommendations regarding optimal selection of these parameters.

- Investigating the effects of geometric features of dual open trench barriers and to develop non-dimensional charts for simplified design of such barriers in active and passive cases. Identifying the effects of various features and laying guidelines on optimal selection of these parameters. Justification on the advantage of such barriers over isolated open trenches.

- Investigation on isolation effectiveness of a vibration isolation scheme comprising of a pair of softer barriers including the effects of barrier geometric features and backfill material parameters. Non-dimensional design charts showing amplitude reduction against barrier cross-sectional features and backfill shear wave velocity ratio. Conclusions regarding the effects of the participating parameters and recommendations on the selection of these parameters for optimal effectiveness of such barriers. Justification on the usefulness of such barriers over isolated in-filled (softer) trenches.

CHAPTER 3
METHODOLOGY

This study adopts a numerical approach using a finite element package PLAXIS 2D, which has especially been developed for deformation and stability analyses of soil and rock mechanics problems. This chapter presents the overall methodology adopted in this study. The chapter contains justification on the use of 2-D models, basics of finite element modelling scheme in PLAXIS (i.e. units and sign convention, elements, model geometry, boundary conditions and non-reflecting boundaries, material model and parameters, dynamic load, mesh generation, and summary of the key steps of modelling), and overall approach of the study including estimation of amplitude reduction by barriers.

3.1. MODEL JUSTIFICATION

The analyses are carried out considering a 2-D soil profile. Realistic 3-D cases are often analyzed with 2-D slices assuming the same material properties, especially in wave barrier analyses. In passive isolation problems, 2-D models provide reasonably accurate results; whereas in active case 2-D study may overestimate the barrier effectiveness as it neglects the waves propagating across the side of the trench (Al-Hussaini and Ahmad, 1996). Nevertheless, 2-D assumption considers wave propagation only in two directions, neglecting the transverse component of vibration (i.e., a circular wave front replacing a spherical one). This assumption overestimates the wave propagation in the directions considered and thus underestimates the efficiency of the trench (El Naggar and Chehab, 2005), thereby compensating the aforementioned effect. Moreover, when the barrier length (dimension perpendicular to the plane of the paper) is much larger then its width and study is confined to the centerline of barrier, the problem essentially reduces to a 2-D scenario.

Extensive study using FEM and BEM shows that 2-D models provide results qualitatively comparable to those of 3-D models over a wide range of frequencies

(Andersen and Jones, 2006). Accuracy of 2-D analyses over realistic 3-D models or full-scale experimental results has been manifested in several other studies (Adam and Estorff, 2005; Alzawi, 2011; Alzawi and El Naggar, 2011; Bo *et al.*, 2014; Dasgupta *et al.*, 1990). In view of the above, 2-D models are considered appropriate for the current study.

3.2. FINITE ELEMENT MODELLING IN PLAXIS

3.2.1. Units and Sign Convention

A PLAXIS program starts with the selection of a set of suitable basic units from a list of standard units. The set of basic units comprises of a unit of length, force, and time which are selected as meter (m), kiloNewton (kN), and second (s) respectively.

Although, PLAXIS 2D is a 2-D program, stresses are based on a 3-D Cartesian coordinate system as shown in *Figure 3.1*.

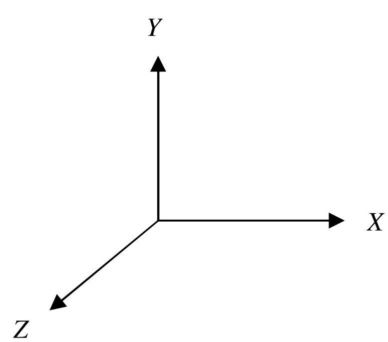

Figure 3.1: Coordinate system in PLAXIS

The Z direction points towards the user, whereas the model geometry is generated in the X-Y plane of the global coordinate system.

3.2.2. Elements

PLAXIS facilitates the use of either 6-node or 15-node triangular elements to model soil or other material clusters. In the current study, 15-node triangular elements are used as they are more potent than 6-node elements and provide high quality stress results in difficult problems. It involves a fourth order interpolation for displacements and twelve stress points for numerical integration. Positions of nodes and stress points in a 15-node element are shown in *Figure 3.2*.

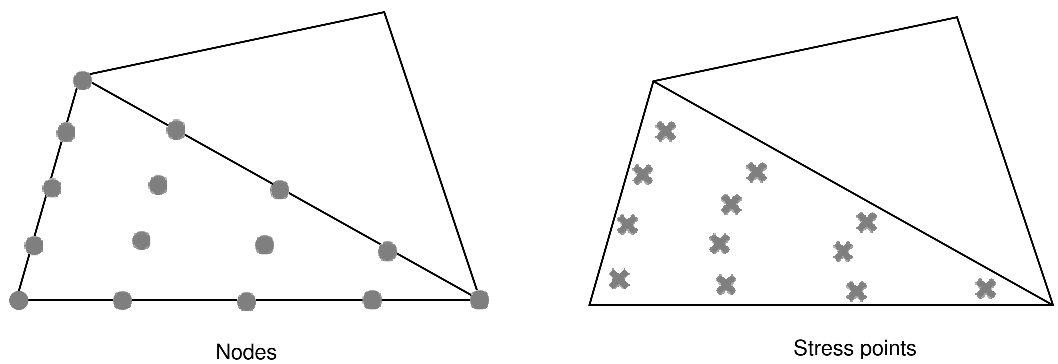

Figure 3.2: Positions of nodes and stress points in 15-node triangular elements (after Brinkgreve et al., 2010)

3.2.3. Model Geometry

Finite element modelling starts with creating the model geometry representing the problem of interest. The basic components of creating geometry are the points, lines, and clusters. The adequate model dimension required for the study is decided on the basis of convergence studies (refer *Section 4.3.2*).

PLAXIS 2D allows creation of 2-D model geometries using either plane strain or axisymmetric model option. Axisymmetric models are used in case of problems that have spherical symmetry, whereas geometries with unsymmetrical attributes around the central axis are analyzed with plane strain models.

Waves in an axisymmetric model radiate in a way similar to 3-D fashion (Brinkgreve *et al.*, 2010) causing wave attenuation with distance. This can be attributed to geometrical damping (or radiation damping) which is included in axisymmetric model by itself. Axisymmetric models are, therefore, used in this study as the problem is symmetrical about the vertical axis of the source of excitation. Schematic of an open trench isolation scheme in a 2-D half-space and its axisymmetric idealization are shown in *Figure 3.3*.

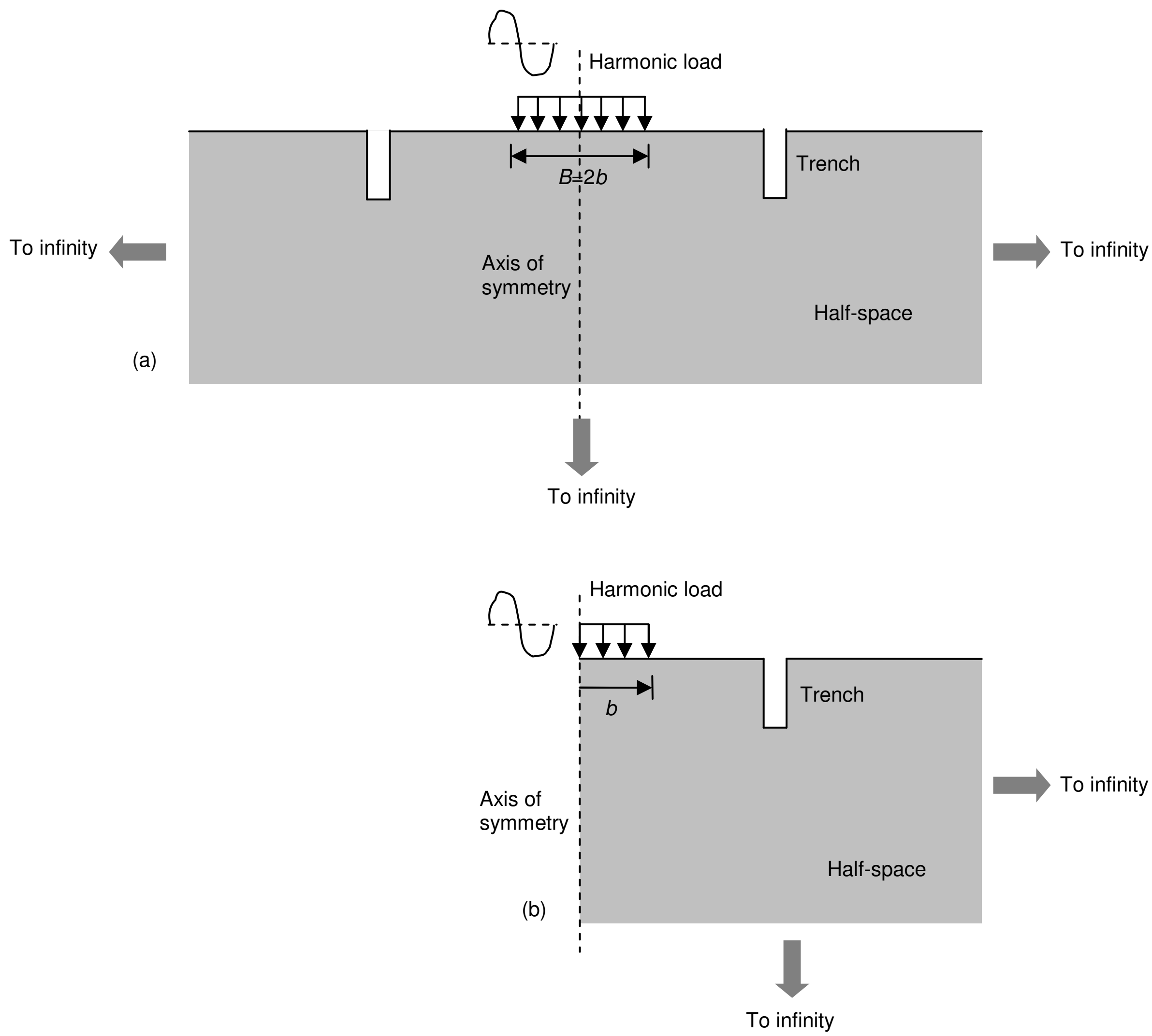

Figure 3.3: (a) A 2-D schematic of an open trench isolation (b) An axisymmetric idealization of the scheme

3.2.4. Boundary Conditions

Boundary conditions can be assigned to the model boundaries in the form of partial or full fixities. Fixities are prescribed displacements equal to zero. In current analyses, the model boundaries are assigned to standard fixities. Selection of standard fixity condition automatically imposes a general set of boundary conditions to the model geometry. These boundary conditions are:

- Vertical geometry lines whose X-coordinate is the lowest or highest X-coordinate in the model attain horizontal fixity (u_x=0).

- Horizontal geometry lines whose Y-coordinate is the lowest Y-coordinate in the model attain full fixity (u_x=u_y=0).

Assigning standard fixity to the present model, the symmetry axis and right hand model boundary are restrained in horizontal direction (u_x=0) and the bottom model boundary is restrained in vertical as well as horizontal direction (u_x=u_y=0). Standard fixity is widely used as a convenient boundary condition in many practical applications.

3.2.5. Absorbent Boundaries

In case of static deformation analyses, model boundaries may be completely or partially restrained as the deformation behaviour of the structure is not affected by boundaries. In dynamic analyses, the boundaries should, in principle, be sufficiently placed apart. The stress waves will otherwise undergo reflections at the model boundaries, causing perturbations. However, placing the boundaries far away requires many extra elements necessitating lot more extra memory and computational time.

To allow for absorption of stress waves, the absorbent boundary condition in PLAXIS is created with dampers. The damper ensures that incoming stress waves on the boundary are absorbed without rebounding. The absorbent boundary condition in PLAXIS uses

Lysmer and Kuhlemeyer (1969) dampers. Schematic of an axisymmetric model with boundary conditions and absorbent boundaries is depicted in *Figure 3.4*.

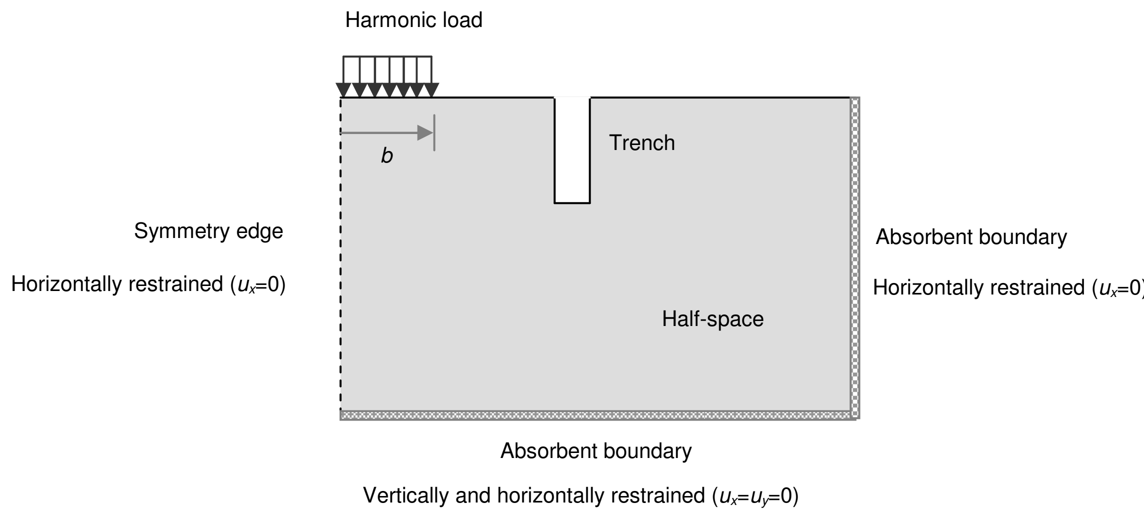

Figure 3.4: Schematic of an axisymmetric model with boundary conditions

Absorbent boundary conditions are assigned to the right hand boundary and bottom boundary of the model in order to artificially create the semi-infinite scenario. The adequacy of the absorbent boundaries is further ensured by convergence studies (refer *Section 4.3.2*).

3.2.6. Material Model and Material Parameters

Choice of a constitutive model is largely dependant on the stress-strain behaviour of geo-materials. Based on the variation of shear modulus with shear strain, three strain ranges are defined: very small strain, small strain, and large strain corresponding to elastic, elasto-plastic, and failure states of stress (Ishihara, 1996; Sawangsuriya, 2012; Sawangsuriya *et al.*, 2005).

The very small strain range corresponds to the range of strain below the order of approximately 10^{-3}% and 10^{-2}%. When a geologic material undergoes strain less than this elastic threshold strain, the deformation exhibited by it is purely elastic and recoverable. The phenomenon associated with such small strains would be vibrations or wave propagations through soils (Ishihara, 1996). Within this range, the shear modulus of geomaterials is independent of strain amplitude.

The small strain problems range from elastic threshold strain to 1% where the shear modulus is non-linear and strain-dependent. Behaviour of soils within this strain range is elasto-plastic and produces irrecoverable permanent deformation. The large strain range corresponds to strain, generally exceeding 1%. In large strain problems, the shear modulus of geomaterials substantially decreases with shear strain by orders of magnitude. Slides in slope, liquefaction are phenomenon typically associated with large strain problems.

Many a problem of soil dynamics, particularly those involving machine-induced vibrations are essentially very low strain problems for which linear elastic material model is truly valid. Accordingly, the material model of half-space and backfill (in case of in-filled trenches) soils is assumed to be linear elastic.

The linear elastic material model obeys Hook's law of isotropic linear elasticity. A linear elastic material regains its original shape after the removal of stress, and unloading path is same as the loading path. The model involves two stiffness parameters, Young's modulus (*E*), and Poisson's ratio (ν) along with mass density (ρ) of material.

It is necessary to include some material damping to the soil since a geologic material inherits material damping caused by its viscous properties, friction etc. In order to obtain realistic results, material damping is included in soil by assigning Rayleigh mass and stiffness matrix coefficients (α_R and β_R) conforming to the excitation frequency (*f*). The relationship between these two parameters can be expressed as (Brinkgreve et al., 2010):

$$\alpha_R + \beta_R \omega^2 = 2\omega\xi \tag{3.1}$$

Where, $\omega = 2\pi f$ is the angular frequency of excitation and ξ is the material damping (in terms of damping ratio) to be assigned to the soil.

3.2.7. Dynamic Load Input

The load is assumed to act as a distributed load over the surface of a massless footing. The footing mass is ignored in the numerical computations as the isolation effect, and not the foundation response is the aspect of interest of this work. Previous study shows that the difference between isolation effectiveness of a barrier for zero and non-zero footing masses is only 1.5% (Beskos *et al.*, 1986), which can practically be ignored.

In the present study, periodic load producing steady-state vibration is considered which is simulated by introducing harmonic load. A harmonic load in PLAXIS is defined as:

$$P(t) = P_i M Sin(wt + \phi) = P_0 Sin(wt + \phi) \qquad (3.2)$$

Where, $w = 2\pi f$ =angular frequency of excitation

ϕ = initial phase angle in degrees

P_i =Default input value of harmonic load

M = Amplitude multiplier

The amplitude multiplier is, in fact, a scaling factor applied to the default input which is set to unity. The product of default input and amplitude multiplier gives the actual magnitude of the dynamic load.

3.2.8. Mesh Generation

Mesh generation is an essential step for the calculation program to begin with. There are five different options for setting global coarseness in PLAXIS ranging from 'very coarse' to 'very fine'. The number of elements and average element size depends on the global coarseness setting. An average estimate of mesh elements against each type of coarseness setting are shown in *Table 3.1*.

Table 3.1: Global coarseness settings and mesh elements (after Brinkgreve *et al.*, 2010)

Type of coarseness setting	Number of elements
Very coarse	Around 75
Coarse	Around 150
Medium	Around 300
Fine	Around 600
Very fine	Around 1200

The number of elements generated against a particular coarseness setting shown in *Table 3.1* is only approximate and depends on the model geometry and more specifically, on the use of local refinements. Against a particular coarseness setting, the number of elements can be much higher and average element size will be rather small if local refinements are used.

In the present case, the mesh discretization is done with the ‘very fine’ coarseness setting option. In addition, local refinements are used along the surface and backfill cluster (in case of in-filled trenches). The use of local refinement tool enables rather finer division of mesh elements, thereby ensuring higher degree of precision.

3.2.9. Modelling Steps

The key steps involved in generating a finite element model and analysis can be briefed as follows:

- Creating model geometry by setting the model type as axisymmetric.

- Applying boundary conditions to the geometry by means of standard fixity option. This option automatically imposes a standard set of boundary conditions to the geometry as explained in *Section 3.2.4*.

- Applying absorbent boundaries to allow absorption of dynamic stresses on the boundaries. Absorbent boundaries are assigned to the right and bottom boundaries of the model to replicate the semi-infinite condition.

- Imposing distributed load over one-half of the imaginary footing width as axisymmetric models are used. The load is set as a dynamic load system.

- Creating material data set for half-space soil and backfill as required. As previously stated, the material model is chosen to be linear elastic. The elastic parameters, i.e. elastic modulus, Poisson's ratio, mass density are to be specified. The material damping is assigned by means of Rayleigh mass and stiffness matrix coefficients.

- Assigning material property to the appropriate cluster/clusters.

- Generating the mesh by selecting very fine element distribution option in the global coarseness setting.

- Using local refinement along the surface and in backfill cluster (as applicable) to enable extremely finer mesh division and so to ensure higher degree of accuracy.

- To run the calculation program by selecting the calculation type as dynamic. The total time interval, numbers of steps etc. are to be specified for dynamic computation. The amplitude multiplier, frequency, and initial phase angle of the harmonic excitation needs to be specified in the harmonic load multiplier tab sheet to activate the load. Before the program runs, nodes are selected at specified points on the model surface for generating displacement-time curves at the end of analyses.

3.3. OVERALL APPROACH OF STUDY

The study is conducted in PLAXIS 2D using 2-D axisymmetric finite element models. Methodology regarding finite element modelling has already been discussed in the preceding sections of this chapter. There are numerous possibilities of sub-soil stratification and it is impractical to analyze all such cases. A homogeneous half-space is, therefore, considered in this study to draw generalized conclusions.

This study adopts a non-dimensional approach which is of much significance from application point of view. Results of a non-dimensional study are independent of the assumed soil parameters and frequency of excitation. That is why such studies have got an edge over case-specific studies which are based on absolute parameters. Since vibration isolation is primarily accomplished by screening of Rayleigh waves, the barrier geometric features are normalized against the Rayleigh wavelength of vibration in half-space. In case of in-filled trenches, in addition to normalizing the geometric features, the backfill shear wave velocity is expressed as a ratio of that of half-space.

Seismic wave velocities in half-space and backfill soils can be estimated based on their elastic parameters. The Rayleigh wavelength of vibration can thus be estimated against a particular frequency of excitation. Material parameters assigned to half-space and backfill and harmonic load parameters (its magnitude and frequency of excitation) are discussed in *Sections 4.1* and *5.1* of the subsequent chapters. Detailed non-dimensional approaches are discussed in the relevant chapters (refer *Sections 4.2, 5.1,* and *6.1*).

3.3.1. Amplitude Reduction by Barriers

The screening effectiveness of wave barriers are evaluated in terms of amplitude reduction factor (A_R) which is the ratio between surface displacements amplitudes with and without barrier (Woods, 1968a; 1968b). The amplitude reduction factors are not uniform over a range of investigation (*s*). It is, therefore, more logical to express the overall degree of isolation in terms of average amplitude reduction factor (A_m) which is the weighted average of the amplitude reduction factors obtained at different distances from source (*x*) over the specified range of study. Smaller the value of A_m better is the screening effect and vice-versa. For example, A_m =0.4 implies that 60% vibration is being screened off by the barrier.

$$A_R = \frac{\text{Displacement amplitude of ground surface with barrier}}{\text{Displacement amplitude of ground surface without barrier}} \tag{3.3a}$$

$$A_m = \frac{1}{s}\int_0^s A_R(x)dx \tag{3.3b}$$

With reference to *Figure 3.5*, one can have a clear picture why amplitude reduction factors need to be averaged to express the overall amplitude reduction over the zone of study. The illustrated problem is an isolation example by an open trench where the trench is located at a distance of 3 m from the source and the amplitude reduction factors are computed up to a distance of 30 m at regular intervals of 1.5 m. Within the zone of study, A_R values are not uniform. The overall amplitude reduction over the zone is hence evaluated in terms of average amplitude reduction factor, A_m.

To start with, an undisturbed (barrier-free) half-space and the particular problem of barrier isolation are analyzed with the current modelling scheme. The peak surface displacement amplitudes are obtained from displacement-time histories at specifically selected nodes in a model. The amplitude reduction factor at a particular node is the ratio of surface displacement amplitudes with and without barrier. Weighted average of all such amplitude reduction factors obtained at specifically selected nodes over the zone of study gives the average amplitude reduction factor.

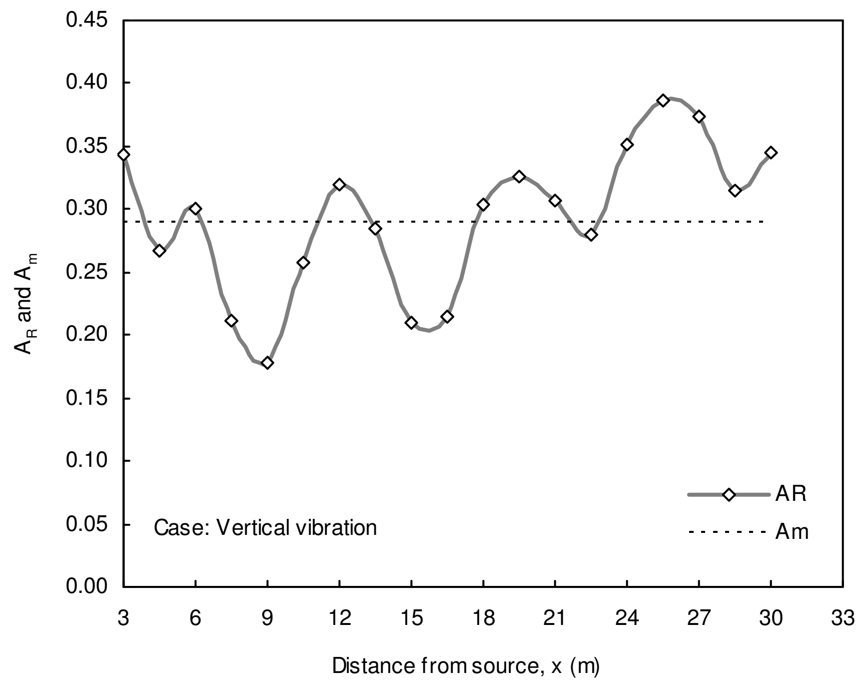

Figure 3.5: Example showing estimation of average amplitude reduction factor

CHAPTER 4
VIBRATION ISOLATION USING OPEN TRENCHES

This chapter deals with description of the scheme of study and a subsequent investigation on vibration isolation by open trenches. The scheme of study includes the basic assumptions, non-dimensional approach, and application of finite element method to the stated problem with validation by typical examples. In the subsequent study on open trench isolation, effects of various barrier features on barrier screening effectiveness are extensively analyzed, discussed, and the key observations are summarized. Effects of barrier features on amplitude reduction are presented in non-dimensional graphical forms which would serve as design charts in practical application of such barriers. This chapter also contains a set of regression models exclusively deduced for simplified design of open trench barriers.

4.1. BASIC ASSUMPTIONS

The half-space is assumed to be linear elastic, isotropic, and homogeneous. A linear elastic material is characterized by its elastic modulus (*E*), mass density (ρ), and Poisson's ratio (ν). It is necessary to include some material damping to obtain realistic results. Assumed values of input parameters for linear elastic material model are listed in *Table 4.1*.

Table 4.1: Input parameters of material model

Parameter	Notation	Value
Elastic modulus	E	46,000 kN/m^2
Mass density	ρ	1800 kg/m^3
Poisson's ratio	ν	0.25
Material damping	ξ	5%

The unit weight (γ) assigned to half-space soil (corresponding to a mass density of 1800 kg/m^3) is 18 kN/m^3. A steady-state vibrating source of unit magnitude (P_0=1 kN) and frequency (*f*) 31 Hz is assumed to act as a distributed load over a massless footing of width 1 m. The source magnitude, its frequency, and material parameters of half-space are assumed in accordance with previous study of Yang and Hung (1997). For the chosen frequency of excitation and soil parameters, the shear modulus (*G*), shear wave velocity (V_s), Rayleigh wave velocity (V_R), and Rayleigh wavelength (L_R) of vibration in half-space can be estimated as shown in *Table 4.2*.

Table 4.2: Ground motion parameters of half-space soil

Parameter	Expression	Value
Shear modulus	$G = E/2(1+\nu)$	18,400 kN/m^2
Shear wave velocity	$V_s = \sqrt{G/\rho}$	101.1 m/s
Rayleigh wave velocity	$V_R = \left(\frac{0.87+1.12\nu}{1+\nu}\right)V_s$	93.02 m/s
Rayleigh wavelength	$L_R = V_R/f$	3 m

4.2. NON-DIMENSIONAL STUDY SCHEME

As already stated, parameters that govern the isolation effectiveness of an open trench are the geometric features of the trench. The trenches are assumed to be vertical and rectangular in cross-section. The geometric features of a rectangular open trench include the barrier depth, width, and its distance from the source of vibration which are normalized against Rayleigh wavelength of vibration in half-space to avoid dependency on source frequency and elastic parameters of half-space. The geometric features are normalized with respect to the Rayleigh wavelength as: $d=D.L_R$, $w=W.L_R$, and $l=L.L_R$. The parameters *d*, *w*, and *l* denotes absolute depth, width, and distance of the barrier from source of excitation respectively, whereas *D*, *W*, and *L* are normalized depth, width, and distance of barrier from source. For example, *D*=1 implies that the actual depth of the trench, *d* is $1L_R$ which is 3 m in this study. The normalized barrier features of an open trench are shown in *Figure 4.1*.

4.3. FINITE ELEMENT ANALYSIS SCHEME

The numerical study is performed with the aid of a finite element tool, PLAXIS 2D. The analyses are carried out using 2-D axisymmetric models as the problem is symmetrical about the centroidal axis of the source of excitation. Models of dimension 35 m $\times$15 m with fifteen noded triangular mesh elements are adopted in this study. Few previous studies in the domain indicate that a zone extending to a distance of 10L_R from the source is sufficient for wave barrier analyses (Ahmad *et al.*, 1996; El Naggar and Chehab, 2005; Yang and Hung, 1997). For the assumed half-space parameters and frequency of excitation, L_R=3 m and consequently, this crucial zone extends to 30 m from source. However, the right hand boundary of the model is set 35 m apart from source. The reason behind adopting somewhat higher length is to avoid any likelihood of undue reflection at the boundaries, so as to nullify the wave interference problem. The adequacy of the chosen model dimension is affirmed by convergence studies. For details of convergence studies, *Section 4.3.2* may be referred to.

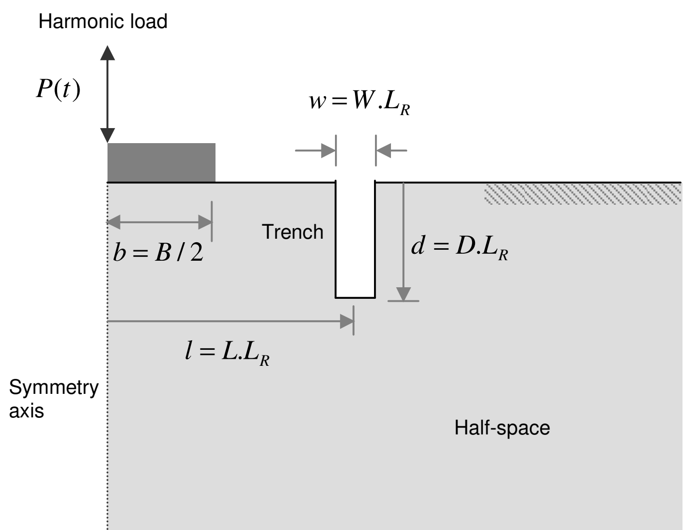

Figure 4.1: An open trench isolation showing normalized barrier features

4.3.1. Boundary Conditions and Other Inputs

The model boundaries are assigned to standard fixities as discussed in *Chapter 3*. The standard fixity option imposes the following set of boundary conditions to the model:

- The symmetry edge and the rightmost boundary of the model are assigned to horizontal fixities (u_x=0).

- The bottom boundary is restrained in both vertical and horizontal directions by applying total fixities (u_x=u_y=0).

Special boundary conditions need to be specified to the bottom and right side model boundaries accounting for the fact that, in reality, soil is a semi-infinite medium. The waves will, otherwise, be reflected at the model boundaries causing perturbations. Absorbent boundary conditions are hence assigned to the bottom and right hand side boundaries to allow for absorption of stresses at these boundaries caused by dynamic loading. The absorbent boundary conditions in PLAXIS use dampers proposed by Lysmer and Kuhlemeyer (1969). The normal (σ_n) and shear stress (τ_s) components absorbed by such dampers are given by:

$$\sigma_n = -C_1 \rho V_p \dot{u}_x \tag{4.1a}$$

$$\tau_s = -C_2 \rho V_s \dot{u}_y \tag{4.1b}$$

Here, ρ is the material density; V_p and V_s denotes pressure wave and shear wave velocities; $\dot{u}_x$ and $\dot{u}_y$ are particle velocities in normal and tangential directions of the boundary respectively. C_1 and C_2 are wave relaxation coefficients introduced to improve the wave absorption at these boundaries. The coefficient, C_1 improves wave absorption in a direction normal to the boundary and C_2 does in the tangential direction. When only pressure waves strike the boundary perpendicularly, relaxation is redundant (C_1=1, C_2=1). In presence of shear waves, damping effect is not sufficient without relaxation, which can be improved by adapting the second coefficient, in particular. Research findings indicate that C_1=1 and C_2=0.25 result in reasonable wave absorption at boundaries (Brinkgreve and Vermeer, 1998; Wang *et al.*, 2009). The wave relaxation coefficients assigned to the absorbent boundaries are hence taken as, C_1=1and C_2=0.25 throughout the study. The overall length of the model is kept somewhat higher than the crucial zone of screening (30 m). Despite of using absorbent boundary conditions to avoid spurious reflections, a chance of small interference always remains and it is, therefore, a sound practice to set the model boundaries some extent apart from the zone of interest. A schematic of a model showing dimensions and boundary conditions are presented in *Figure 4.2*.

The source of excitation is activated by introducing a vertical harmonic load of magnitude 1 kN/m and frequency 31 Hz acting uniformly over a massless footing of width 0.5 m, i.e. over one-half of the assumed footing width as axisymmetric models are used. Linear elastic material model is used in the analyses with the stated parameters considering the material type as drained. The assumed material damping of 5% is introduced into the soil by adapting Rayleigh mass and stiffness matrix coefficients (α_R and β_R) conforming to the applied frequency of excitation. The mesh is discretized with very fine elements using local refinements along the surface and trench periphery. Use of local refinement tool enables finer mesh division and ensures higher degree of precision. The dynamic analyses are performed choosing a time interval (Δt) of 0.5 s. which is sufficient to allow the complete passage of dynamic disturbance in the zone of interest. Numbers of additional steps (*n*) and dynamic sub-steps (*m*) are taken to be 250 and 4, respectively in all analyses for which the time-step of integration ($\delta t = \Delta t / mn$) is 0.0005 s.

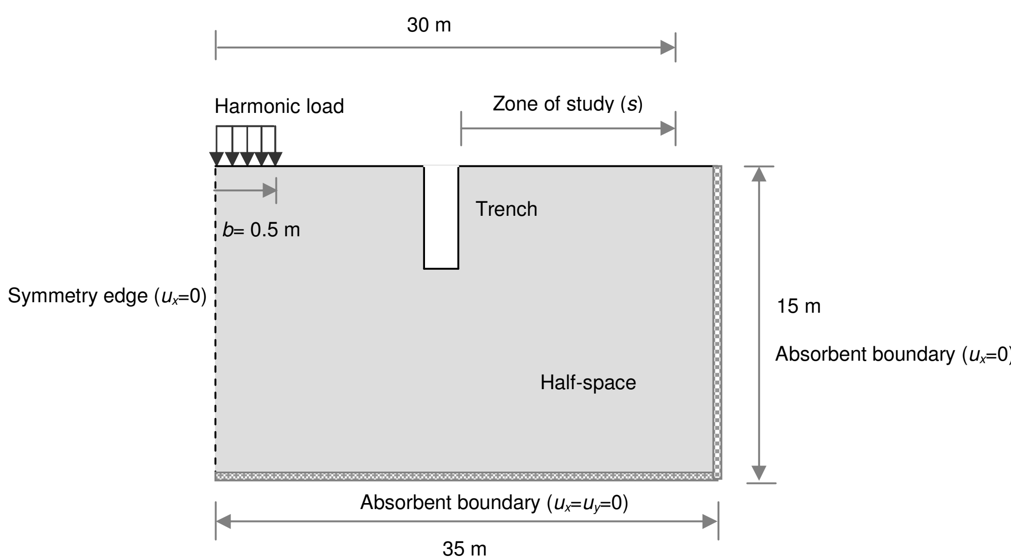

Figure 4.2: Schematic of a model depicting dimensions and boundary conditions

4.3.2. Convergence Study

It is essential to conduct a convergence study for ensuring the adequacy of chosen model dimension. The initial phase of convergence study is performed taking trial model lengths (L_m) as 35 m, 40 m, and 50 m, respectively with a specific trial model depth (H_m) of $5L_R$=15 m. An undisturbed (barrier-free) half-space with the assumed parameters is subjected to a steady-state harmonic excitation of magnitude and frequency as stated earlier. A finite element model of dimension 35 m × 15 m with mesh discretization is shown in *Figure 4.3*. The peak displacement amplitudes of vibration at a desired node can be obtained from the displacement-time history at that particular node. The displacement-time history of vertical vibration component at a point, $7L_R$ (21 m) apart from source for the stated case is illustrated in *Figure 4.4*.

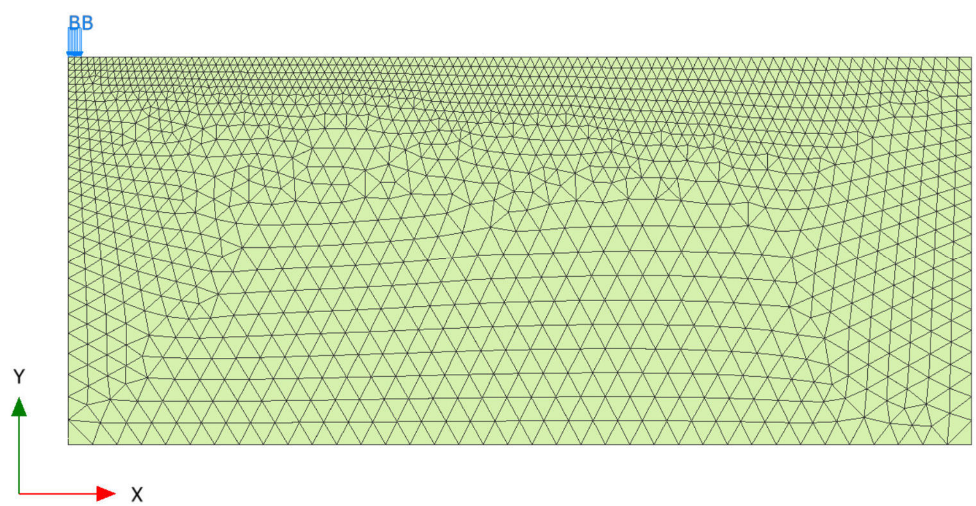

Figure 4.3: Finite element model of a barrier-free half-space

The peak displacement amplitudes of vertical and horizontal vibration components for these cases are plotted against normalized distances from the source ($X=x/L_R$) as shown in *Figure 4.5(a)*. Here, x denotes the absolute distance of a point from source and X is its dimensionless distance (normalized against the Rayleigh wavelength of vibration in soil) from source. For example, normalized distance, X=2 implies that the actual distance from source (x) is $2L_R$ which is equal to 6 m in this study. It is observed that the displacement amplitudes in these cases are showing convergence.

The right hand side model boundary is hence set apart by a distance of 35 m from source in the subsequent analyses.

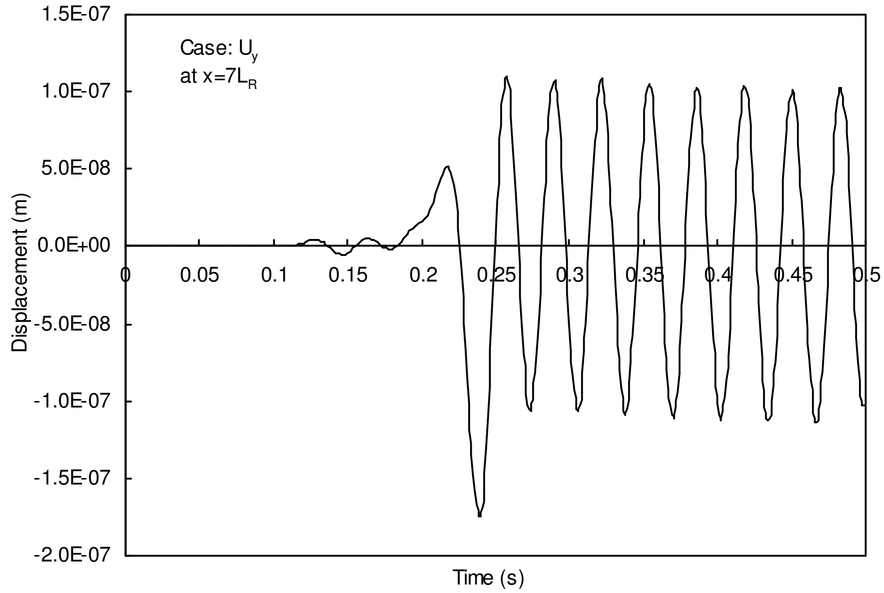

Figure 4.4: Displacement-time history of vertical vibration component in a barrier-free half-space (at x=7L_R)

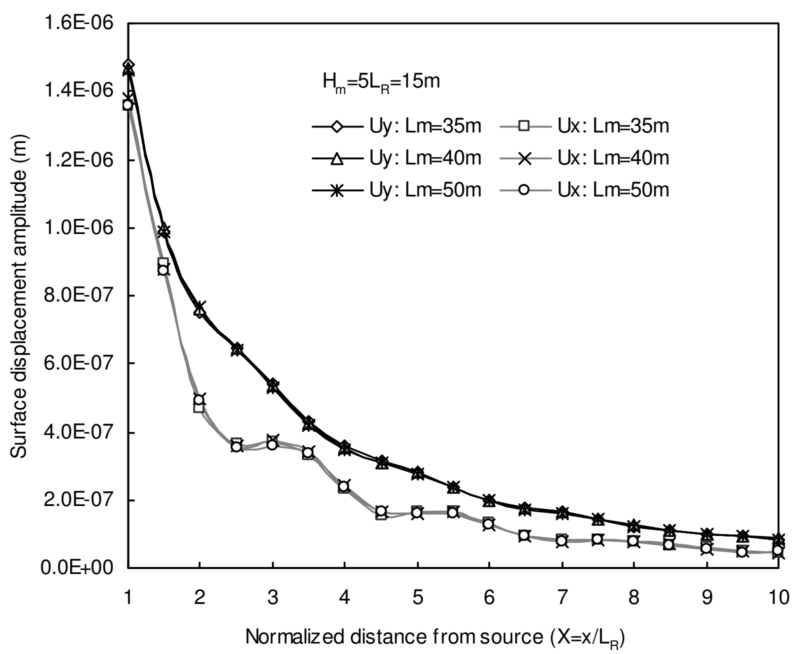

Figure 4.5(a): Convergence study to ensure adequacy of model length (H_m=5L_R)

A further study is carried out to verify the adequacy of model depth with trial depths (H_m) of $5L_R$, $6L_R$, $8L_R$, and $10L_R$ taking the length (L_m) as 35 m. Converging plots between surface displacement amplitudes and normalized distances, identical with the former study, are obtained as shown in *Figure 4.5(b)*.

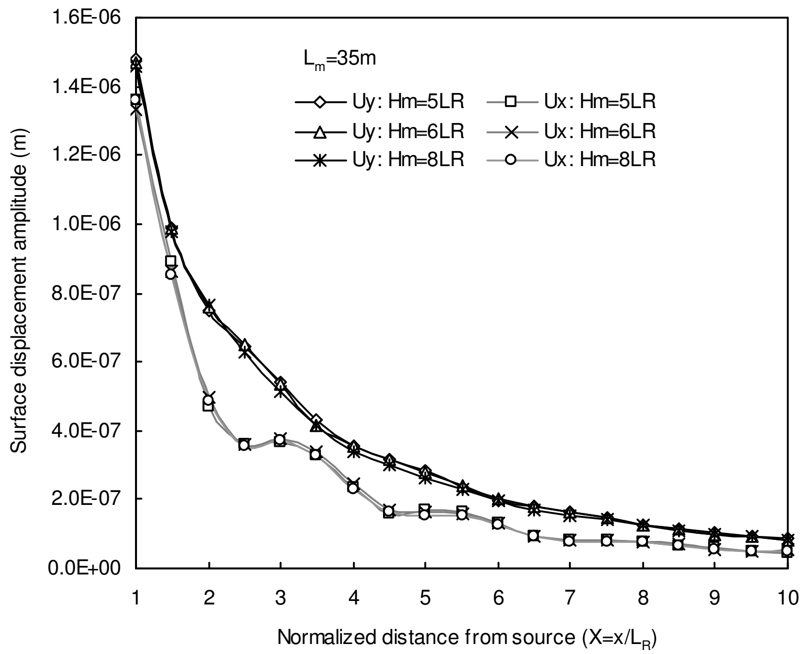

Figure 4.5(b): Convergence study to ensure adequacy of model depth (L_m=35 m)

Models of dimension 35 m × 15 m is hence adopted in all subsequent analyses. It is apparent that the displacement amplitudes at a distance of $10L_R$ are negligible and will be further reduced till the right hand side boundary is reached and if a small portion undergoes reflection, although not likely, is not expected to cause any problem of interference. If this were the case, convergence would have not been attained. The convergence studies affirm that use of absorbent boundary and wave relaxation coefficients assigned to it allow for sufficient wave absorption at the boundaries and the chosen model dimension is adequate for this study.

4.3.3. Estimating Amplitude Reduction: An Example

As already stated, amplitude reduction factor is the ratio between peak surface displacement amplitudes with and without barrier. The peak surface displacement at a certain node can be obtained from displacement-time history at that particular node. This can be accomplished by modelling and analyzing a barrier-free half-space and a half-space with barrier. The problem of a barrier-free half-space is already illustrated in *Section 4.3.2*. Using the same methodology, a half-space with barrier, considering a specific case of isolation by an open trench of dimension, D=1 and W=0.2 at location, L=5 is analyzed. For the chosen set of parameters, an open trench of D=1, W=0.2, and L=5 physically translates to a trench of depth 3 m and width 0.6 m locating at 15 m from source. A finite element model showing the open trench isolation problem is presented in *Figure 4.6*. After the end of dynamic analysis, the displacement-time histories can be obtained at the pre-selected nodes. The displacement-time histories of barrier-free half-space and half-space with the open trench barrier at a point located at $7L_R$ from source is shown in *Figure 4.7*.

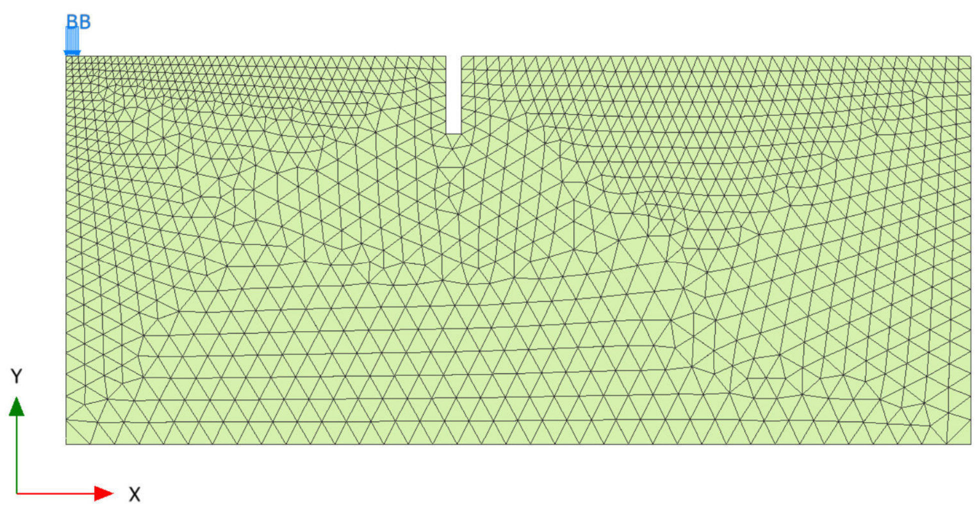

Figure 4.6: Typical Finite element model of an open trench

The ratio between peak displacement amplitudes with and without barrier is 0.19 which is the amplitude reduction factor, A_R for vertical vibration in the present case. The horizontal amplitude reduction factor at a desired point can be obtained in a similar manner just by considering the horizontal vibration components. Nodes are selected beyond the barrier and up to a distance of $10L_R$ (30 m) in intervals of $0.5L_R$. The average amplitude reduction factor is the weighted average of all such reduction factors over the zone of study as explained in *Section 3.3.1*.

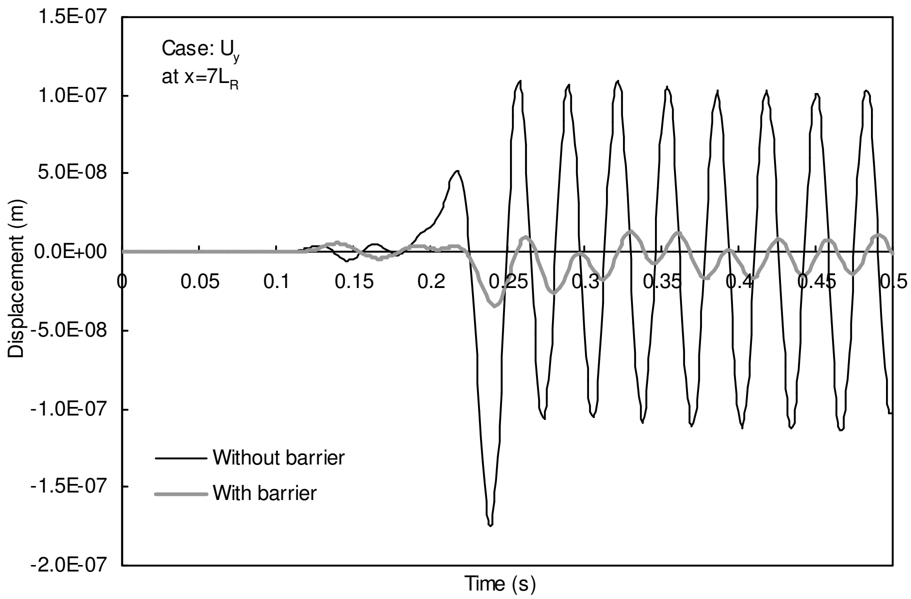

Figure 4.7: Displacement-time histories of vertical vibration component with and without barrier (at x=7L_R)

4.3.4. Model Validation

A specific case of passive isolation by an open trench of depth 1L_R and width 0.1L_R placed at a distance of 5L_R from source acted upon by a harmonic excitation, is referenced in order to validate the current modelling scheme. The plot of vertical amplitude reduction factors versus normalized distance from source ($X=x/L_R$) obtained in this study are compared with published results of Ahmad and Al-Hussaini (1991) and Di Mino *et al.* (2009) and close agreement is obtained. A diagrammatic representation of this study is shown in *Figure 4.8*. The comparative study signifies that current modelling approach provides reasonable accuracy for wave barrier analysis.

Another example of an open trench isolation case (D=0.64, W=0.26, L=5) is referred to for validating the current modelling scheme with an experimental study. A_{my} obtained in present study is 0.27 against the experimental value of 0.21 (Celebi et al., 2009) as shown in *Figure 4.9*. The difference between experimental and present numerical result could be attributed to sub-soil stratification at site, experimental error, or wave propagation in an actual 3-D context in field.

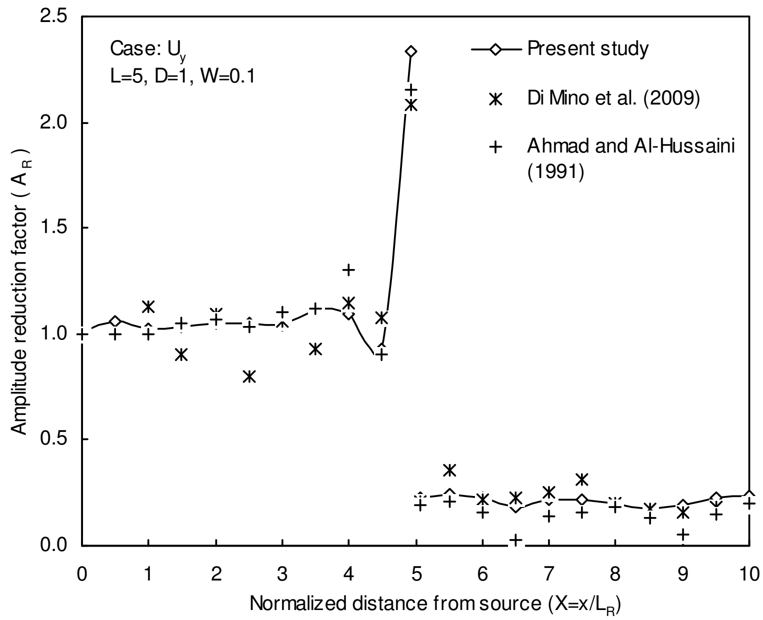

Figure 4.8: Finite element model validation with numerical studies

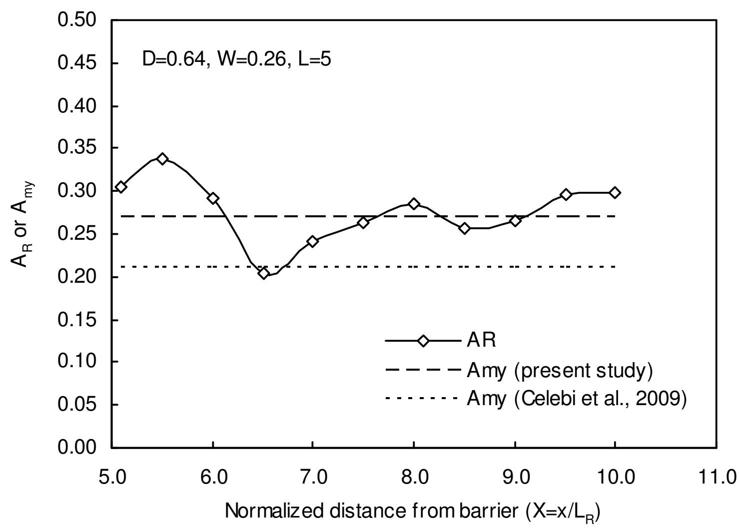

Figure 4.9: Finite element model validation with an experimental study

4.4. STUDY ON OPEN TRENCH ISOLATION: RESULTS AND DISCUSSION

The parametric study aims at investigating the wave attenuation characteristics due to variations in trench depth, width, and distance from source. To accomplish this objective, a large number of cases have been investigated encompassing a wide range trench cross-sectional features and location. The values of different parameters chosen for this study are shown in *Table 4.3*.

Table 4.3: Parameters chosen for open trench isolation study

Parameter	Notation	Range of values
Normalized depth	*D*	0.3, 0.4, 0.6, 1.0, and 1.5
Normalized width	*W*	0.2, 0.4, 0.6, and 0.8
Normalized distance from source	*L*	1, 2, 3, 4, and 5

The trench locations are varied from active (*L*=1) to passive cases (*L*=5). Extensive earlier studies on vibration isolation (Beskos *et al.*, 1986; Klein *et al.*, 1997; Yang and Hung, 1997) indicate that an isolation system truly behaves as an active scheme at barrier location, *L*=1 or close. The influence of body waves are more in active cases where the barrier is close to the source and decreases with distance from source. Dasgupta *et al.* (1990) investigates a passive isolation case for *L*=2. Subsequent study of Yung and Hung (1997) indicates that from $L \geq 2$, the influence of body wave decreases and surface wave starts predominating body waves. However, several previous works considered *L*=5 as true passive isolation case (Ahmad and Al-Hussaini, 1991; Al Naggar and Chehab, 2005; Beskos *et al.*, 1986). On the basis of these studies, the trench location is varied from *L*=1 to *L*=5, i.e. from an active to a passive case which will represent a true picture of the effects of geometric features of the barrier on its screening effectiveness with respect to a particular case.

The amplitude reduction is evaluated both in terms of vertical and horizontal components of vibration. The vertical and horizontal vibration cases are denoted by U_y and U_x respectively and other notations will have their usual meanings as already explained. Notations, A_{my} and A_{mx} are used to indicate average amplitude reduction factors of vertical and horizontal vibration components. Results of vertical and horizontal vibration cases are discussed in the *Sub-Sections 4.4.1* and *4.4.2* of this section.

4.4.1. Vertical Vibration

Variation of average vertical amplitude reduction factors (A_{my}) are first investigated against barrier locations (*L*) and widths (*W*) for the cases of some constant depths (*D*) and shown in *Figures 4.10(a)-4.10(e)*. The range of values of *L*, *W*, and *D* are taken in accordance with *Table 4.3*.

In the subsequent investigation, variation of A_{my} versus *L* and *D* are studied against a few constant widths (*W*=0.2, 0.4, and 0.6) which are depicted in *Figures 4.11(a)-4.11(c)*. Other than *W*=0.8 case, values of *L*, *D*, and *W* are otherwise same as in the previous case. *W*=0.8 cases are not included in this study as Figures 4.10(a)-(e) show that trenches of larger widths (*W*=0.8) either adversely affects the screening effectiveness or does not have any beneficial effect (discussed in the concluding paragraphs of this section).

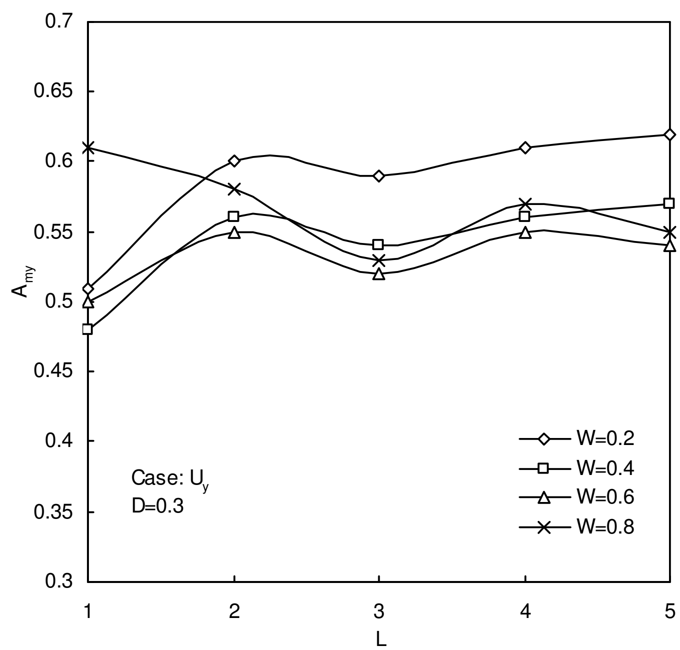

Figure 4.10(a): Variation of A_{my} versus *L* and *W* (*D*=0.3)

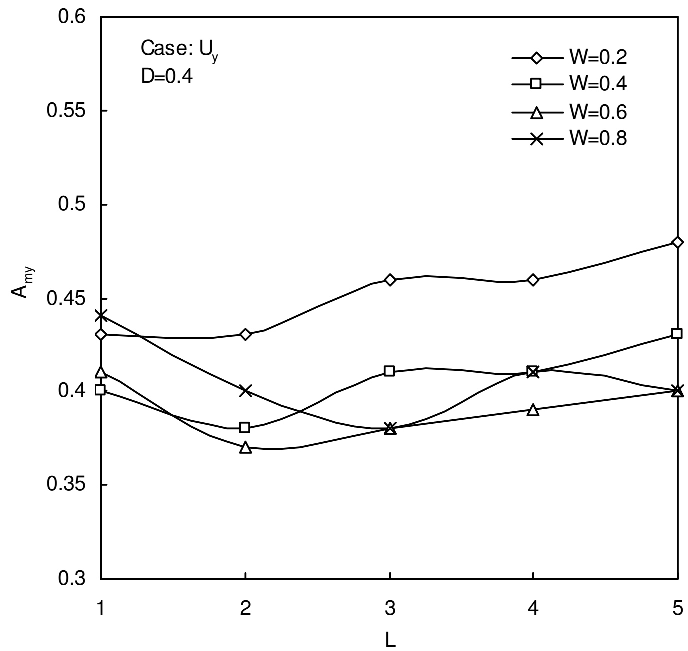

Figure 4.10(b): Variation of A_{my} versus L and W (D=0.4)

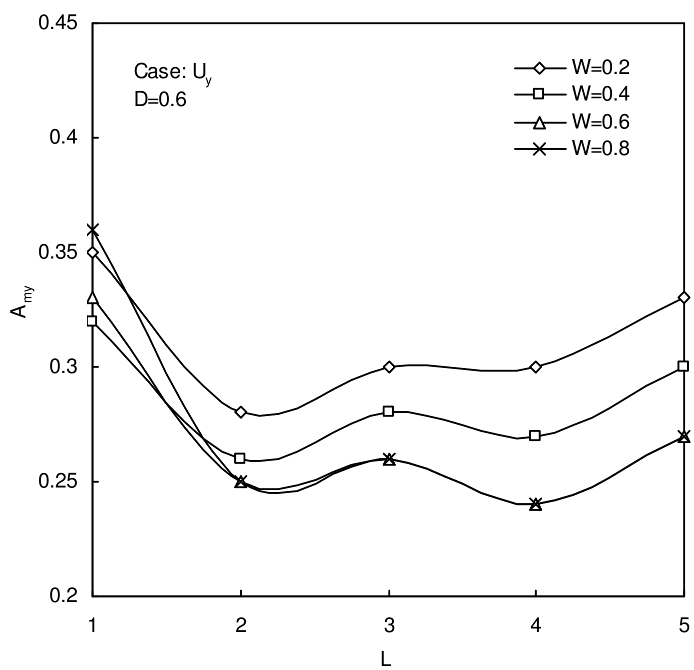

Figure 4.10(c): Variation of A_{my} versus L and W (D=0.6)

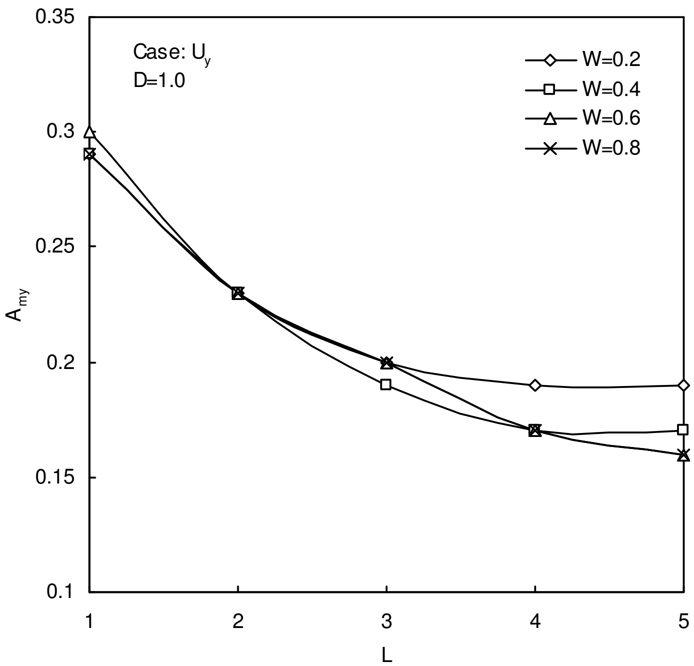

Figure 4.10(d): Variation of A_{my} versus L and W (D=1.0)

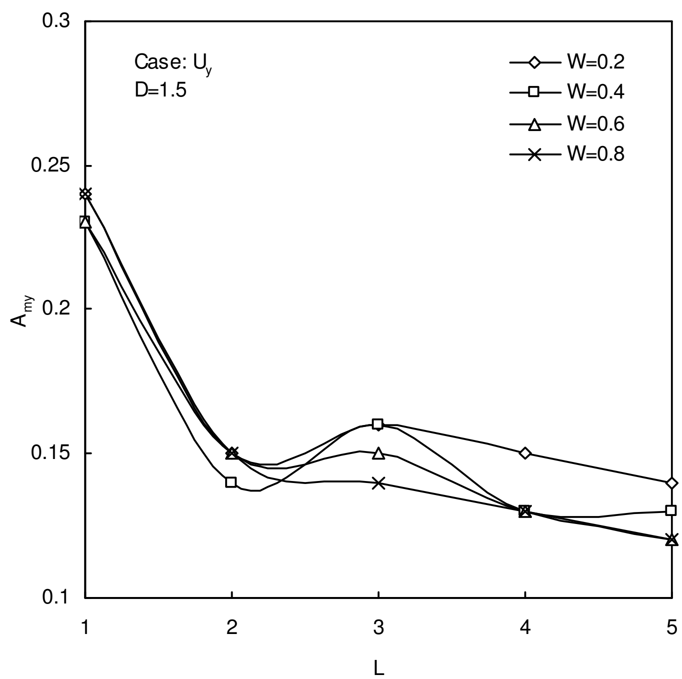

Figure 4.10(e): Variation of A_{my} versus L and W (D=1.5)

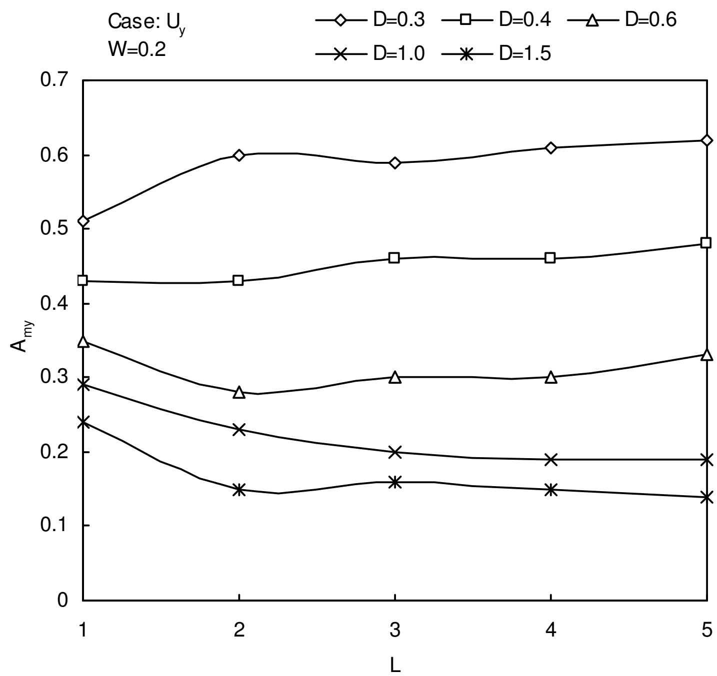

Figure 4.11(a): Variation of A_{my} versus L and D (W=0.2)

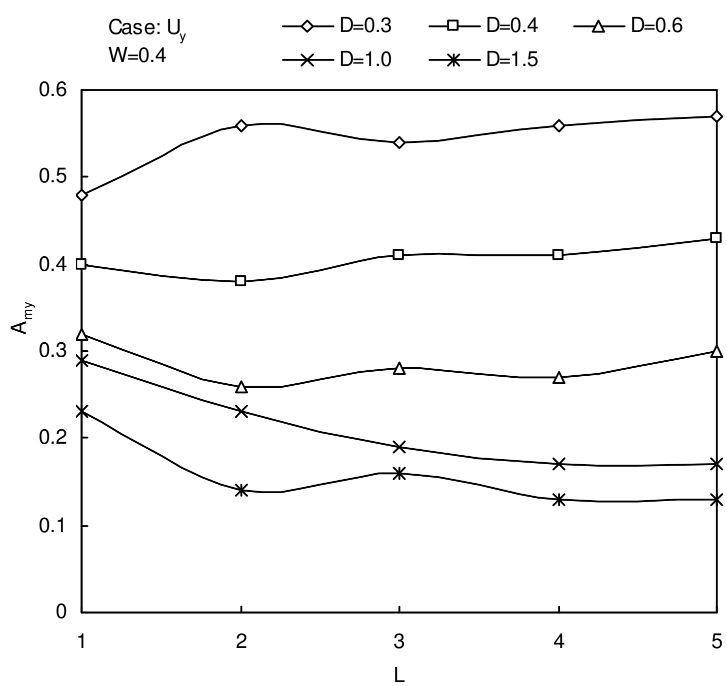

Figure 4.11(b): Variation of A_{my} versus L and D (W=0.4)

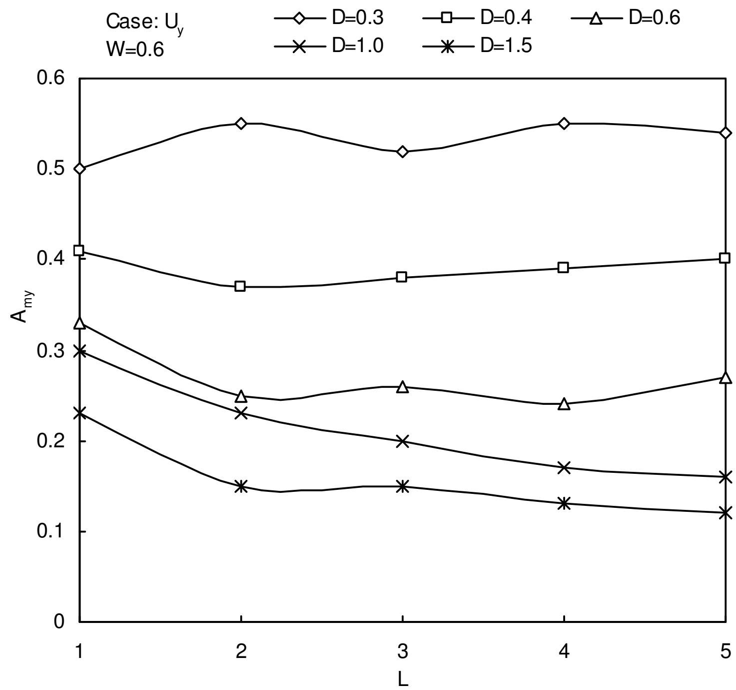

Figure 4.11(c): Variation of A_{my} versus L and D (W=0.6)

As can be seen from *Figures 4.10(a)-4.10(e)* and *4.11(a)-4.11(c)*, the parameter that chiefly governs isolation effectiveness of an open trench is the normalized depth of the trench, whereas effect of width is of secondary significance. For example, it is apparent from *Figure 4.11(a)* that A_{my} of a trench of normalized width, W=0.2 in passive case (L=5) drops abruptly from 0.62 to as low as 0.14 when its normalized depth, D is increased from 0.3 to 1.5. Conversely, *Figure 4.10(a)* shows that A_{my} of a trench of D=0.3 at L=5 decreases from 0.62 to 0.54 only when its normalized width, W is increased from 0.2 to 0.6. A deeper trench reflects the ground waves deep into the half-space, resulting in a better isolation than shallower trenches. However, A_{my} is not directly proportional to the trench depth.

A_{my} marginally decreases with increase in normalized widths of open trenches. The effect of width is somewhat more in cases where the trench is located far-off from source, i.e. passive cases (L=5). However, too large a width (W>0.6) adversely affects screening efficiency of shallow trenches ($D \leq 0.6$) for active isolation cases (L=1) in particular. The adverse effect of wider trench diminishes with its depth and distance from source of excitation. This is because when the trench is located close to the source, body waves play a role more important than surface waves. A trench of shallow depth ($D \leq 0.6$) closer to the source allows the passage of a bulk portion of body waves below the trench bed. Wider trenches (W>0.6), in this case, provides a larger free surface; thereby allowing more conversion of body waves into surface waves. On the other hand, when the trench is located far-off from the source (passive case), surface waves predominate the body waves. This is the reason why adverse effect of wider trenches is insignificant in passive cases.

The effect of width on A_{my} is somewhat more in passive cases. This is due to the lesser influence of body waves at larger distances from source and rapid decrease of surface waves as it travels down a wider trench. However, irrespective of location and depth, W=0.6 can be considered as an upper limit of normalized width of an open trench beyond which the isolation efficiency is either adversely affected (in active cases) or remains virtually unaffected (passive cases).

Open trench of normalized depth, D=0.6 or larger gives the lowest A_{my} in passive cases. This is in accordance with the literature of Yang and Hung (1997) where variation of A_{my} was studied against varying trench locations (from L=1 to L=5) in case of an open trench of dimensions, D=1.0 and $W \approx 0.3$. Nevertheless, the same conclusion does not apply for shallow trenches (D<0.6), where the best efficiency is obtained in active cases (L=1) except the results for W=0.8. For illustration, one may refer *Figure 4.11(a)* which shows that A_{my} of an open trench of D=0.3 and W=0.2 at locations, L=1 and 5 are 0.51 and 0.62 respectively. On the other hand, a trench of D=1 and of identical width gives A_{my}=0.29 and 0.19 at L=1 and 5 respectively, showing a diminishing trend. With few exceptions, majority of the observations shows that irrespective of trench cross-sectional features, variation of A_{my} with L occurs mostly up to L=2 and remains virtually constant thereafter.

4.4.2. Horizontal Vibration

Amplitude attenuation characteristics of horizontal vibration component are studied in a way similar to the vertical vibration cases. Variations in amplitude reduction (A_{mx}) with trench locations (L) and widths (W) against a few specific depths (D=0.3, 0.4, 0.6, 1.0, and 1.5) are depicted in *Figures 4.12(a)-4.12(e)*. Variations of the same versus barrier locations and depths against a few constant widths (W=0.2, 0.4, and 0.6) are shown in *Figures 4.13(a)-4.13(c)*.

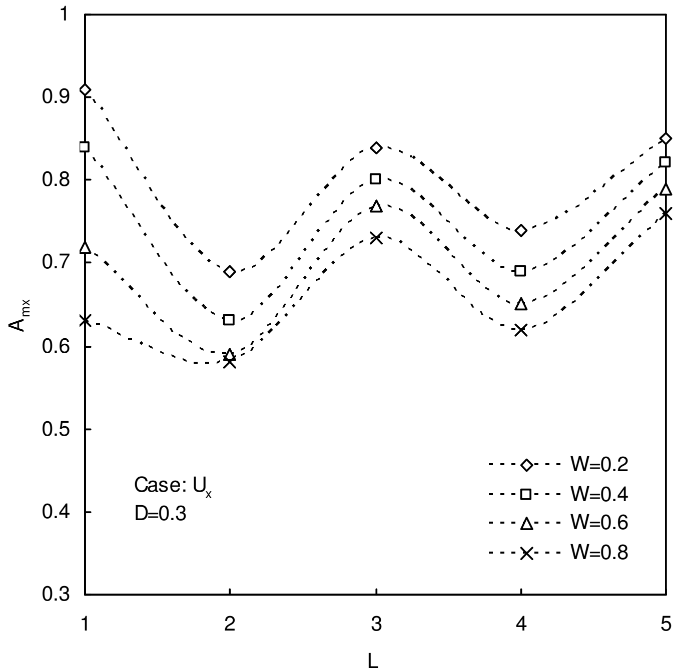

Figure 4.12(a): Variation of A_{mx} versus L and W (D=0.3)

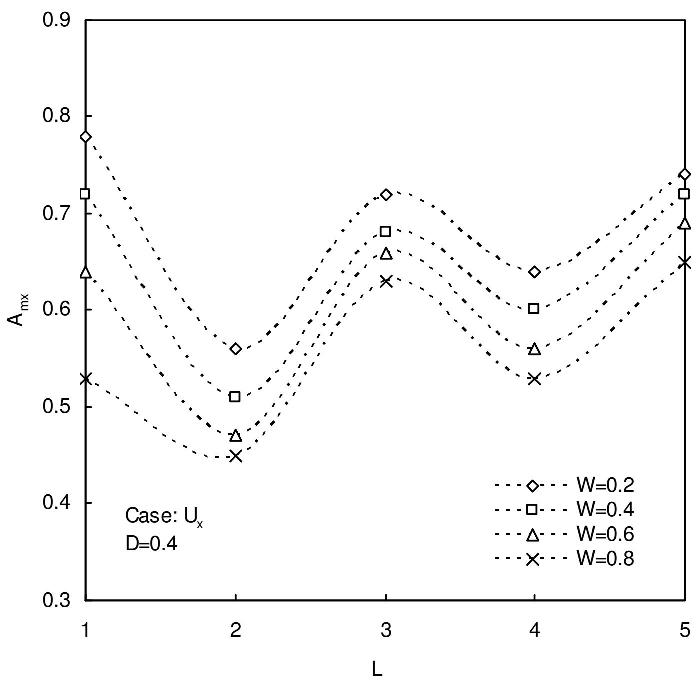

Figure 4.12(b): Variation of A_{mx} versus L and W (D=0.4)

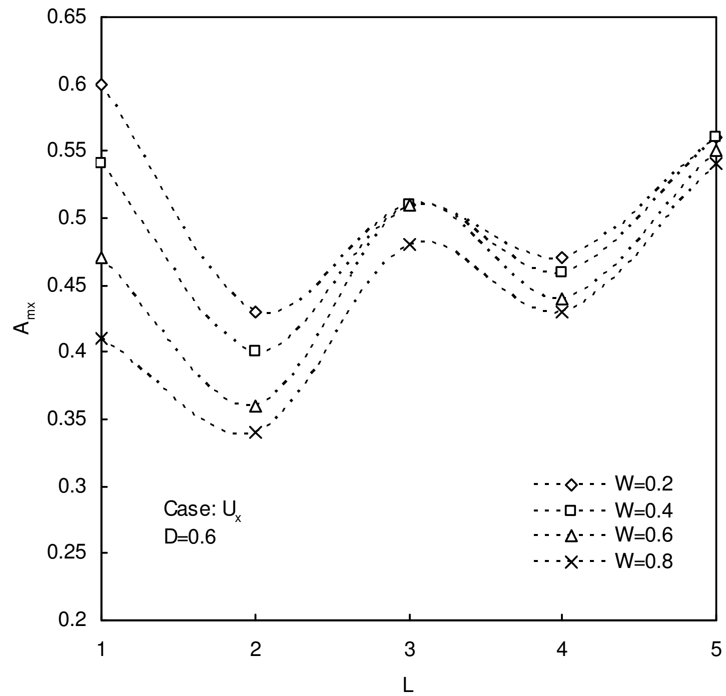

Figure 4.12(c): Variation of A_{mx} versus L and W (D=0.6)

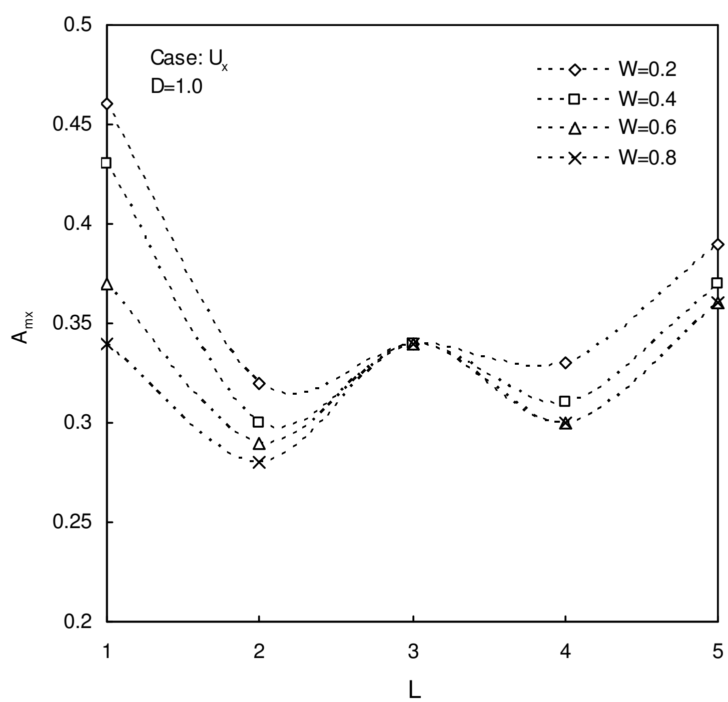

Figure 4.12(d): Variation of A_{mx} versus L and W (D=1.0)

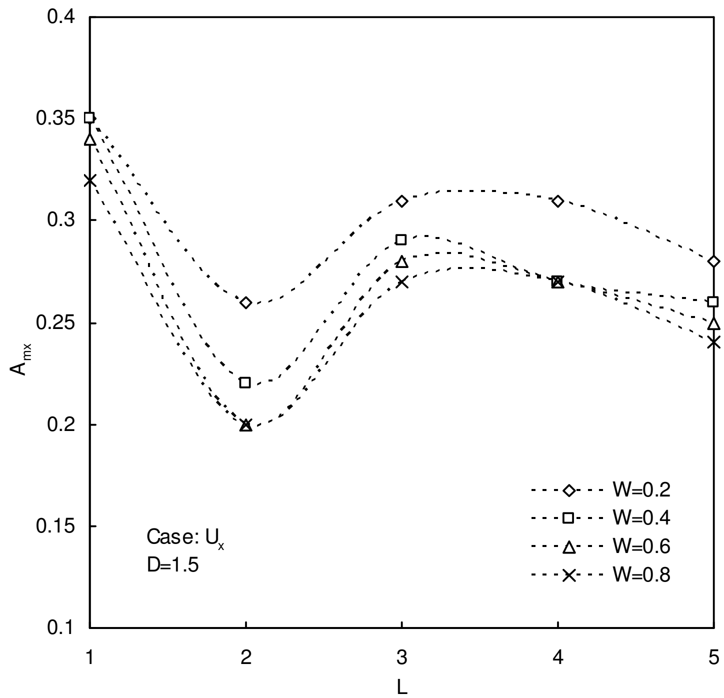

Figure 4.12(e): Variation of A_{mx} versus *L* and *W* (*D*=1.5)

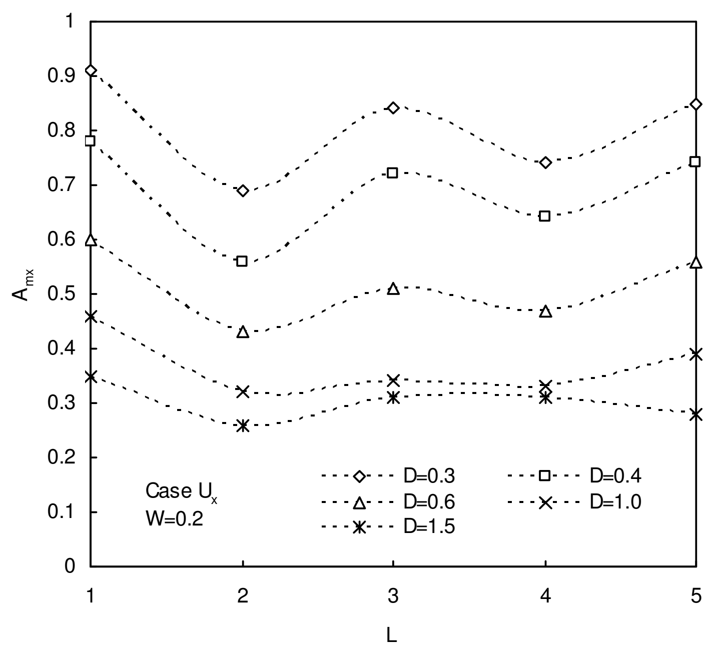

Figure 4.13(a): Variation of A_{mx} versus *L* and *D* (*W*=0.2)

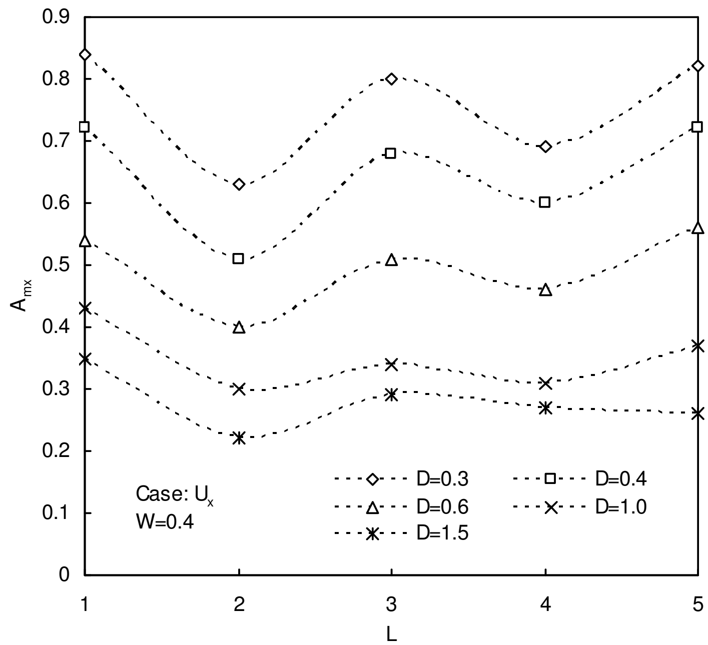

Figure 4.13(b): Variation of A_{mx} versus *L* and *D* (*W*=0.4)

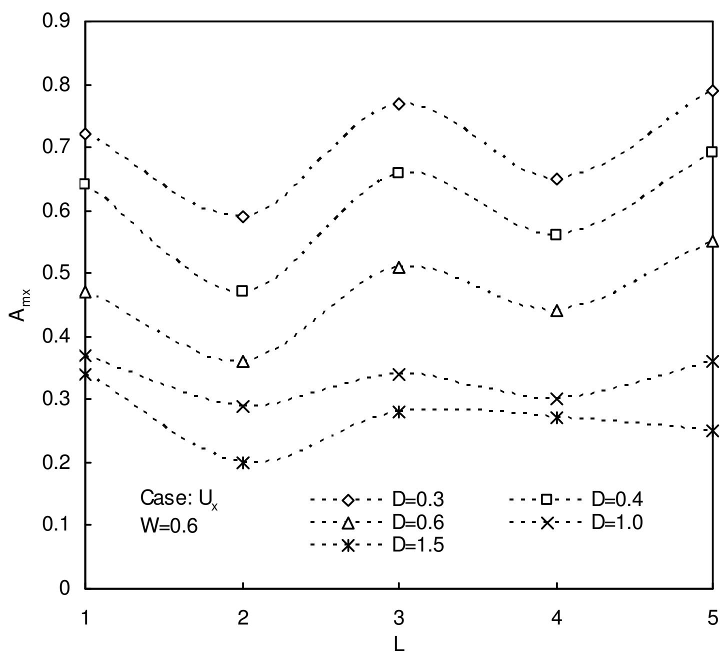

Figure 4.13(c): Variation of A_{mx} versus *L* and *D* (*W*=0.6)

It is apparent that irrespective of any location and width, increase in trench depth causes drastic decrease in A_{mx} resulting in a better isolation effect. It can be seen from *Figures 4.13(a)-4.13(c)*, where variations of A_{mx} against *L* and *D* are shown against a few specific widths. With reference to *Figure 4.13(a)* for instance, A_{mx} of a trench of W=0.2 in active case (L=1) decreases from 0.91 to 0.35 as D increases from 0.3 to 1.5.

In most of the cases, increase in normalized width results in a decrease in A_{mx} by some extent with the trend being more pronounced for active isolation cases. For example, as can be seen from *Figure 4.13(a)* that A_{mx} of a trench of depth, D=0.3 drops from 0.9 to 0.63 as W increases from 0.2 to 0.8 at barrier location, L=1. Conversely, increase in W by the same extent against the same depth case causes A_{mx} to decrease from 0.85 to 0.76 only at barrier location, L=5. Increase in normalized width causes consistent decrease in A_{mx} and hence no upper limit of W is observed for horizontal vibration.

It is difficult to draw any generalized conclusion on A_{mx} regarding trench location as A_{mx} varies with normalized distance of trench (L) in an irregular pattern. However, this can be concluded that variation of A_{mx} with L decreases for higher values of depths, i.e. D=1 or larger.

It can be concluded, in general, that open trench barriers are more effective in isolating the vertical vibration component than horizontal. As illustrated in *Figures 4.10(d)* and *4.12(d)*, an open trench of dimension, D=1 and W=0.2 at barrier location, L=1 gives A_{my}=0.29 and A_{mx}=0.46, implying that it is capable of reducing 71% of vertical vibration as compared to 54% of horizontal vibration reduction. This is because an open trench reflects the vertical component of vibration into the half-space, not the horizontal one. The horizontal component, therefore, participates little in the mode conversion process and suffers only geometrical attenuation as it travels below the trench bed. This is the reason why A_{mx} consistently decreases with increasing normalized widths, while A_{my} is adversely affected in some specific cases.

4.4.3. Simplified Regression Models

In order to formulate simplified design expressions, variations of A_{my} and A_{mx} against normalized depths and widths are sorted out for two distinct locations, L=1 and 5, representing active and passive cases. In addition to the chosen values of D, two extra cases, D=0.8 and 1.2 have been studied at these two locations. As stated earlier, the normalized depth (D) is the primary parameter and width (W) has little significance on the screening effectiveness of open trenches. Isolation of the vertical vibration component by shallow trenches in active case is an exception in which increasing W beyond 0.6 adversely affects the isolation efficiency. It is difficult to incorporate all these effects in a simple model because the pattern is somewhat irregular. Nevertheless, for narrow trenches ($W \leq 0.6$), simple curves can be drawn (best-fit curves) through the average data points for the entire depth range. The simplified model of horizontal amplitude reduction factor (A_{mx}) in active case (L=1) is restricted to $W \leq 0.4$ because, in this case, increase in W causes marked decrease in A_{mx}. The simplified models are depicted in *Figures 4.14(a)-4.14(d)*.

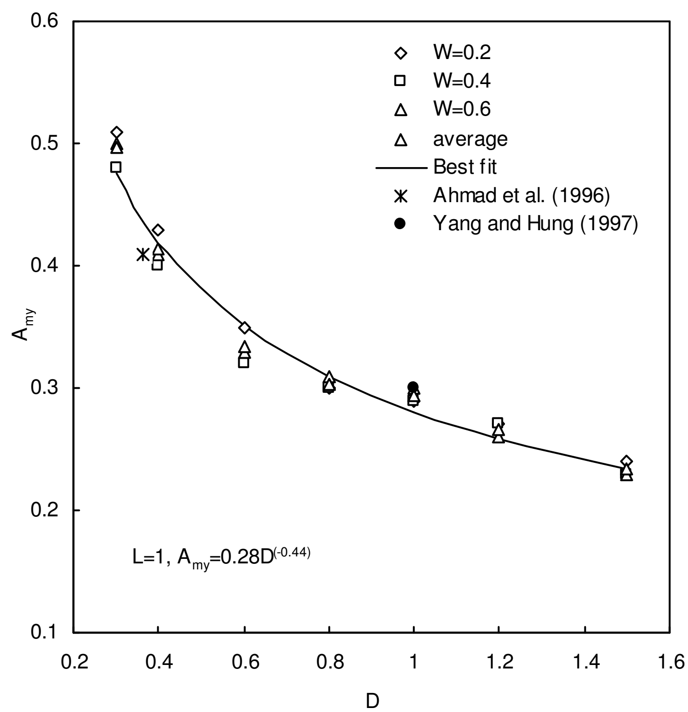

Figure 4.14(a): Simplified model for estimating A_{my} in active case

The expression of A_{my} in active case ($A_{my} = 0.28D^{-0.44}$) is compared with published results of Ahmad *et al.* (1996) where A_{my}=0.41 was obtained in active isolation by an open trench of dimension, D=0.363, W=0.183 and Yang and Hung (1997) where A_{my}=0.3 was obtained against a trench of D=1.0, $W \approx 0.3$. The present and previous results are found to be in close agreement as depicted in *Figure 4.14(a)*.

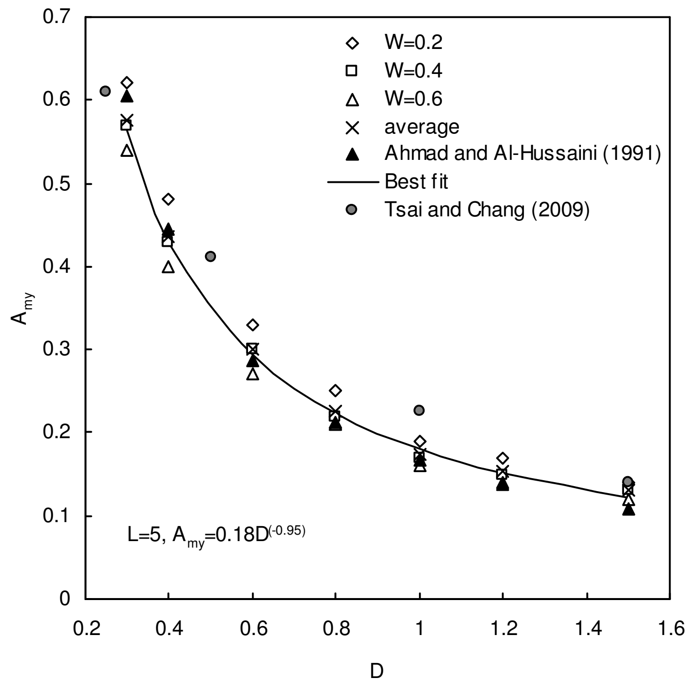

Figure 4.14(b): Simplified model for estimating A_{my} in passive case

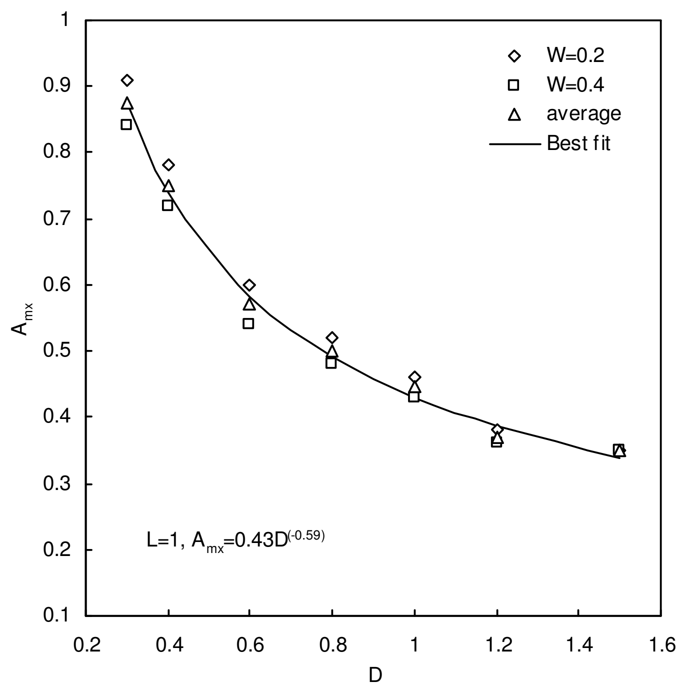

Figure 4.14(c): Simplified model for estimating A_{mx} in active case

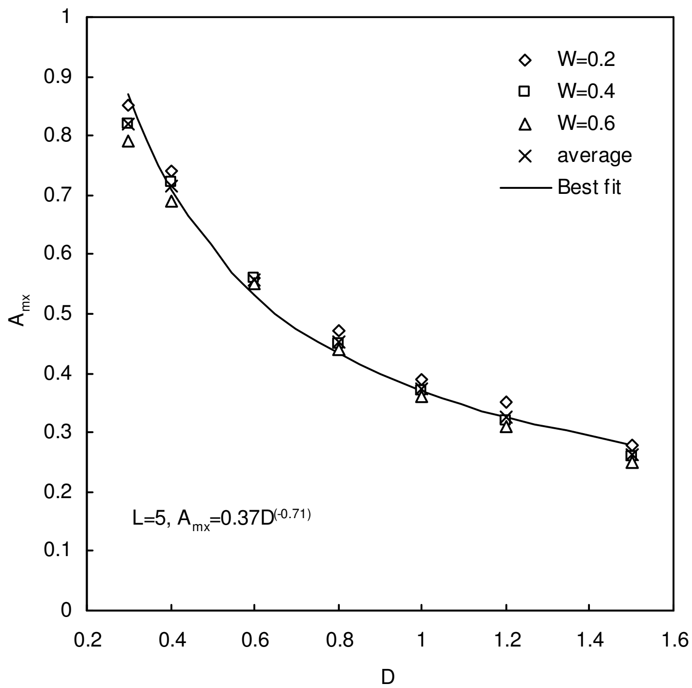

Figure 4.14(d): Simplified model for estimating A_{mx} in passive case

The simplified model involving A_{my} in passive case ($A_{my} = 0.18D^{-0.95}$) shows close agreement with previously developed model of Ahmad and Al-Hussaini (1991) and results obtained by Tsai and Chang (2009) in case of passive isolation by an open trench of varying depths and a specific width, W=0.2 as shown in *Figure 4.14(b)*. Remaining expressions corresponding the horizontal component ($A_{mx} = 0.43D^{-0.59}$ for L=1; $A_{mx} = 0.37D^{-0.71}$ for L=5) cannot be validated due to lack of published results.

Although, the regression models consider two specific barrier locations, L=1 and 5, signifying active and passive cases, the expressions involving A_{my} are still applicable for L lying within this range. As can be seen from *Figures 4.11(a)-4.11(c)*, average vertical amplitude reduction factor (A_{my}) shows marginal variation with barrier location from L=2 onwards in most of the observations. This implies that the expression deduced for A_{my} in passive case holds good for barrier locations $L \geq 2$. But the expression involving A_{my} in active case is exclusively applicable for L=1. When L lies between 1 and 2, linear interpolation may be used.

So far as the horizontal component is concerned, it is difficult to make such recommendation as the variation of A_{mx} with L is irregular by a considerable margin. This implies that the expressions deduced for A_{mx} would not be appropriate if applied for any value of L other than 1 and 5. For estimating A_{mx} in case of any intermediate value of L between 1 and 5, one may refer the dimensionless chart solutions presented in *Sections 4.4.1* and *4.4.2*.

Practical application of the design charts/models requires determination of Rayleigh wavelength of vibration which, in turn, requires determination of frequency of excitation and elastic parameters of half-space. Knowing the Rayleigh wavelength of vibration, one can decide the dimension of an open trench required to achieve a desired degree of isolation.

4.5. SUMMARY

In brief, isolation effectiveness of open trench barriers primarily increases with D. Effect of W has relatively less significance except for horizontal vibration screening in active case, where increase in width causes some noticeable increase in isolation effectiveness. In case of vertical vibration, W=0.6 can be considered as an upper limit beyond which increase in W either shows adverse effect or nearly no effect on A_{my}. Concerning A_{mx}, no such upper limit is observed. Open trenches are found more effective in isolating vertical vibration component than the horizontal.

In case of vertical vibration, deeper trenches ($D \geq 0.6$) provide somewhat better isolation effect in passive cases, whereas trenches shallower than D=0.6 are more effective in active cases. Variation in A_{my} with L chiefly occurs up to L=2 and thereafter remains nearly constant. In case of horizontal vibration component, variation of A_{mx} with L is inconsistent and no conclusion can hence be made. However, it is apparent that variation of A_{mx} with L decreases for higher depths ($D \geq 1.0$).

Regression models are developed for designing open trenches in active and passive cases and their applicability are discussed. In circumstances where applications of these models are limited, the dimensionless chart solutions may be referred to.

CHAPTER 5
VIBRATION ISOLATION USING IN-FILLED TRENCHES

This chapter presents a comprehensive study on vibration isolation by softer in-filled trenches. Introductory part of this chapter provides a discussion on the scheme of study including the fundamental assumptions, non-dimensional parameters, and method of finite element analysis. In the parametric study, effects of barrier geometric features and backfill material parameters are extensively analyzed and crucial observations are made regarding optimal selection of these parameters. Softer backfill is considered in the analyses as trenches backfilled with softer material are found to provide significantly better screening effectiveness than stiffer backfilled trenches. Non-dimensional design charts are presented for practical application of such barriers. Crucial observations are summarized at the end of the study.

5.1. BASIC ASSUMPTIONS AND NON-DIMENSIONAL STUDY SCHEME

The half-space and backfill soils are assumed to be linear elastic, isotropic, and homogeneous. The half-space soil parameters and dynamic load inputs in the current context are same as assumed in case of open trenches (refer *Section 4.1*). For the chosen set of parameters, the shear wave velocity, Rayleigh wave velocity, and Rayleigh wavelength of vibration in half-space are estimated to be 101.1 m/s, 93.02 m/s, and 3 m as shown in *Table 4.2*.

Elastic modulus of backfill (E_b) is treated as a variable in this study, while its density (ρ_b), Poisson's ratio (ν_b), and material damping (ξ_b) are assumed to be 1500 kg/m^3, 0.25, and 5% respectively. The backfill unit weight (γ_b) is taken to be 15 kN/m^3.

Normalization of geometric features are done in a way similar to open trenches (refer *Section 4.2*) since an in-filled trench do not differ geometrically from an open trench. The absolute depth (*d*), width (*w*), and distance of the barrier from source (*l*) are expressed as: d=$D.L_R$, w=$W.L_R$, and l=$L.L_R$. Here, L_R is Rayleigh wavelength and D, W, and L are the corresponding dimensionless parameters.

Unlike open trenches, screening effectiveness of an in-filled trench also needs to be investigated with respect to backfill material properties besides the geometric features. The material damping (ξ_b) of backfill soil are considered identical to that of half-space as screening effectiveness of an in-filled trench is found unaffected due to the variations in material damping of backfill with respect to parent soil (Ahmad and Al-Hussaini, 1991; Yang and Hung, 1997). Rather than varying the elastic parameters, i.e. elastic modulus, density, and Poisson's ratio independently, it is more convenient to express them in terms of a single parameter called shear wave velocity. The shear wave velocity is a function of elastic modulus, density, and Poisson's ratio of soil. This implies that variations of any of these parameters of soil would, in turn, bring about a change in its shear wave velocity. A parameter called shear wave velocity ratio (V_b/V_s) is, therefore, introduced to investigate the effect of backfill material characteristics on isolation effectiveness of the barrier. V_b/V_s is the ratio between shear wave velocities of backfill and parent soil. For example, V_b/V_s=0.2 signifies that the backfill shear wave velocity (V_b) is 0.2 times of that of the surrounding soil. The ratio of the shear wave velocities of the barrier and the soil is an indicator of the relative stiffness between the two. Consequently, a barrier softer than the surrounding soil will have V_b/V_s less than unity. The shear wave velocity of backfill is varied by changing its elastic modulus, keeping other parameters same.

5.2. FINITE ELEMENT ANALYSIS SCHEME

2-D axisymmetric models of dimension 35 m × 15 m with fifteen noded triangular mesh elements are used for finite element modelling and analyses. The adequacy of model dimension is already verified by convergence studies as explained in *Section 4.3.2*. The model boundaries are assigned to standard fixities. Absorbent boundary conditions are assigned to the right hand side and bottom model boundaries to allow for absorption of dynamic stresses.

A vertical harmonic load of magnitude 1 kN/m and frequency 31 Hz is imposed over a width of 0.5 m, i.e. one-half of the assumed footing width. Linear elastic constitutive model is used for soil and backfill considering the material type as drained. Material damping of 5% is assigned to half-space soil and backfill by adapting Rayleigh mass and stiffness matrix coefficients (α_R and β_R) conforming to the applied frequency of excitation. The mesh discretization is done with very fine elements using local refinements along the surface, trench periphery, and in the backfill cluster to ensure higher degree of precision. A time interval (Δt) of 0.5 s. is chosen for the dynamic analyses which is sufficient to allow the complete passage of dynamic disturbance in the zone of study. Number of additional steps (n) and dynamic sub-steps (m) are taken as 250 and 4, respectively for which the time-step of integration ($\delta t = \Delta t / mn$) is 0.0005 s. For details of finite element modelling and analyses, *Section 4.3* may be referred to. Typical finite element model of an in-filled trench is shown in *Figure 5.1*.

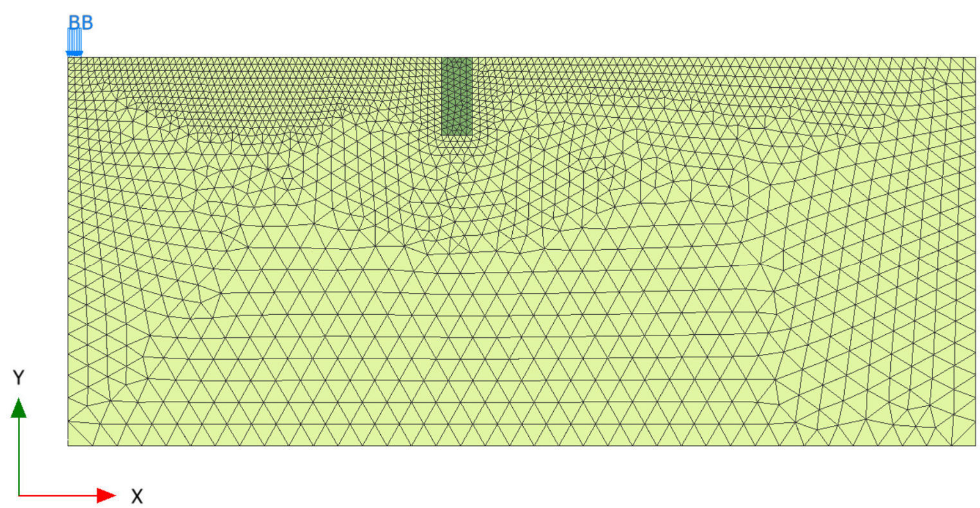

Figure 5.1: Typical Finite element model of an in-filled trench

The amplitude reduction by in-filled trench barriers is evaluated in terms of amplitude reduction factors, taking both vertical and horizontal vibration components into account. The overall degree of isolation over a zone is expressed in terms of average amplitude reduction factor as already discussed in *Chapter 4*.

5.2.1. Model Validation

The passive isolation case by an open trench of depth $1L_R$ and width $0.1L_R$ located at a distance of $5L_R$ from the source illustrated in *Section 4.3.4* can be referred to in this context too. An open trench barrier, in reality, is a material discontinuity on the surface of an otherwise undisturbed half-space. Therefore, in-filled trench of near-zero shear wave velocity ratios would act as an open trench of identical cross-section and location. The problem is first analyzed with an open trench of stated dimensions and location and then by considering an identical in-filled trench of $V_b/V_s \approx 0$. This is done by assigning a negligible value of elastic modulus (E_b=1 kN/m^2) to the backfill cluster keeping other parameters unaltered so that $V_b/V_s \approx 0$. The plots between vertical amplitude reduction factors and normalized distances from source ($X=x/L_R$) in these two cases are found indistinguishable and in close agreement with two previous studies (Ahmad and Al-Hussaini, 1991; Di Mino *et al.*, 2009) as shown in *Figure 5.2*.

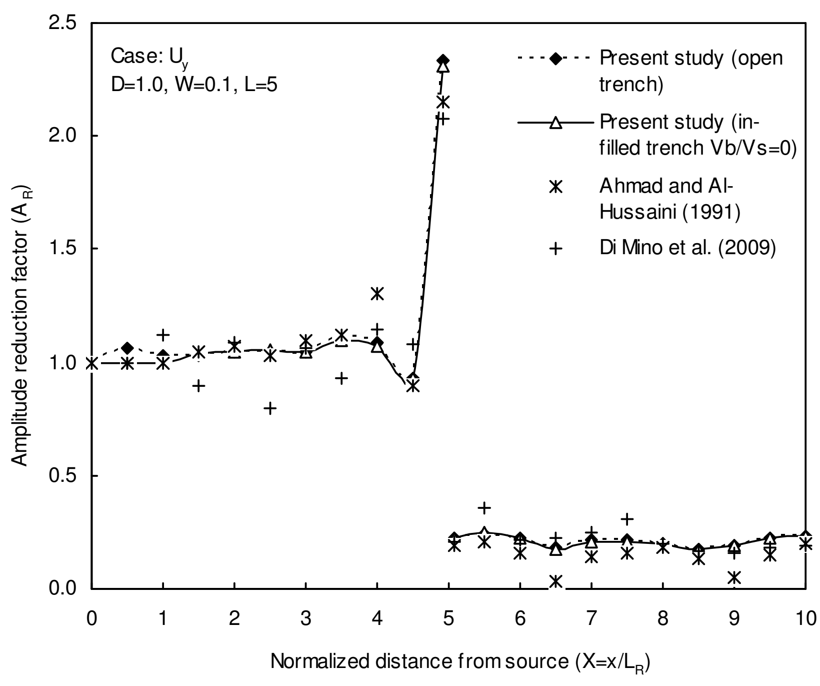

Figure 5.2: Finite element model validation

This validates the current modelling scheme and justifies the choice of shear wave velocity ratio in studying the effect of in-fill material parameters on vibration attenuation. An open trench is, in fact, a special case of an in-filled trench of $V_b/V_s \approx 0$.

For further validation, example of an active vertical vibration isolation case by a softer barrier (V_b/V_s=0.2) located at a distance $1L_R$ from source and of depth $0.6L_R$ and width $0.5L_R$, is referenced. The average vertical amplitude reduction factor obtained in present study (A_{my}=0.27) is found to be in excellent agreement with previous result (A_{my}=0.28) of Al-Hussaini and Ahmad (1996) as shown in *Figure 5.3*. The comparative study implies that current modelling approach provides reasonable accuracy for wave barrier analysis.

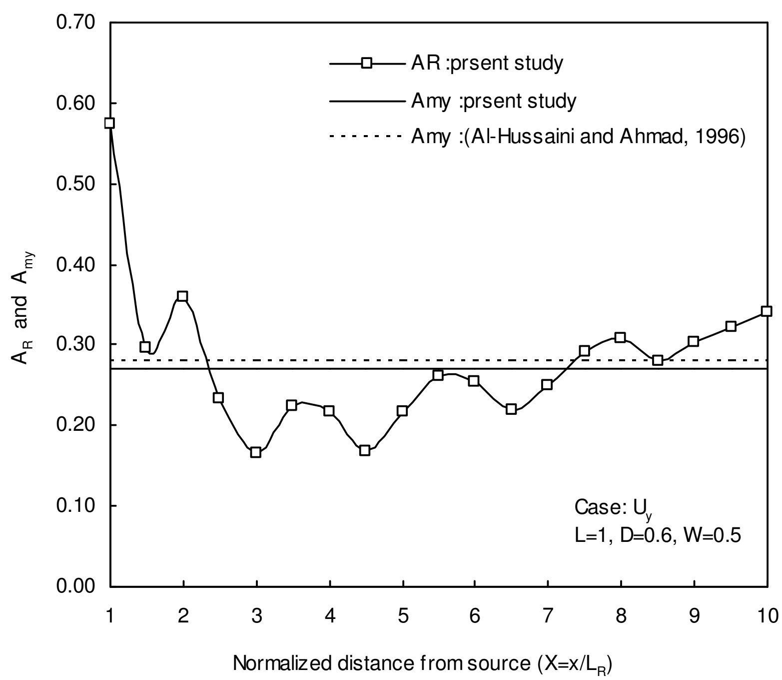

Figure 5.3: Comparative study on vibration isolation by a softer barrier

5.3. STUDY ON IN-FILLED TRENCH ISOLATION: RESULTS AND DISCUSSION

As previously stated, the barrier cross-sectional features, its location with respect to the source, and in-fill material characteristics are the parameters that govern isolation effectiveness of in-filled trenches. Effects of these parameters on vibration screening effectiveness of in-filled trenches are discussed in the following sections (*Sections*

5.3.1 to *5.3.3*). Effects of geometric features and backfill material are respectively studied in terms of non-dimensional geometric parameters and backfill shear wave velocity ratio as discussed in *Section 5.1*. Other than *Section 5.3.1*, softer wave barriers characterized by shear wave velocity ratios less than unity are considered as they are found significantly effective than stiffer barriers. Non-dimensional charts are developed for designing softer barriers in active and passive schemes and presented in *Section 5.3.4* of this study. In *Section 5.3.5*, some previously documented results on softer wave barriers are compared with the results obtained from the design charts.

5.3.1. Effect of Shear Wave Velocity Ratio

Although it has been manifested that softer barriers provide better screening effect than stiffer ones (Al-Hussaini and Ahmad, 1996; Adam and Estorff, 2005; El Naggar and Chehab, 2005), few such cases have been investigated justifying the choice of softer barriers in this study. The trench is assumed to have a specific depth (D=1) and location (L=5) and varying widths, W=0.3, 0.5, and 0.8. The backfill shear wave velocity ratio is varied from 0.1 to 0.7 for softer barriers and 2 to 8 in case of stiffer barriers. The backfill shear wave velocity is varied by changing its elastic modulus keeping other parameters unaltered. Effects of V_b/V_s on A_{my} and A_{mx} are depicted in *Figures 5.4(a)* and *5.4(b)*.

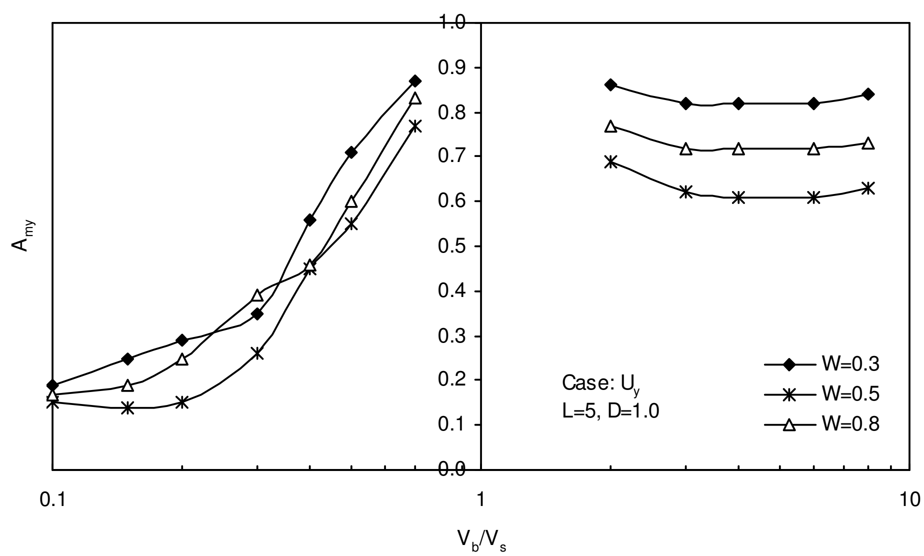

Figure 5.4(a): Effect of backfill shear wave velocity ratio on A_{my}

It is evident that to cause vibration attenuation, the backfill must differ from the half-space in terms of shear wave velocities. This implies that the backfill should have either lower or higher shear wave velocities than the parent soil. The amplitude reduction curves would reach unity irrespective of the trench configurations at V_b/V_s=1, signifying that the isolation scheme would behave as if there were no barrier if the shear wave velocity of backfill is identical to that of half-space.

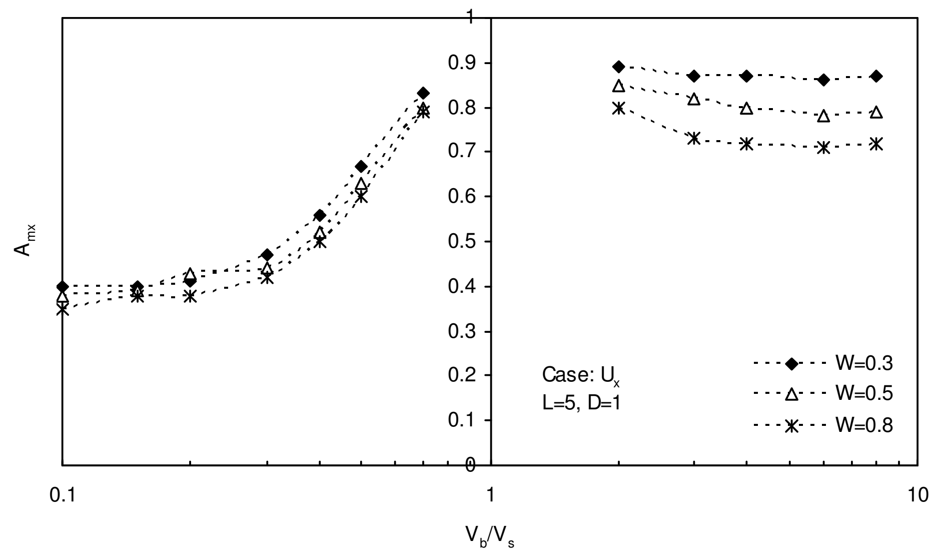

Figure 5.4(b): Effect of backfill shear wave velocity ratio on A_{mx}

Another crucial observation in this context is that in-filled trenches isolate vertical vibration component more effectively than the horizontal. Nevertheless, the screening performances of softer barriers are found significantly higher than stiffer ones. Softer backfill characterized by shear wave velocity ratios less than unity are hence considered in the subsequent analyses. It is apparent that in order to achieve a good degree of isolation, V_b/V_s should be around 0.3 or preferably less.

5.3.2. Effect of Barrier Location

To study the effect of barrier location on amplitude reduction, the distance of the barrier from source is varied from an active to a passive case; i.e. from L=1 to L=5 and average amplitude reduction factors (A_{my} and A_{mx}) are estimated at each of these locations. The study is performed by considering trenches of depth, D= 0.5, 0.75, 1.0, and 1.25 and width, W=0.3 and 0.5. The shear wave velocity ratio, V_b/V_s is taken to be 0.2 in this study. Variations of A_{my} versus L and D against the specific widths are plotted in *Figures 5.5(a)* and *5.5(b)*. Variations of A_{mx} against L and D for the same width cases are presented in *Figures 5.6(a)* and *5.6(b)*.

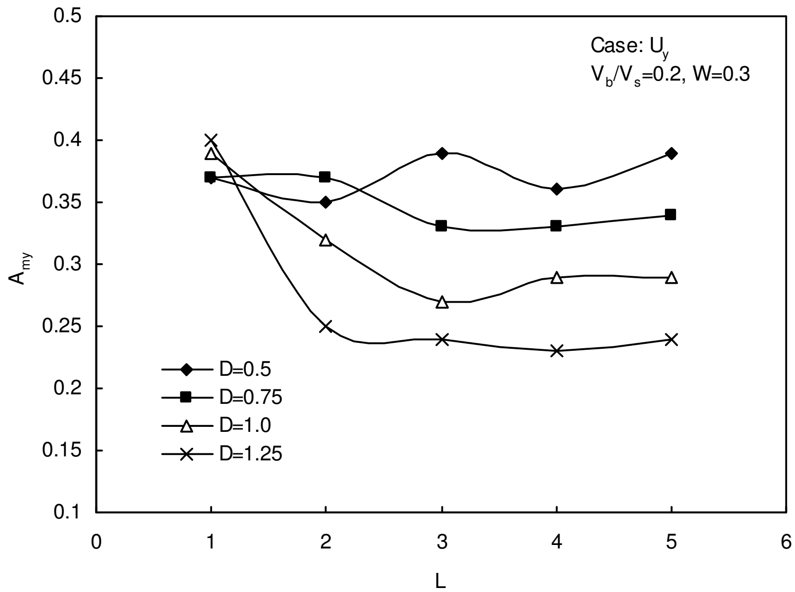

Figure 5.5(a): Variation of A_{my} versus L and D (W=0.3)

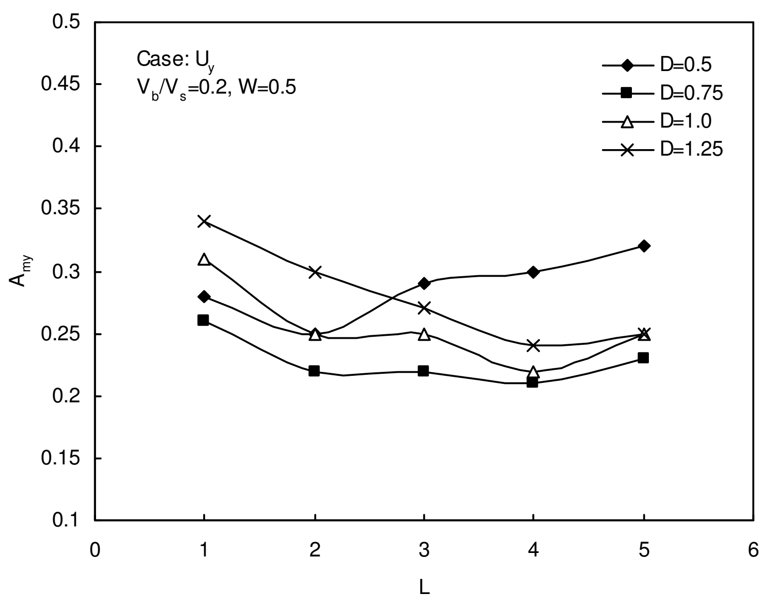

Figure 5.5(b): Variation of A_{my} versus L and D (W=0.5)

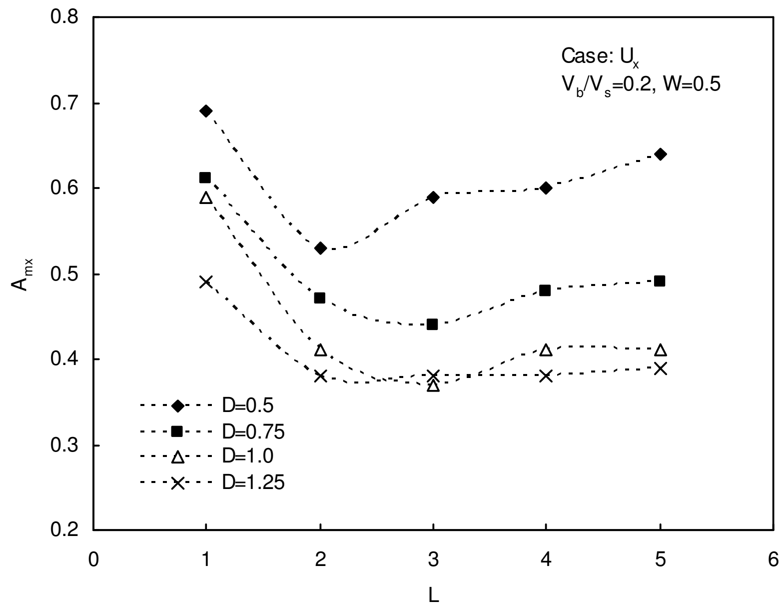

Figure 5.6(a): Variation of A_{mx} versus L and D (W=0.3)

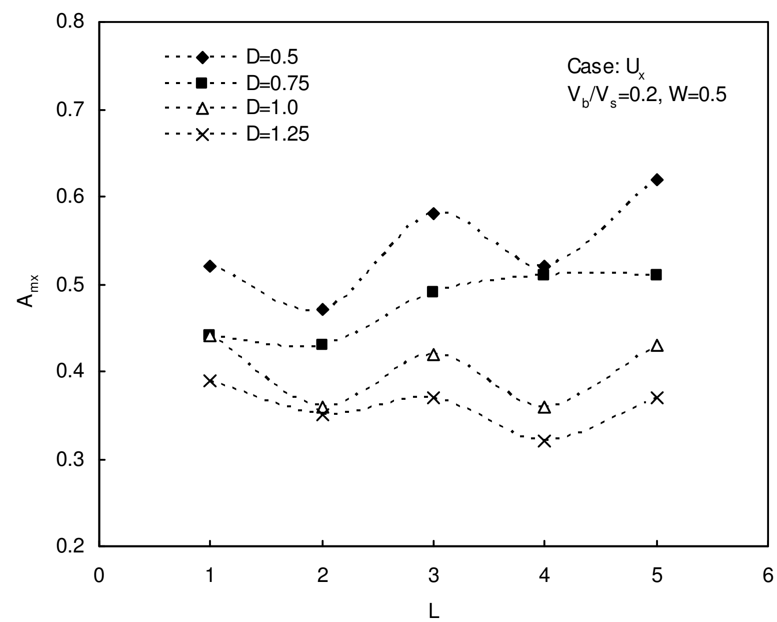

Figure 5.6(b): Variation of A_{mx} versus L and D (W=0.5)

In case of vertical vibration component, trenches of depths larger than $0.5L_R$ are found more effective at locations remote from the source (passive cases). However, variation in screening effectiveness from active to passive cases decreases as the trench width increases from W=0.3 to 0.5. In case of shallow (D=0.5) trenches, A_{my} shows inconsistent variation with barrier location (L) and hence no firm conclusion can be made in such cases. In most of the observations, other than D=0.5, the screening effectiveness increases with L up to L=2 to 3 and thereafter remains more or less constant.

In case of horizontal vibration component, narrow trenches (W=0.3) are observed to be more effective in passive cases, in general. In these cases, average amplitude reduction factor (A_{mx}) decreases with L, roughly up to 2 and remains nearly constant thereafter. When normalized width, W is increased to 0.5, variation of A_{mx} with L becomes highly inconsistent and no definite conclusion can be drawn.

5.3.3. Effect of Depth and Width

The effect of barrier cross-sectional features are studied in terms of variations in amplitude reduction in case of trenches of varying depths (D=0.25, 0.5, 0.75, 1.0, 1.25, and 1.5) and widths (W=0.3, 0.5, 0.8, and 1.0). This study considers two specific barrier locations, L=1 and 5, representing active and passive cases. The backfill shear wave velocity ratio, V_b/V_s is taken to be 0.2 in this study. Variations of A_{my} against D and W in active and passive cases are shown in *Figures 5.7(a)* and *5.7(b)*, while the variations of A_{mx} against the same in active and passive cases are depicted in *Figures 5.8(a)* and *5.8(b)*.

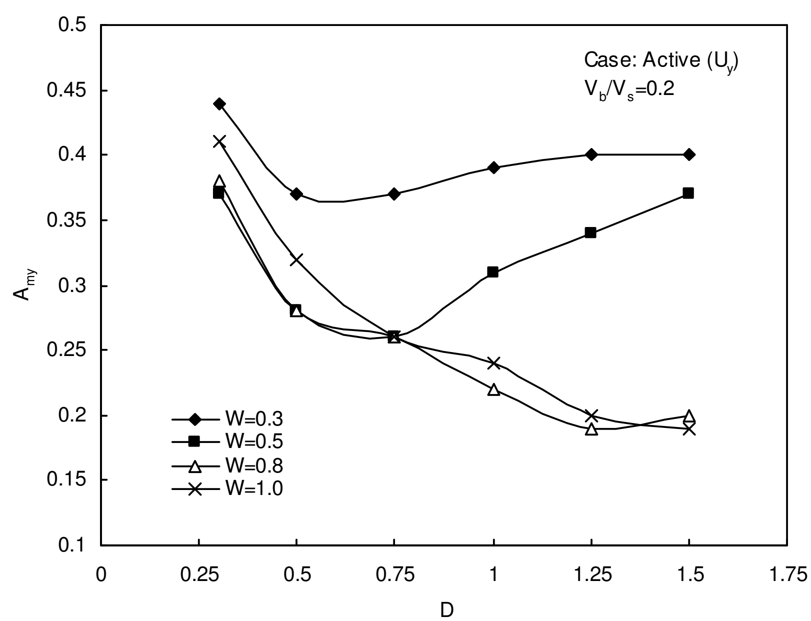

Figure 5.7(a): Effect of D and W on A_{my} in active case (L=1)

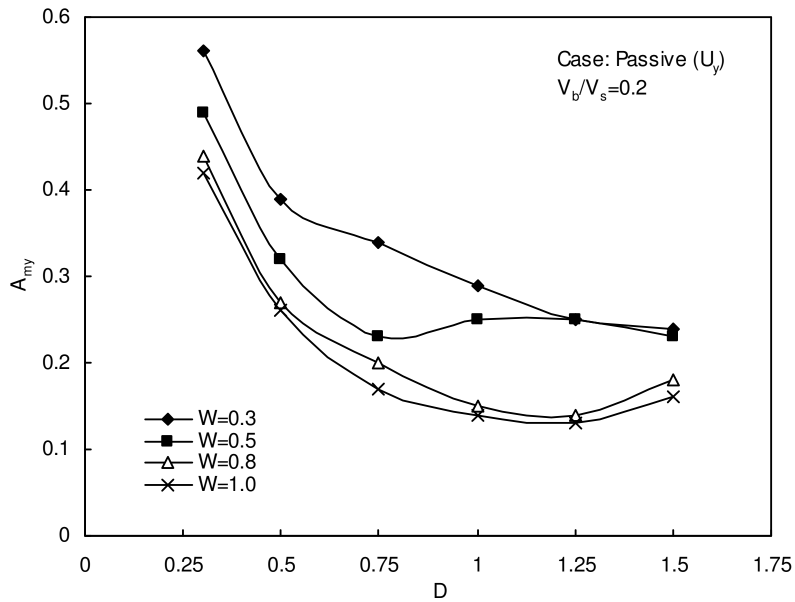

Figure 5.7(b): Effect of *D* and *W* on A_{my} in passive case (*L*=5)

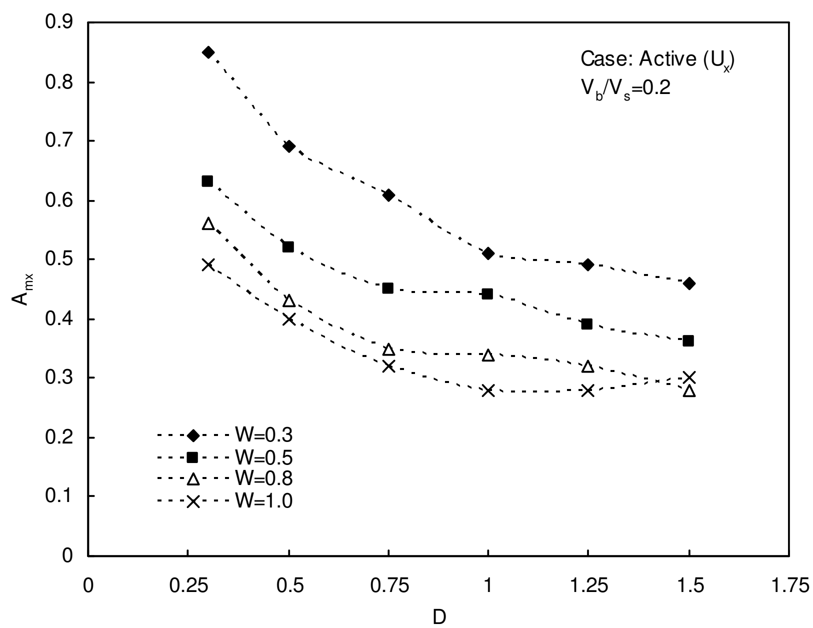

Figure 5.8(a): Effect of *D* and *W* on A_{mx} in active case (*L*=1)

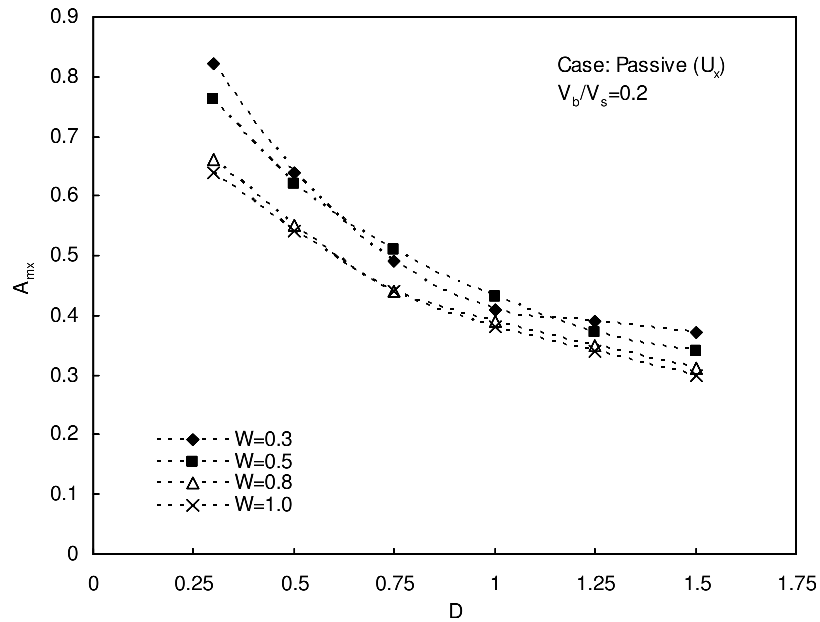

Figure 5.8(b): Effect of *D* and *W* on A_{mx} in passive case (*L*=5)

It is apparent from *Figures 5.7(a)-5.7(b)* that vertical vibration amplitude not necessarily decreases with increase in *D* regardless of the case whether active or passive. In case of narrow trenches, the optimum effectiveness is achieved at a shallower depth; while for wider trenches the same is achieved at a higher depth. This implies that in order to attain optimum screening effectiveness, a specific value of *D* must be accompanied by a particular value of *W* and vice-versa. There remains a certain value of *D*/*W* at which a softer barrier provides maximum efficiency. This is illustrated by plotting the variations of A_{my} and A_{mx} against *D*/*W* in active and passive cases in *Figures 5.9(a)-5.9(b).* As can be seen from these figures, the optimum screening effect is attained in most of the observations at *D*/*W* value lying within a range of roughly, 1.2 to 1.6, the only exception being *W*=0.3 case in passive scheme.

In case of horizontal vibration component, with reference to *Figures 5.8(a)-5.8(b)*, no such relationship exists between *D* and *W* as A_{mx} consistently decreases with increase in trench depth (*D*) irrespective of its width (*W*). Increase in trench width (*W)* has a prominent effect on reducing A_{mx} in active cases, while the same has little significance in passive cases. However, regardless of the vibration component and type of scheme (whether active and passive), *W*=0.8 can be considered as an upper limit of barrier width in all cases, beyond which increasing the same has little to no significance either on A_{my} or A_{mx}.

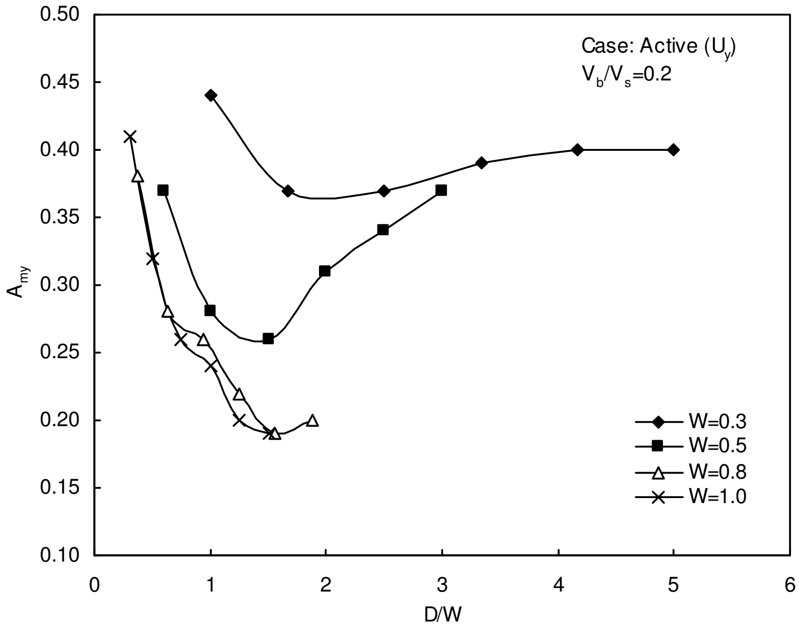

Figure 5.9(a): Effect of D/W on A_{my} in active case (L=1)

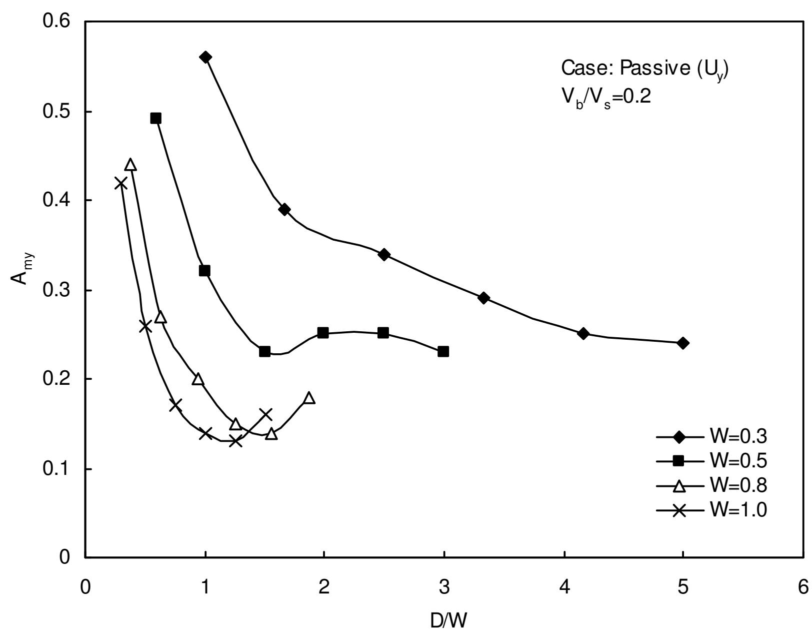

Figure 5.9(b): Effect of D/W on A_{my} in passive case (L=5)

5.3.4. Design Charts

Preceding discussions certainly help to develop an understanding on the effects of various parameters on the screening effectiveness of softer in-filled trench barriers but are limited to some specific cases. To frame generalized design guidelines, non-dimensional design charts are developed encompassing a wide range of barrier configurations and backfill shear wave velocity ratios for active and passive cases separately. The values of different parameters adopted in these charts are shown in *Table 5.1*.

Table 5.1: Values of parameters adopted in design charts

Parameter	Notation	Adopted values
Normalized depth	D	0.5, 0.75, 1.0, 1.25, and 1.5
Normalized width	W	0.3, 0.5, and 0.8
Normalized distance from source	L	1 (active case) and 5 (passive case)
Backfill shear wave velocity ratio	V_b/V_s	0.1, 0.15, 0.2, 0.3, 0.4, 0.5, and 0.7

The design charts are developed considering two distinct locations, L=1 and 5 indicating active and passive cases. In these charts, variations of A_{my} or A_{mx} are plotted against V_b/V_s and W in case of a few specific depths. Design charts concerning the isolation of vertical vibration component in active case are depicted in *Figures 5.10(a)-5.10(e)*, while the same in passive cases are shown in *Figures 5.11(a)-5.11(e)*. Amplitude reduction of horizontal vibration components in active and passive cases are shown respectively in *Figures 5.12(a)-5.12(e)* and *5.13(a)-5.13(e)*.

For practical application of these charts, one has to determine shear wave velocity of half-space soil and Rayleigh wavelength of vibration, knowing the half-space material parameters and source frequency. The backfill shear wave velocity also needs to be determined for estimating V_b/V_s. The trench dimension required to achieve a certain degree of isolation, thus can be estimated using these charts depending on whether the scheme is active or passive. Alternately, if the barrier dimension is decided beforehand, one can use these charts to choose a proper backfill to attain a targeted degree of isolation.

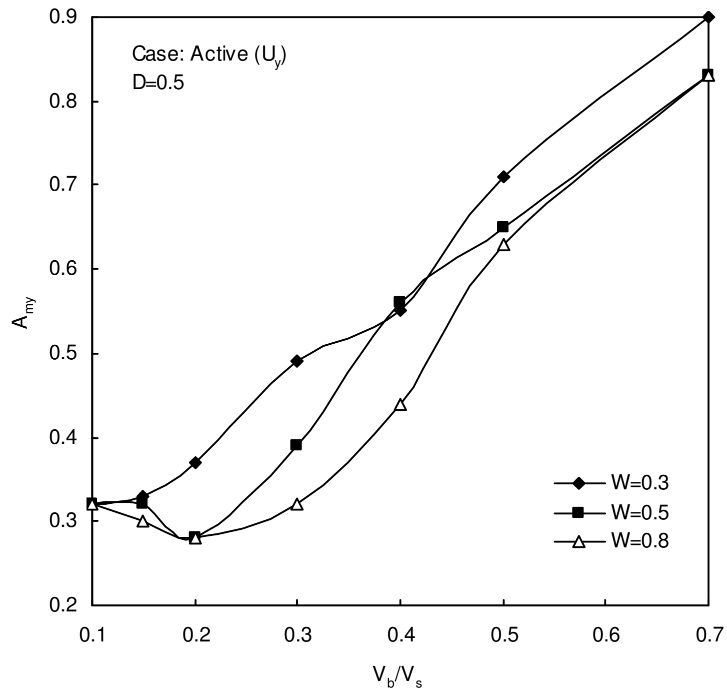

Figure 5.10(a): Variation of A_{my} with V_b/V_s and W in active case (D=0.5)

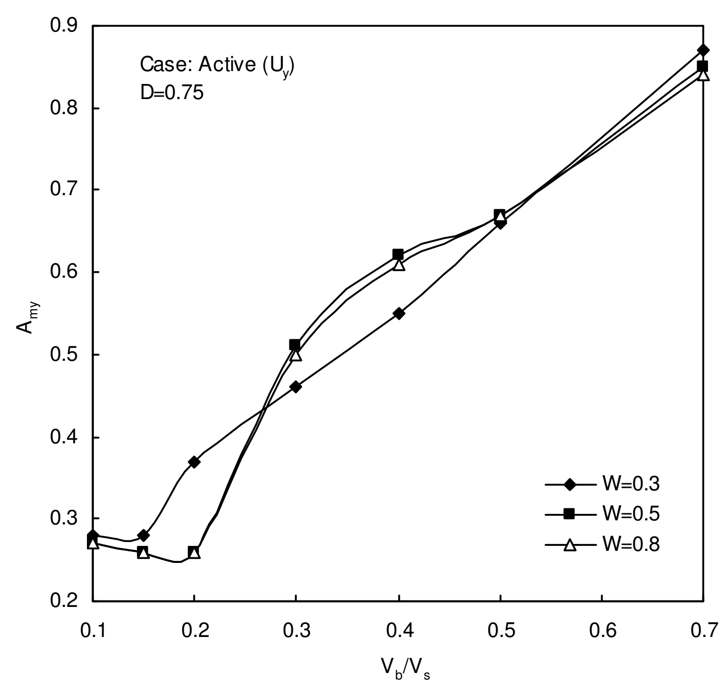

Figure 5.10(b): Variation of A_{my} with V_b/V_s and W in active case (D=0.75)

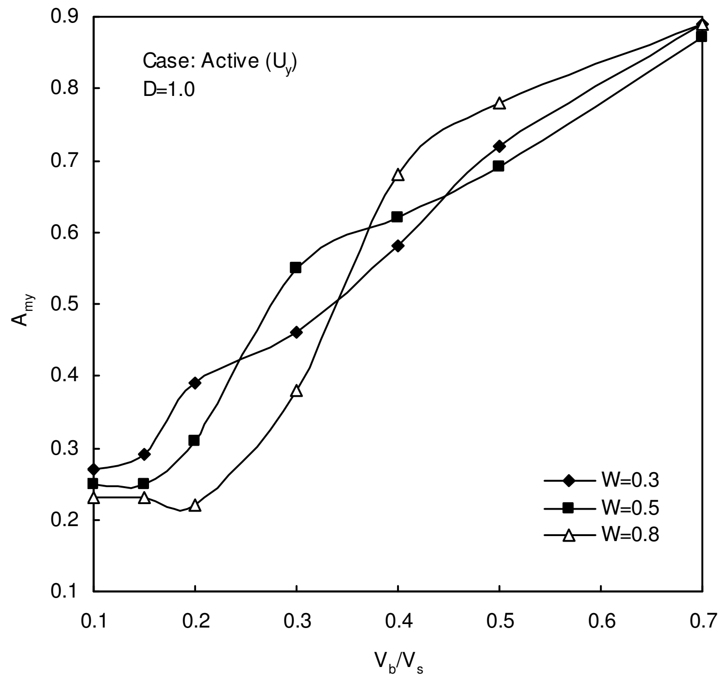

Figure 5.10(c): Variation of A_{my} with V_b/V_s and W in active case (D=1.0)

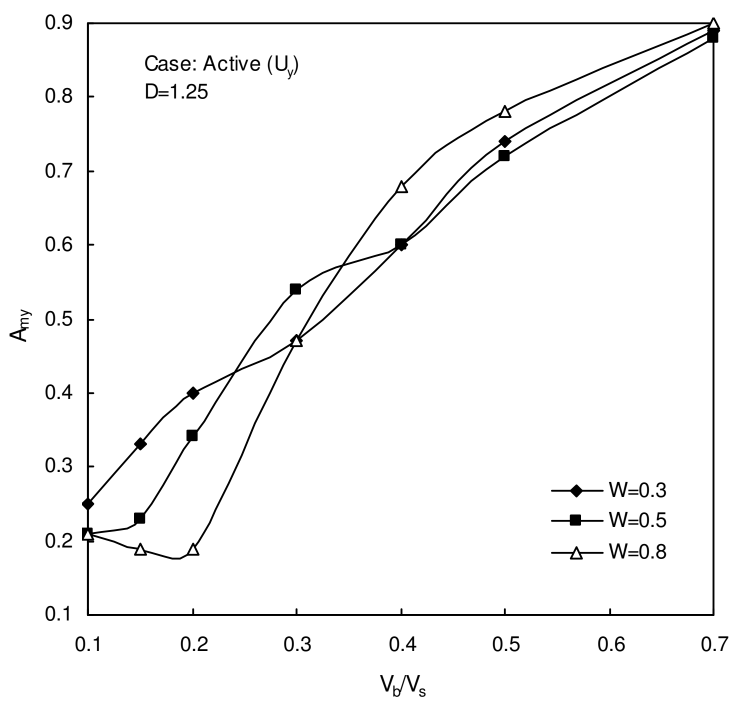

Figure 5.10(d): Variation of A_{my} with V_b/V_s and W in active case (D=1.25)

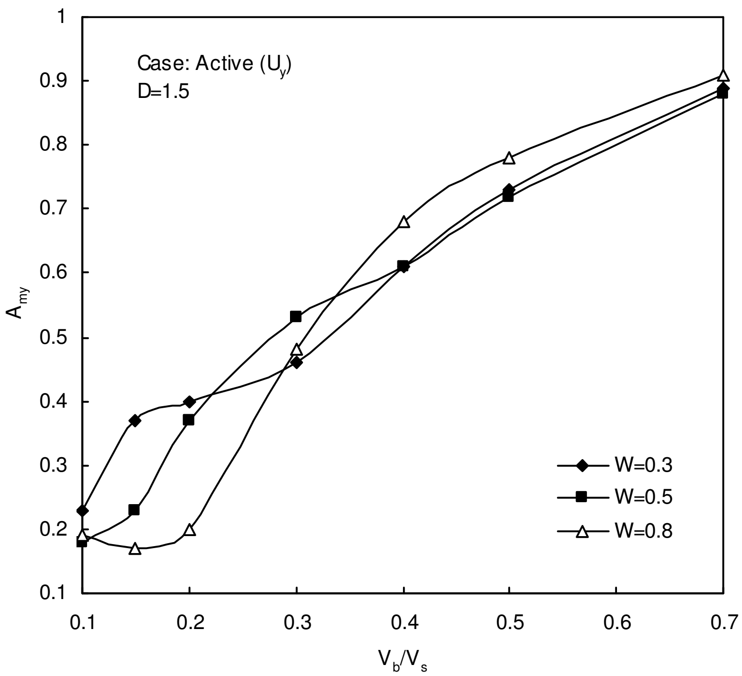

Figure 5.10(e): Variation of A_{my} with V_b/V_s and W in active case (D=1.5)

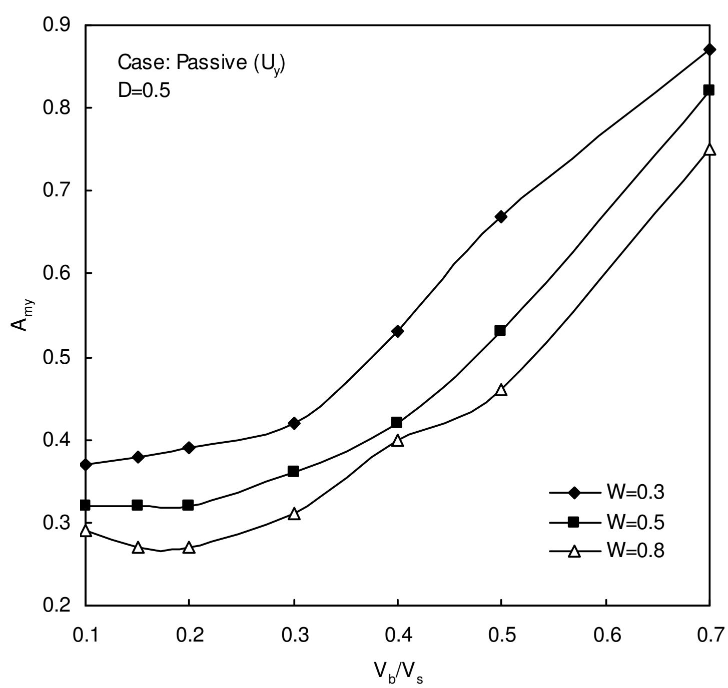

Figure 5.11(a): Variation of A_{my} with V_b/V_s and W in passive case (D=0.5)

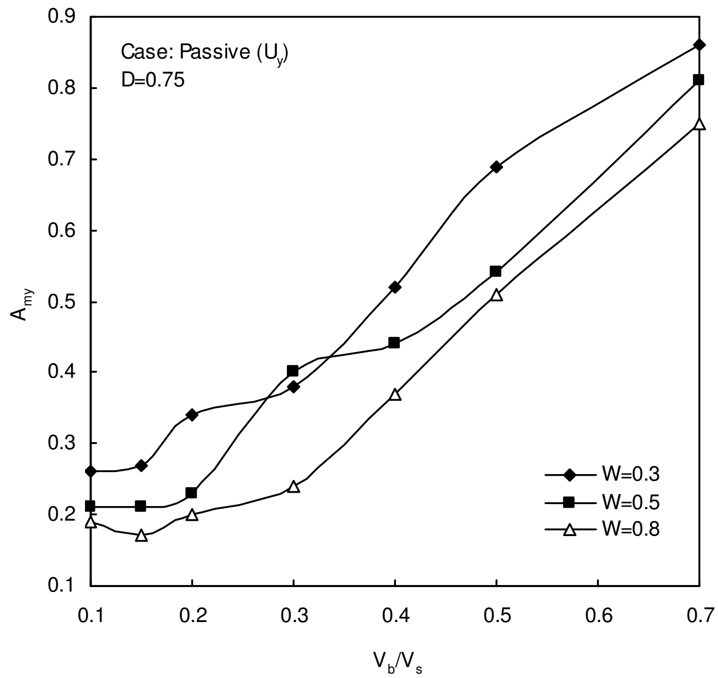

Figure 5.11(b): Variation of A_{my} with V_b/V_s and W in passive case (D=0.75)

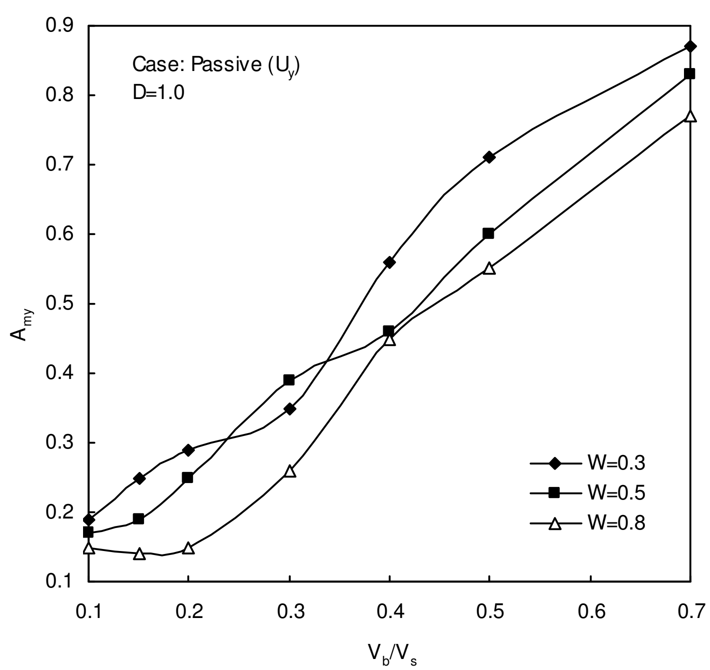

Figure 5.11(c): Variation of A_{my} with V_b/V_s and W in passive case (D=1.0)

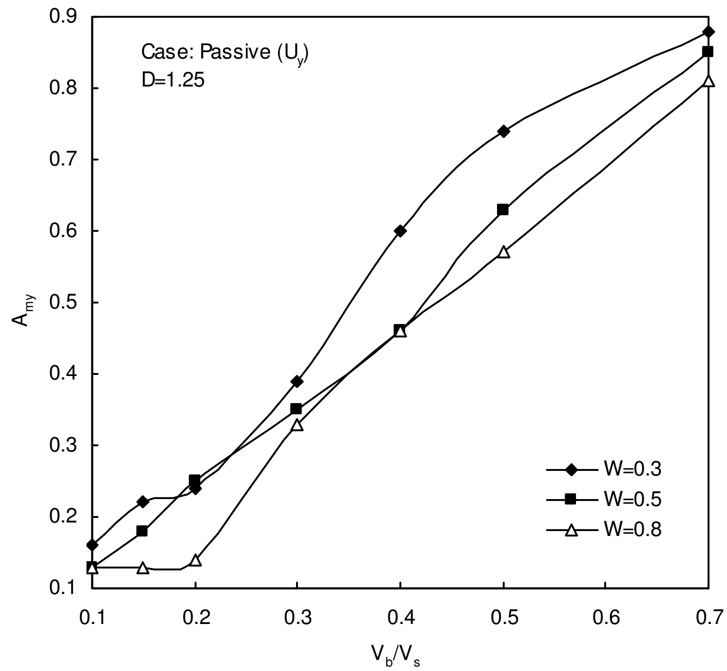

Figure 5.11(d): Variation of A_{my} with V_b/V_s and W in passive case (D=1.25)

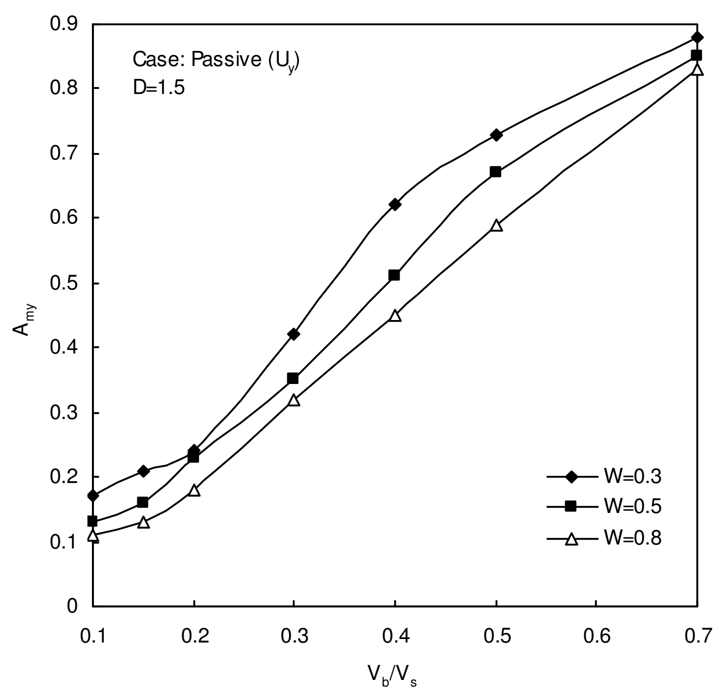

Figure 5.11(e): Variation of A_{my} with V_b/V_s and W in passive case (D=1.5)

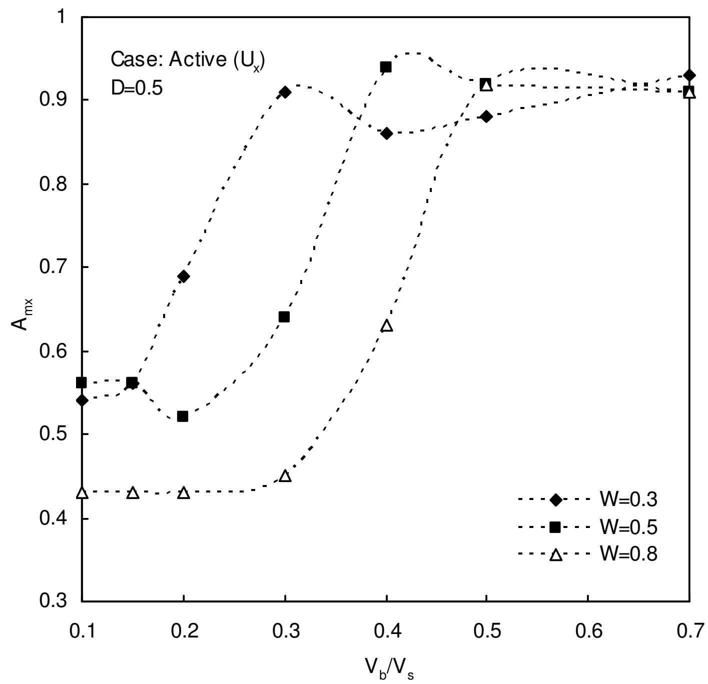

Figure 5.12(a): Variation of A_{mx} with V_b/V_s and W in active case (D=0.5)

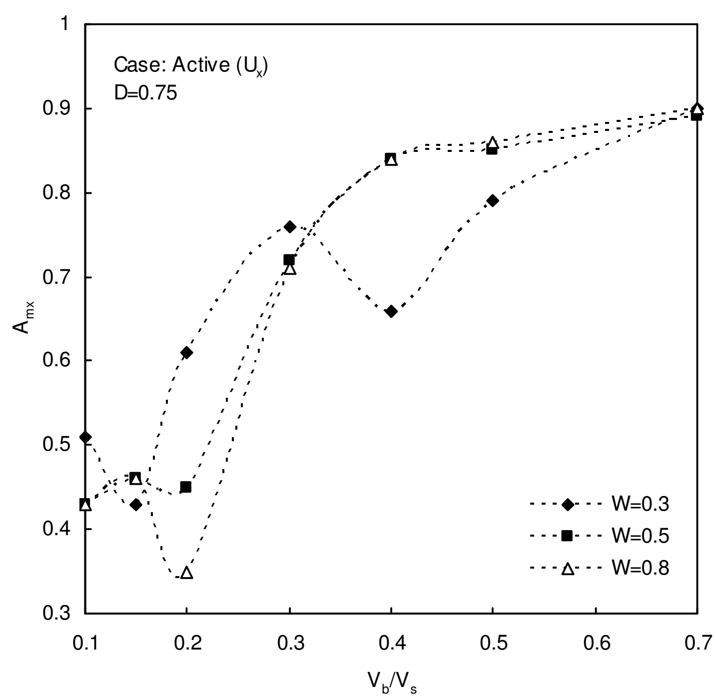

Figure 5.12(b): Variation of A_{mx} with V_b/V_s and W in active case (D=0.75)

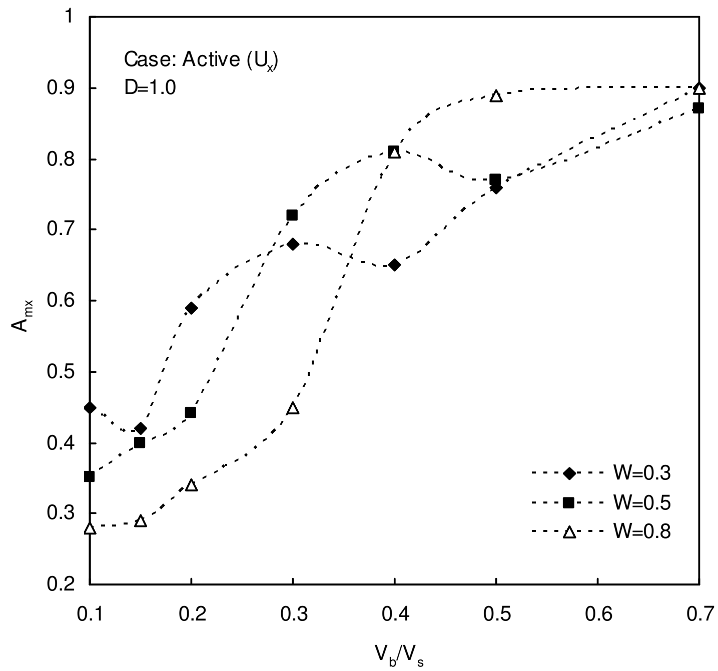

Figure 5.12(c): Variation of A_{mx} with V_b/V_s and W in active case (D=1.0)

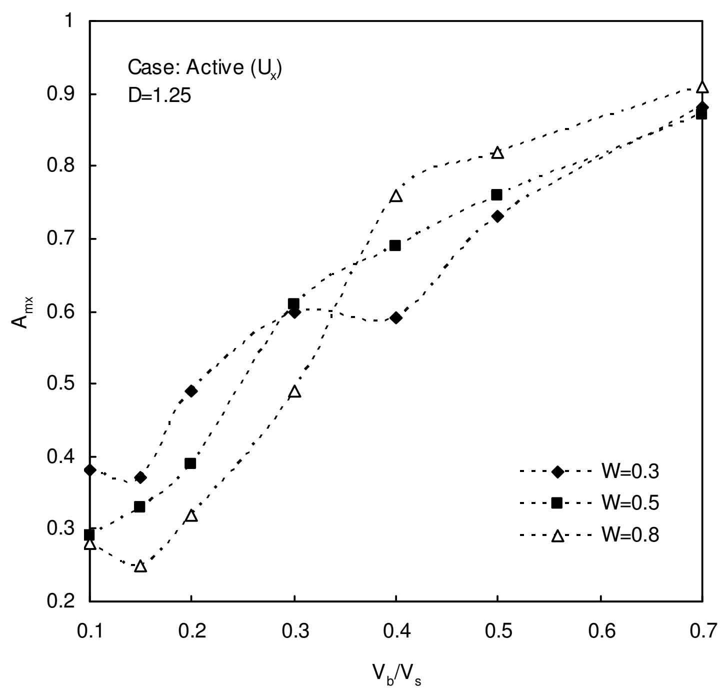

Figure 5.12(d): Variation of A_{mx} with V_b/V_s and W in active case (D=1.25)

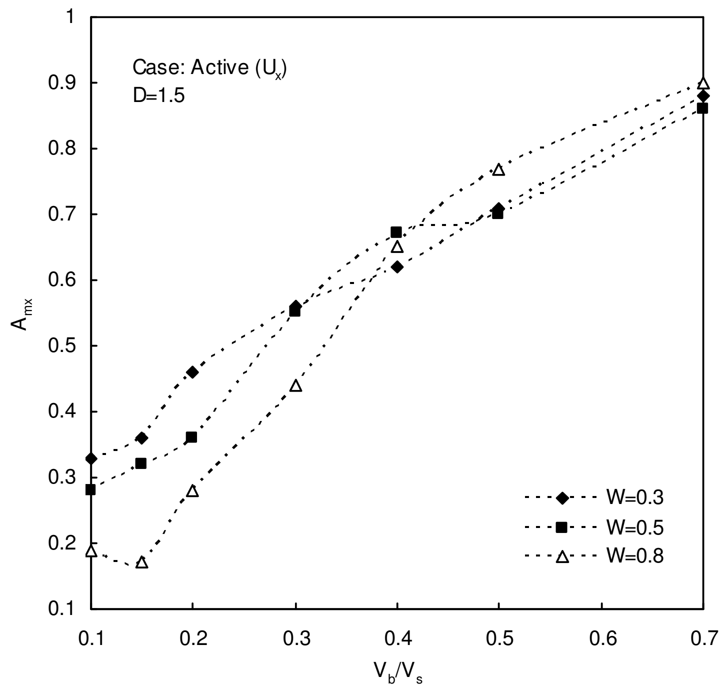

Figure 5.12(e): Variation of A_{mx} with V_b/V_s and W in active case (D=1.5)

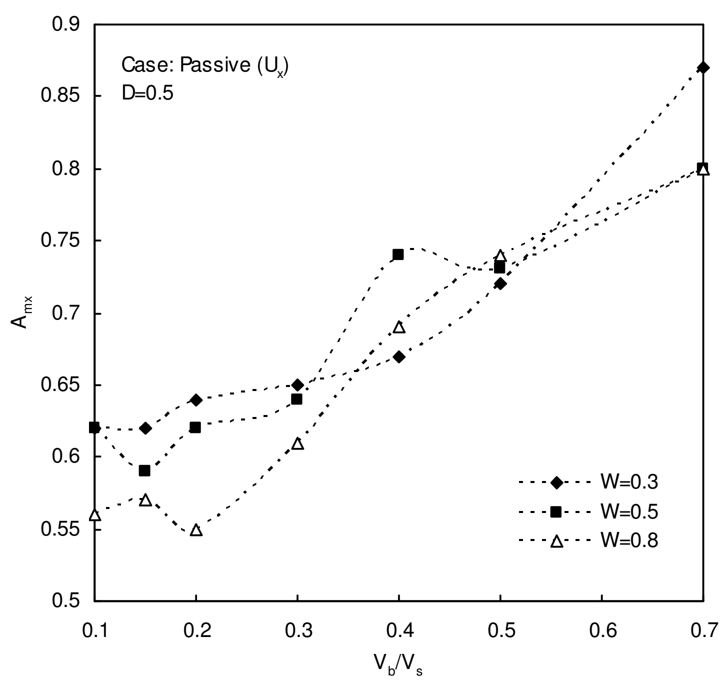

Figure 5.13(a): Variation of A_{mx} with V_b/V_s and W in passive case (D=0.5)

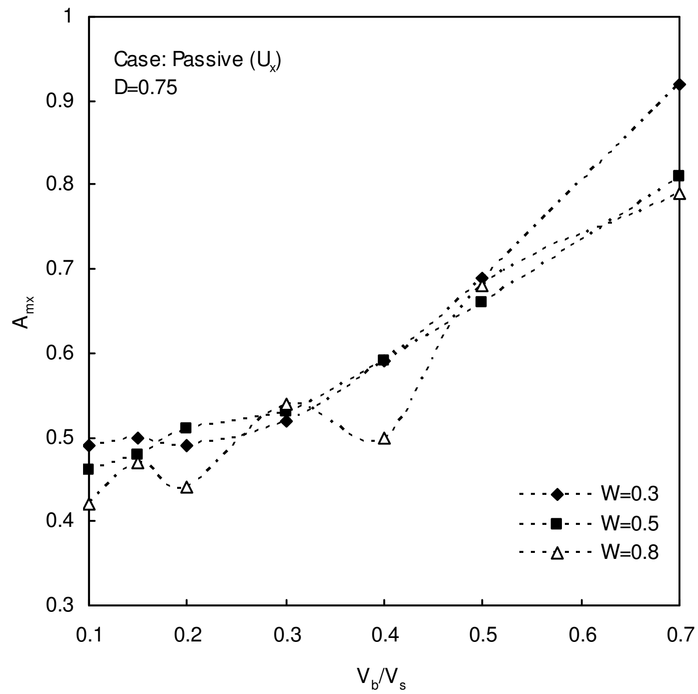

Figure 5.13(b): Variation of A_{mx} with V_b/V_s and W in passive case (D=0.75)

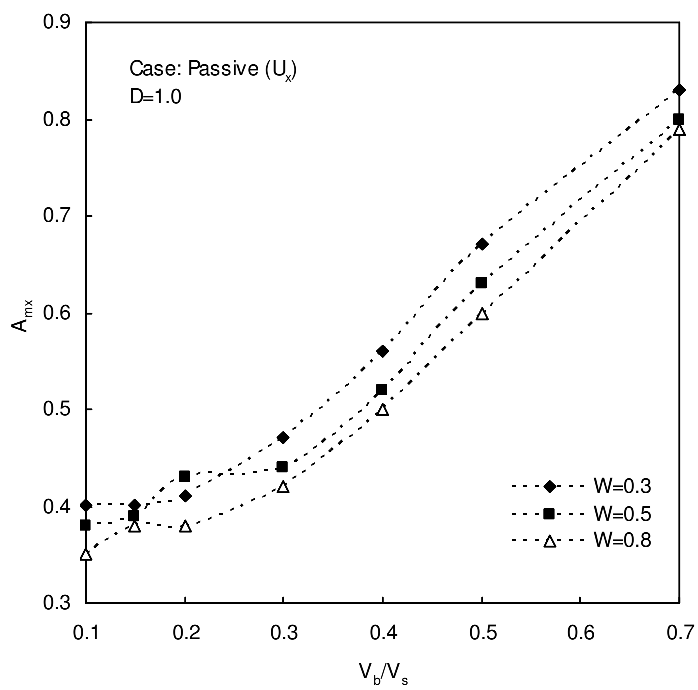

Figure 5.13(c): Variation of A_{mx} with V_b/V_s and W in passive case (D=1.0)

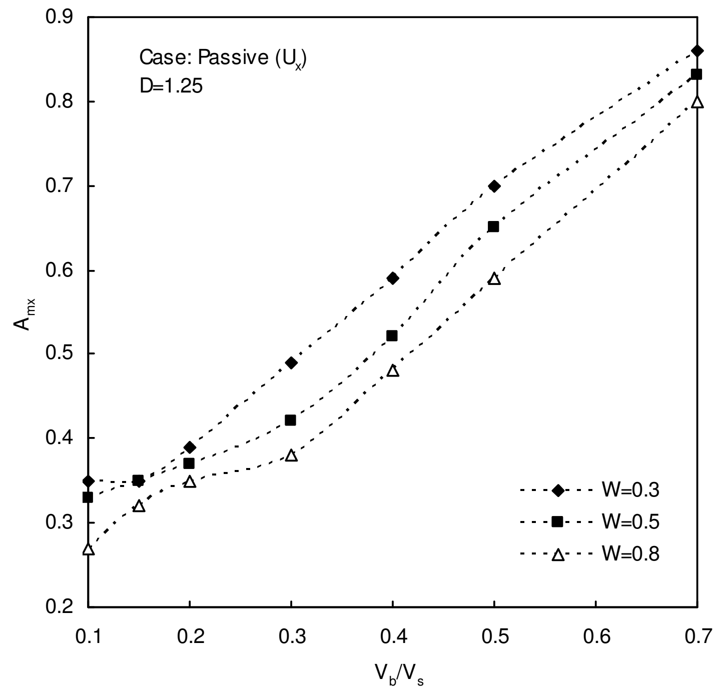

Figure 5.13(d): Variation of A_{mx} with V_b/V_s and W in passive case (D=1.25)

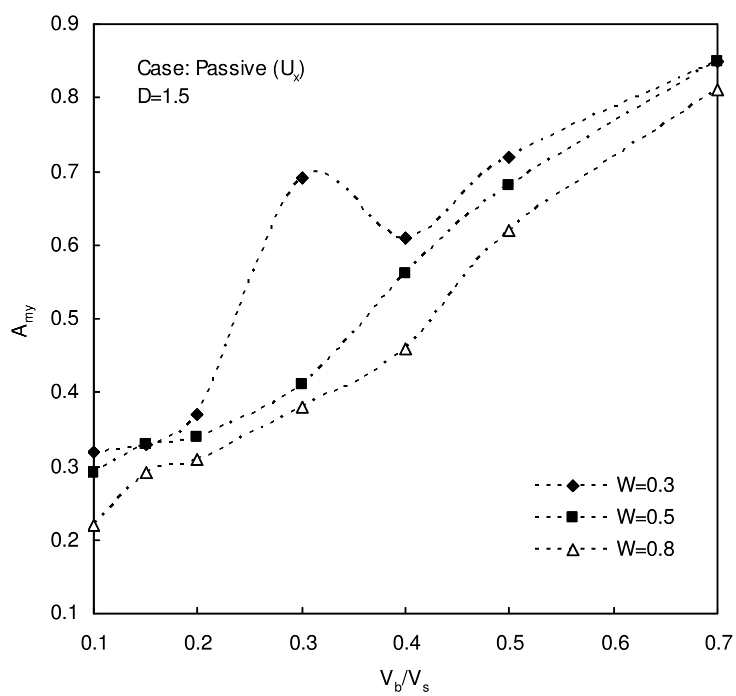

Figure 5.13(e): Variation of A_{mx} with V_b/V_s and W in passive case (D=1.5)

It is apparent from these charts that there exists a particular value of shear wave velocity ratio, V_b/V_s beyond which decreasing the same not necessarily increases the isolation effectiveness. In most of the observations, the optimum efficiency of the barrier is achieved at V_b/V_s lying within a range of 0.1 to 0.2.

5.3.5. Comparison with Previous Results

Some results documented in previous literatures on softer wave barriers are compared with results obtained from the design charts and presented in *Table 5.2*. It is to be noted that results of Yang and Hung (1997) are given against impedance ratios that are converted to equivalent shear wave velocity ratios for comparison. It can be seen that the design charts provide results that are qualitatively agreeable to the published values. The results in case of barrier features other than those shown in the design charts are linearly interpolated.

Table 5.2: Comparison with published results

L	V_b/V_s	D	W	A_{my}/A_{mx}		Reference
				Documented	Design charts	
1	0.2	0.6	0.3	A_{my}=0.40	A_{my}=0.37	Al-Hussaini and Ahmad (1996)
1	0.2	0.6	0.5	A_{my}=0.28	A_{my}=0.27	Do
1	0.1	0.6	0.3	A_{my}=0.25	A_{my}=0.30	Do
1	0.1	0.8	0.5	A_{my}=0.27	A_{my}=0.27	Do
1	0.1	1.0	0.5	A_{my}=0.20	A_{my}=0.25	Do
1	0.13	1.0	0.33	A_{my}=0.31	A_{my}=0.29	Yang and Hung (1997)
1	0.13	1.0	0.33	A_{mx}=0.42	A_{mx}=0.42	Do

5.4. SUMMARY

An open trench is a special case of an in-filled trench of $V_b/V_s \approx 0$. To cause vibration attenuation, the backfill shear wave velocity must be different from that of half-space. To achieve a good degree of isolation, V_b/V_s should be around 0.3 or preferably less. In-filled trenches are more effective in isolating the vertical vibration component than the horizontal.

In case of the vertical vibration screening, deeper ($D \geq 0.75$) barriers are more effective in passive cases. However, variation in A_{my} from active to passive cases decreases as W increases from 0.3 to 0.5. In these cases, screening effectiveness increases mostly up to L=2 to 3 and thereafter remains nearly constant. For shallow (D=0.5) trenches, variation of A_{my} with L is inconsistent and no definite conclusion can hence be made.

Concerning the horizontal vibration component, better screening effect is observed in passive cases when the trench is narrow (W=0.3). In these cases, amplitude reduction factor decreases with L, roughly up to 2 and remains virtually constant thereafter. However, no definite conclusion can be made for wider trenches (W=0.5).

Increase in barrier depth not necessarily decreases A_{my}. There exists a certain value of D/W at which a softer barrier provides optimum isolation efficiency. This critical D/W value lies roughly within 1.2 to 1.6 in most of the observations. No such relationship between D and W is observed in case of horizontal vibration screening as A_{mx} consistently decreases with increase in either D or W. However, effect of W is prominent only in active cases and has little significance in passive cases. In all cases, W=0.8 can be considered as an upper limit beyond which A_{my} and A_{mx} remains practically unaltered with further increase in width.

Non-dimensional charts are developed for practical application of such barriers. It is observed that backfill should have shear wave velocities within 0.1 to 0.2 times of that of parent soil to achieve optimum screening effect.

CHAPTER 6
VIBRATION ISOLATION USING DUAL TRENCHES: OPEN AND IN-FILLED

This chapter deals with a comprehensive study on vibration isolation by dual trenches: open and in-filled. The chapter starts with a preliminary discussion on the scheme of study which is somewhat different from the other chapters. Effects of various barrier features on amplitude attenuation are studied and conclusions are made regarding optimal selection of these parameters. Effects of the participating parameters are expressed in non-dimensional graphical forms which would serve as design guidelines in practical application of such barriers. Advantages of dual trench barriers over isolated trenches are justified with examples.

6.1. ASSUMPTIONS AND NON-DIMENSIONAL PARAMETERS

This study is based on the same assumptions made in case of open and in-filled trench isolation studies presented in *Chapters 4* and *5*. Accordingly, the dynamic load magnitude, its frequency, material constitutive model, elastic parameters of half-space and backfill including material damping values are same as assumed in *Sections 4.1 and 5.1*. The shear wave velocity, Rayleigh wave velocity, and Rayleigh wavelength of vibration in half-space are, respectively 101.1 m/s, 93.02 m/s, and 3 m as estimated in *Table 4.2*.

For wave isolation by a pair of open trenches, parameters that govern the screening effectiveness are the geometric features of trenches. Geometric features that are treated as variables are locations of the trenches from source of excitation (l_1 and l_2), their depths (d_d), and widths (w_d). These parameters are expressed as functions of Rayleigh wavelength (L_R) as: d_d=$D_d.L_R$, w_d=$W_d.L_R$, l_1=$L_1.L_R$, and l_2=$L_2.L_R$. The dimensionless parameters, D_d and W_d are termed as normalized depths and widths of each trench; while L_1 and L_2 denotes normalized distances of the first and second trench from source respectively. Schematic of an isolation scheme comprising of a pair of open trenches is shown in *Figure 6.1*. The trenches are assumed to be identical in cross-sections.

In case of dual in-filled trenches, the geometric parameters and their corresponding non-dimensional equivalents are same as that of dual open trenches. They differ from dual open trenches only in terms of backfill material effect which is studied in terms of backfill shear wave velocity ratio (V_b/V_s) as discussed in *Section 5.1*. Softer backfill characterized by shear wave velocity ratios less than unity are considered in the analyses.

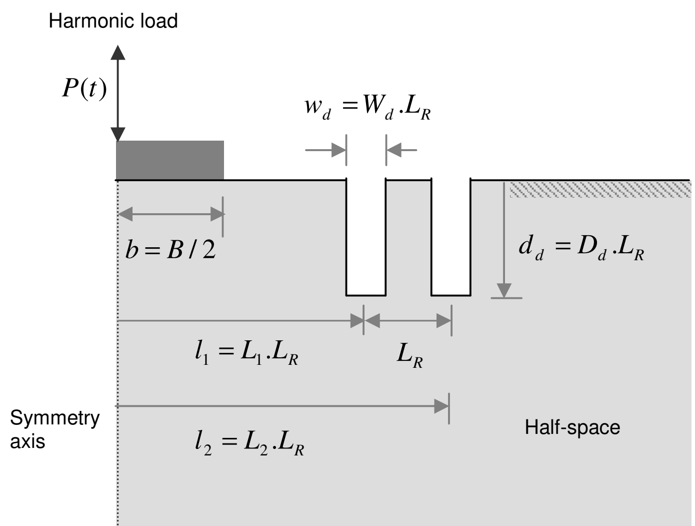

Figure 6.1: Normalized geometric features of a dual trench barrier

6.2. FINITE ELEMENT ANALYSIS

The finite element modelling and analyses are done in a way similar to open and in-filled trenches as discussed in *Chapters 4* and *5*. Axisymmetric models of dimension 35 m × 15 m with fifteen nodded triangular mesh elements are adopted. The model boundaries are assigned to standard fixities and absorbent boundary conditions as already discussed. Steady-state harmonic excitation of stated magnitude and frequency is imposed over one-half of the imaginary footing width. The mesh generation is done with very fine element option and local refinements are made along the surface, trench periphery, and backfill clusters as appropriate. Dynamic analyses are performed in a time interval of 0.5 s. For details of finite element analysis *Sections 4.3* and *5.2* may be referred. Amplitude reduction factors and average amplitude reduction factors are estimated in a manner similar to the previous studies. Typical finite element models of dual open and in-filled trench barriers are depicted in *Figures 6.2(a)* and *6.2(b)*.

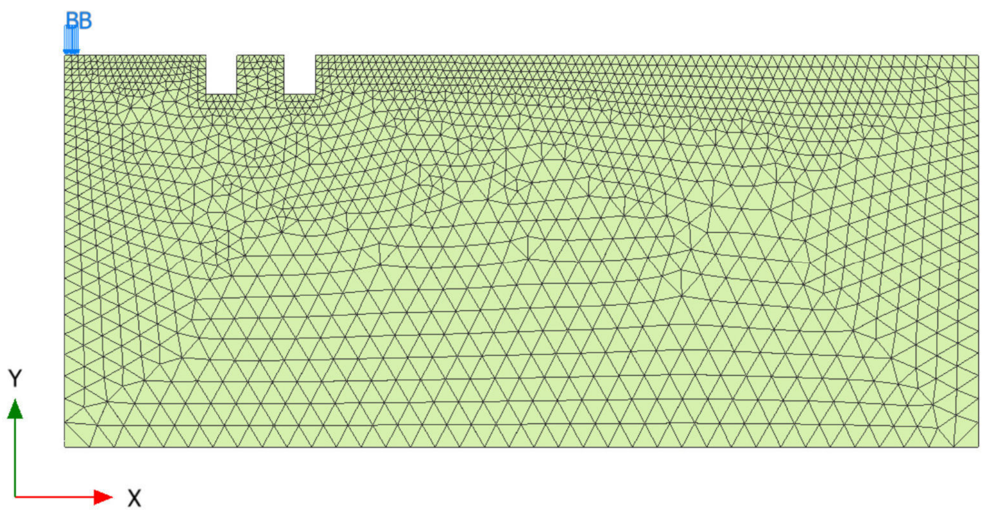

Figure 6.2(a): Typical finite element model of a dual open trench barrier

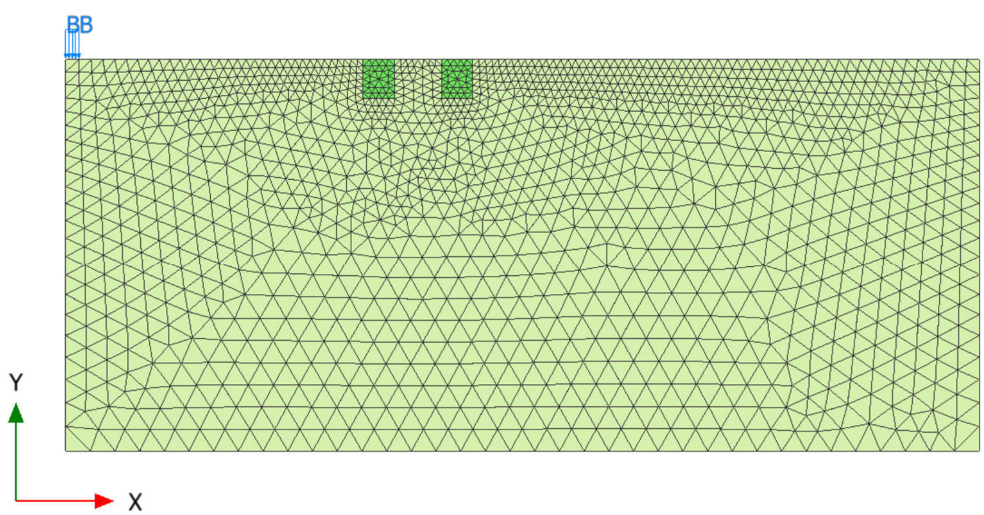

Figure 6.2(b): Typical finite element model of a dual in-filled trench barrier

6.3. STUDY ON DUAL OPEN TRENCHES: RESULTS AND DISCUSSION

The parametric study of dual open trenches involves investigating the effects of barrier locations, their depths, and widths on reducing vertical and horizontal components of vibration. Effects of these features are studied in terms of non-dimensional parameters and are discussed in the following sub-sections. The non-dimensional plots relating overall amplitude reduction factors with barrier depths and widths in active and passive cases would serve as design guidelines in actual engineering practice. Usefulness of dual open trench barriers over isolated open trenches is justified with examples in *Section 6.5*.

6.3.1. Effect of Barrier Location

To study the effect of barrier locations, a trench pair of specific cross-section is placed at varying distances from source and average amplitude reduction factors (A_{my} and A_{mx}) are estimated against each of these locations as shown in *Figure 6.3*. The distance between the trenches is, however, kept constant as $1L_R$ for this study (refer *Figure 6.1*). The depths and widths of each trench are taken to be $0.5L_R$ and $0.2L_R$ (in terms of normalized parameters, D_d=0.5 and W_d=0.2). Variations of average amplitude reduction factors are plotted against the distance of the first trench from source (L_1) for which L_2=L_1+1. For example, when L_1=1, L_2=2 and so on.

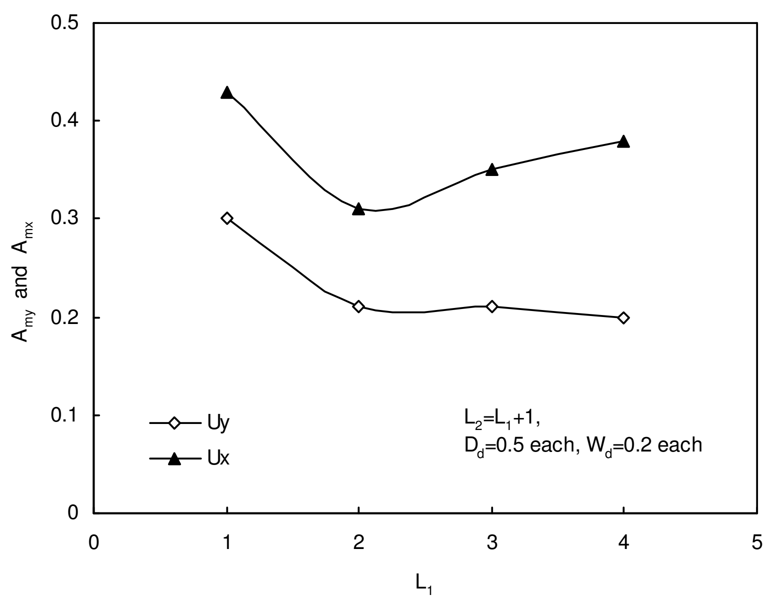

Figure 6.3: Variation of A_{my} and A_{mx} with trench locations

As can be seen from *Figure 6.3*, isolation efficiency is least when the trenches are located close to the source, i.e. at L_1=1 and L_2=2. This implies that isolation efficiency of a dual open trench barrier is lowest in active isolation case. The screening performance increases when the barriers are placed at larger distances from source. In vertical vibration case, from L_1=2 and L_2=3 onwards the screening efficiency remains practically unaltered. For horizontal vibration cases, such conclusions are difficult to make as the amplitude attenuation pattern is somewhat irregular. But it can still be concluded that isolation effectiveness is minimum in active case. The results also demonstrate that dual trench barriers can isolate vertical vibration component more effectively than horizontal.

6.3.2. Effect of Width and Depth of Trenches

Effect of widths and depths of trenches are studied against two distinct cases, active and passive. In active case trench locations are considered as L_1=1 and L_2=2, whereas in passive case the same are placed at L_1=4 and L_2=5. The normalized depths (D_d) of each trench are taken as 0.2, 0.3, 0.4, 0.5, 0.6, and 0.75. The normalized widths (W_d) are taken to be 0.2, 0.3, 0.4, and 0.5. Effects of normalized depths (D_d) and widths (W_d) on A_{my} in active and passive cases are depicted in *Figures 6.4(a)-6.4(b)*. Effects of D_d and W_d on A_{mx} in active and passive cases are shown in *Figures 6.5(a)-6.5(b)*.

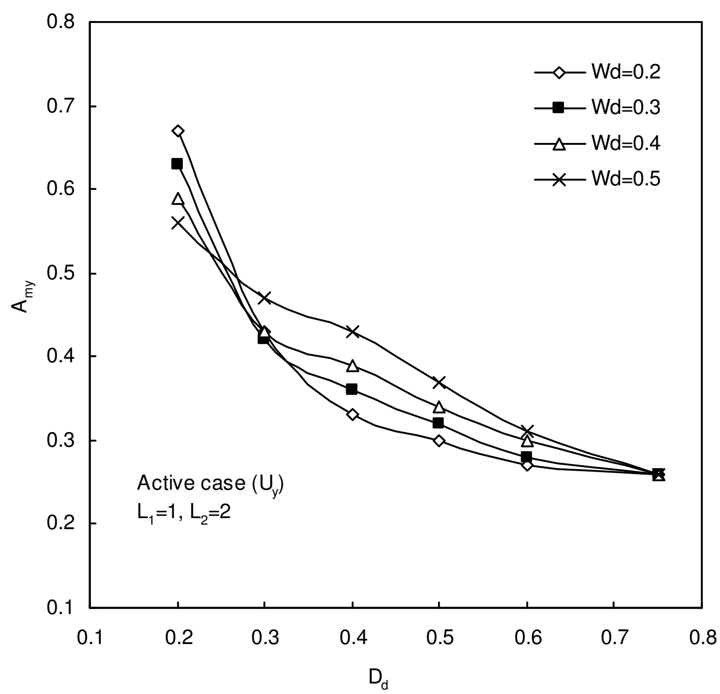

Figure 6.4(a): Variation of A_{my} versus D_d and W_d in active case

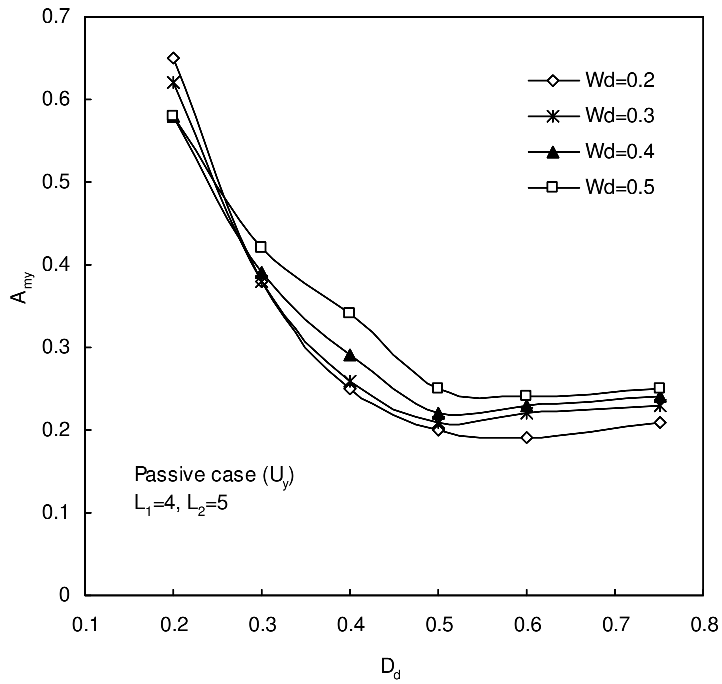

Figure 6.4(b): Variation of A_{my} versus D_d and W_d in passive case

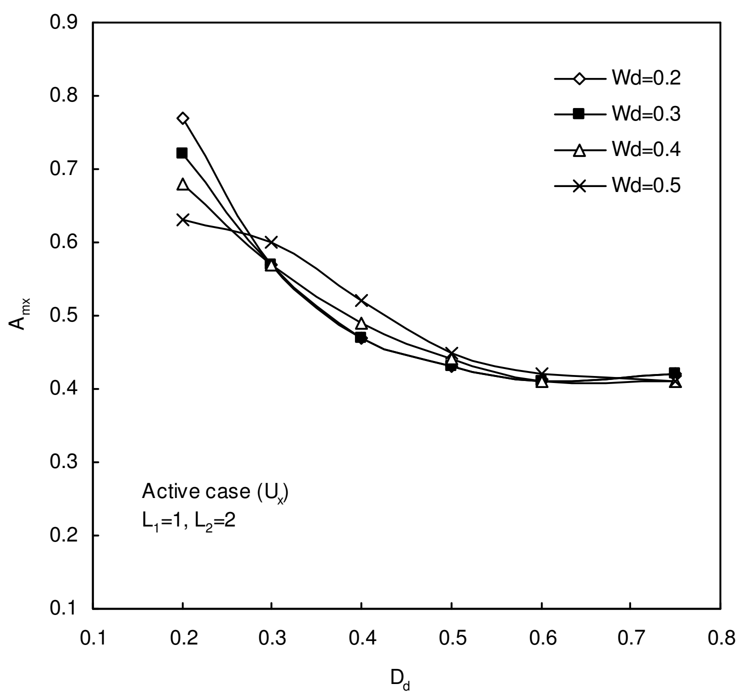

Figure 6.5(a): Variation of A_{mx} versus D_d and W_d in active case

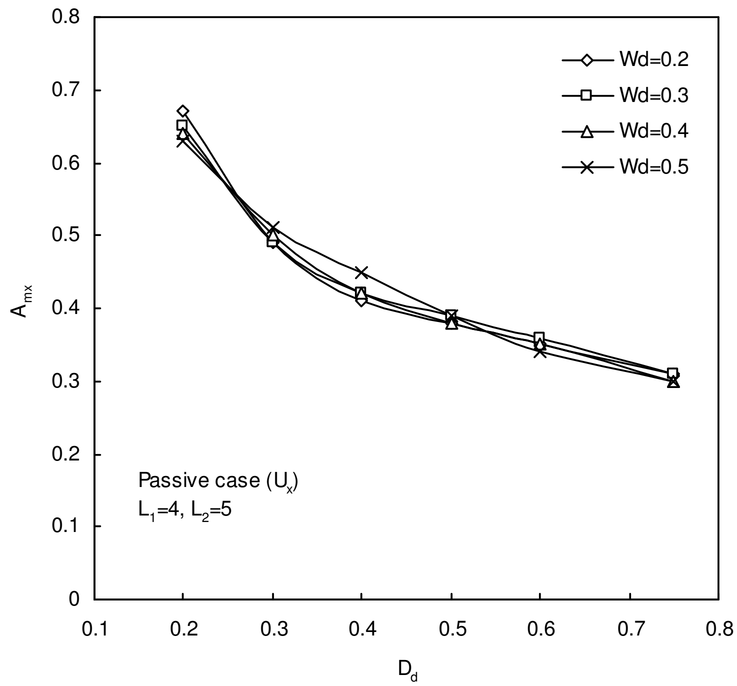

Figure 6.5(b): Variation of A_{mx} versus D_d and W_d in passive case

It is apparent from *Figures 6.4(a)-6.4(b)* that vertical vibration component attenuates with increase in depths of the trenches. However, there exists a critical depth $0.5L_R$-$0.6L_R$ beyond which further increase in depth does not result in any significant increase in isolation effect. In fact, in passive cases, increase in depths beyond this is observed to have marginal adverse effect on the isolation effectiveness of the barrier. Increasing the widths of trenches not necessarily increases the screening efficiency. In fact, the isolation efficiency decreases with increasing widths, except in case of very shallow trenches ($D_d \leq 0.25$) for which increasing the trench widths causes marginal increase in isolation efficiency. Nevertheless, trenches of such a shallow depth do not provide any successful isolation. Hence for all practical purposes it may be concluded that increasing the trench widths has no beneficial effect on the screening performance of dual open trench barriers in vertical vibration case. Isolation achieved by wider trench is less compared to narrow trenches beyond the depth specified above. This is because the trench becomes slender as it is deep and narrow and reflects the ground waves deep in to the half-space, thereby resulting in a better isolation.

Similar conclusions can be made on the effects of widths and depths in reducing horizontal component of vibration with reference to *Figures 6.5(a)-6.5(b).* There exists a critical depth, nearly $0.6L_R$ beyond which any further increase in depth does not result in any increase in isolation effect in active case. It can be seen from *Figure 6.5(b)* that in passive case some increase in isolation effect is still observed beyond a depth of $0.6L_R$. However, this is marginal and the limiting value of depth of each trench can hence be considered as $0.6L_R$ for all practical purposes. The adverse effect of increased width is less pronounced in horizontal vibration cases. In either case, increase in trench widths has virtually no beneficial role on barrier screening effectiveness.

6.4. STUDY ON DUAL IN-FILLED TRENCHES: RESULTS AND DISCUSSION

Vibration isolation by dual in-filled trenches is investigated in terms of the effects of key parameters governing their screening effectiveness. The relevant geometric parameters and their corresponding non-dimensional equivalents are already stated in *Section 6.1*. Effects of barrier locations, depths, widths, and in-fill material characteristics on amplitude reduction are studied in the subsequent sections. Usefulness of dual in-filled trench barriers over isolated in-filled trenches is justified with examples in *Section 6.5*.

6.4.1. Effect of Barrier Location

Effect of barrier location is studied in a way similar to dual open trenches as discussed in *Section 6.3.1*. The barrier is placed at differing distances from source keeping distance between the trenches constant as $1L_R$. The depth and width of each trench are taken to be $0.5L_R$ and $0.3L_R$. The shear wave velocity ratio (V_b/V_s) assumed in this case is 0.2. Variations of A_{my} and A_{mx} against the distance of first trench from source (L_1) are shown in *Figure 6.6*. For a particular value of L_1, distance of second trench from source is $L_2=L_1+1$.

As can be seen from *Figure 6.6*, locations of the trenches have little effect on amplitude reduction which may be ignored in all practical purposes. In the subsequent studies, the trench locations will be considered as L_1=4 and L_2=5 which indicates a passive isolation case. The results also demonstrate that dual in-filled trench barriers can more effectively isolate the vertical vibration component than horizontal.

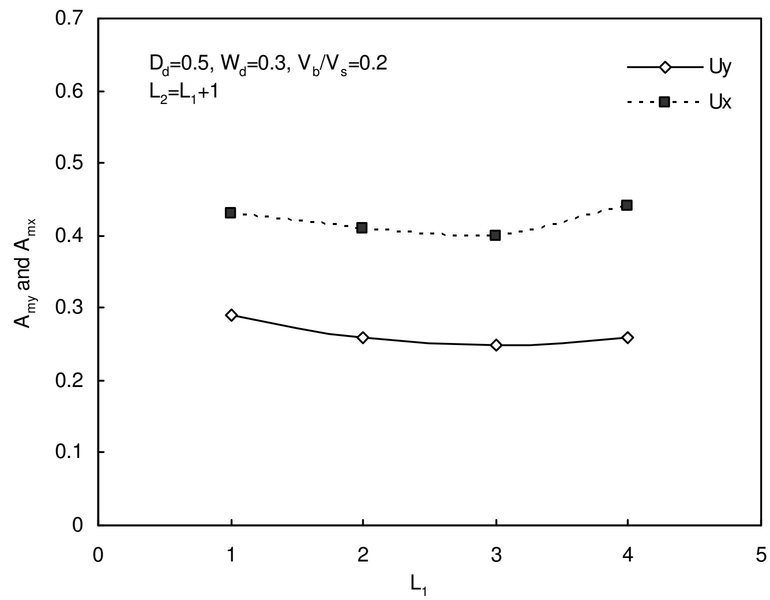

Figure 6.6: Effect of barrier location on A_{my} and A_{mx}

6.4.2. Effect of Barrier Depths and Shear Wave Velocity Ratio

Effects of trench depths and backfill shear wave velocity ratios on amplitude attenuation are studied by considering two identical in-filled trenches placed at L_1=4 and L_2=5 from the source. The normalized depths, D_d of each trench are assumed to be 0.2, 0.3, 0.4, 0.5, 0.6, and 0.75. The normalized widths, W_d are assumed as 0.3, 0.4, and 0.5. The shear wave velocity ratios (V_b/V_s) taken for this study are 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, and 0.7. Different shear wave velocity ratios are ensured by changing the backfill shear wave velocity (V_b) keeping half-space shear wave velocity (V_s) unaltered. The backfill shear wave velocity is altered by varying its elastic modulus, while keeping the other parameters same.

Variations of A_{my} versus backfill shear wave velocity ratios (V_b/V_s) and barrier depths (D_d) against a few specific widths (W_d) are depicted in *Figures 6.7(a)-6.7(c).*

Variations of A_{mx} against V_b/V_s and D_d against the same width cases are shown in *Figures 6.8(a)-6.8(c)*.

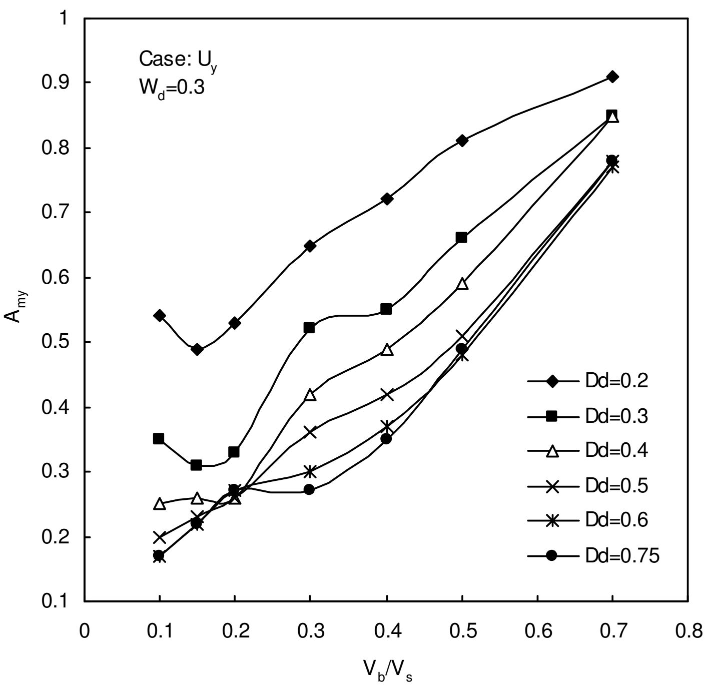

Figure 6.7(a): Variation of A_{my} against D_d and V_b/V_s (W_d=0.3)

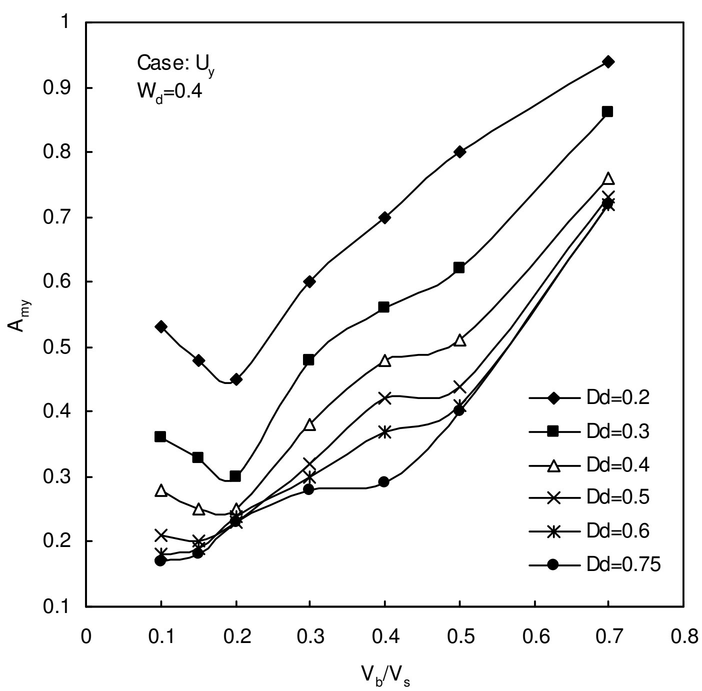

Figure 6.7(b): Variation of A_{my} against D_d and V_b/V_s (W_d=0.4)

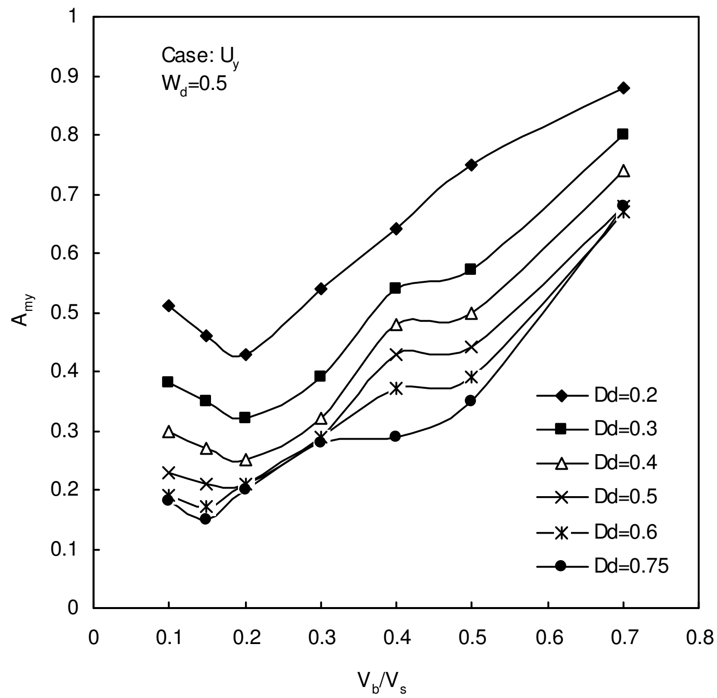

Figure 6.7(c): Variation of A_{my} against D_d and V_b/V_s (W_d=0.5)

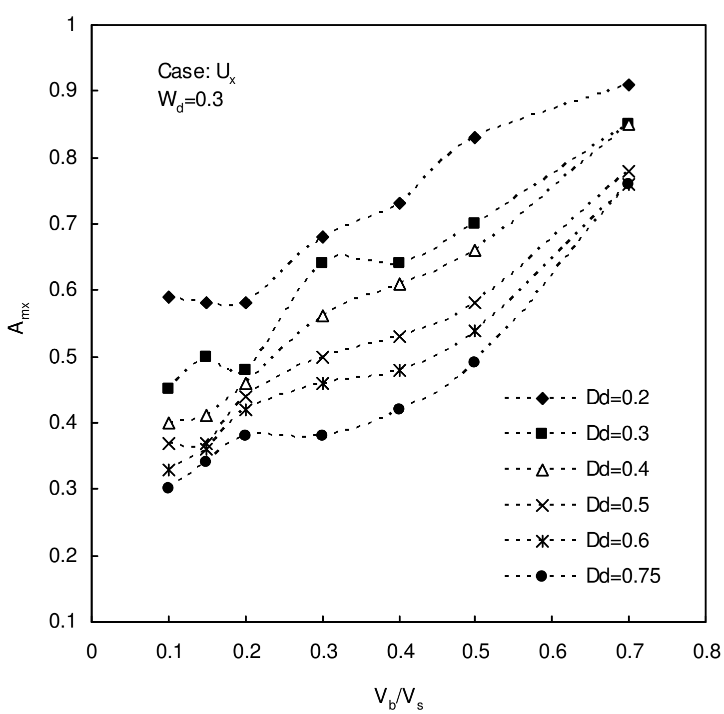

Figure 6.8(a): Variation of A_{mx} against D_d and V_b/V_s (W_d=0.3)

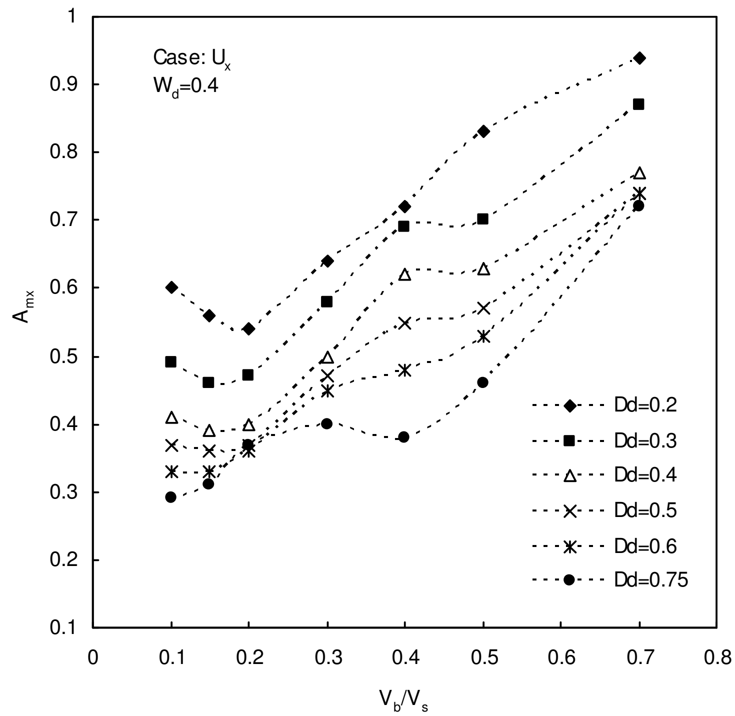

Figure 6.8(b): Variation of A_{mx} against D_d and V_b/V_s (W_d=0.4)

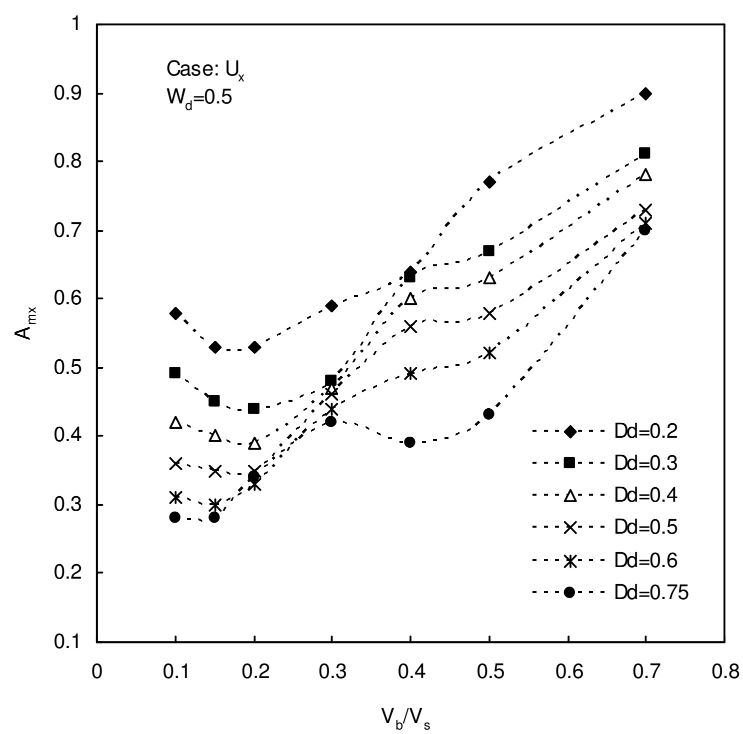

Figure 6.8(c): Variation of A_{mx} against D_d and V_b/V_s (W_d=0.5)

Characteristics of in-fill material play a significant role in wave screening process. In most of the observations, decrease in backfill shear wave velocity with respect to parent soil causes a marked decrease in amplitude reduction factors, resulting in a better isolation effect. A higher shear wave velocity ratio, in contrast, results in higher average amplitude reduction factors, thereby making the isolation scheme less effective. However, decreasing the shear wave velocity ratio to any extent not necessarily leads to a better screening effect. There exists a limiting shear wave velocity ratio, beyond which further decrease of the same adversely affects screening effectiveness of the barrier when the trenches are shallow, in particular. In case of shallow trenches ($d_d \leq 0.5L_R$), the optimum efficiency is obtained for V_b/V_s lying within a range of 0.15 to 0.2. For trenches deeper than this depth, such adverse effect is not prominent but optimum efficiency is still attained at V_b/V_s within a range of 0.1 to 0.15. It may be concluded in general, that the backfill should have shear wave velocities within 0.1 to 0.2 times that of surrounding soil in order to achieve optimum screening effectiveness. The vertical vibration curves are observed to have somewhat steeper gradients than the horizontal ones which imply that shear wave velocity of backfill has more pronounced effect on reducing the vertical component of vibration. It leads to the conclusion drawn in *Section 6.4.1* that a dual trench barrier in-filled with softer backfill is more effective in reducing vertical vibrations.

The depth of trenches shows dominant effect on isolation effectiveness of dual in-filled trench barriers. Increase in trench depth results in a significant increase of the barrier efficiency. It is noted that within the optimum range of V_b/V_s specified above, A_{my} shows consistent reduction with depths up to d_d=0.6L_R. Further increase in depth does not result in an increased efficiency of the barrier. So far as the horizontal component is concerned, marginal increase in screening efficiency are still observed beyond a depth of 0.6L_R. Nevertheless, the differences are small and can be ignored for all practical purposes. A normalized depth, D_d=0.6 may hence be considered, in general, as an upper limit of trench depths beyond which no appreciable increase in isolation efficiency is observed with further increase in depth.

6.4.2. Effect of Barrier Widths and Shear Wave Velocity Ratio

Effect of barrier width can be studied in a way similar to the effect of depth by plotting the variation of A_{my} and A_{mx} versus backfill shear wave velocity ratios and barrier widths against a specific depth.

Variation of A_{my} against shear wave velocity ratios (V_b/V_s) and barrier widths (W) for a few constant depths (D_b=0.2, 0.3, 0.4, 0.5, and 0.6) are shown in *Figures 6.9(a)-6.9(e)*.

Variation of A_{mx} versus V_b/V_s and W against the same depth cases are presented in Figures *6.10(a)-6.10(e)*. Values of normalized trench widths and shear wave velocity ratios assumed for these cases are same as stated in *Section 6.4.2*.

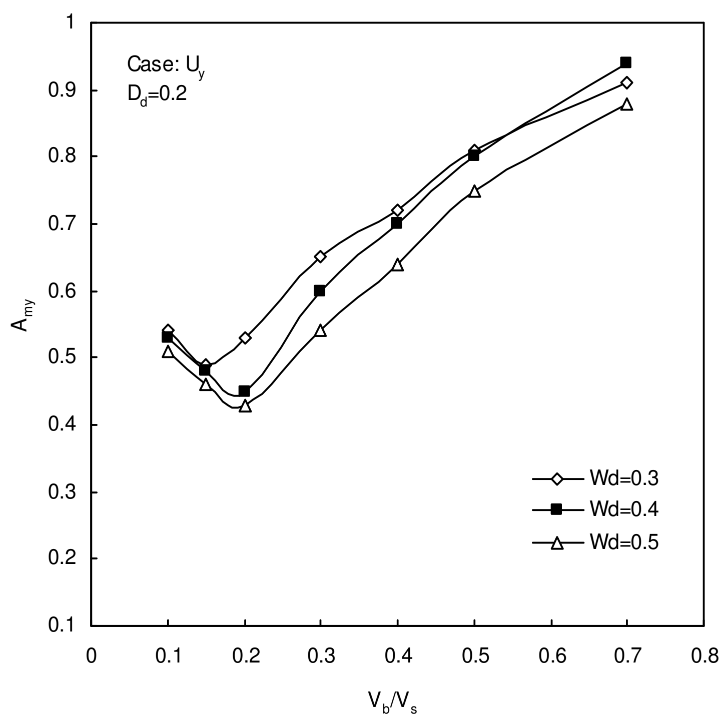

Figure 6.9(a): Variation of A_{my} against W_d and V_b/V_s (D_d=0.2)

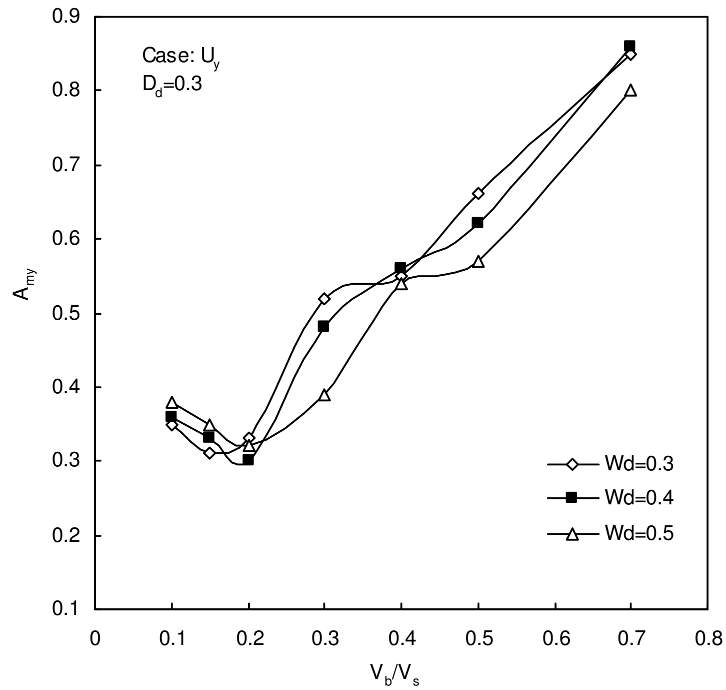

Figure 6.9(b): Variation of A_{my} against W_d and V_b/V_s (D_d=0.3)

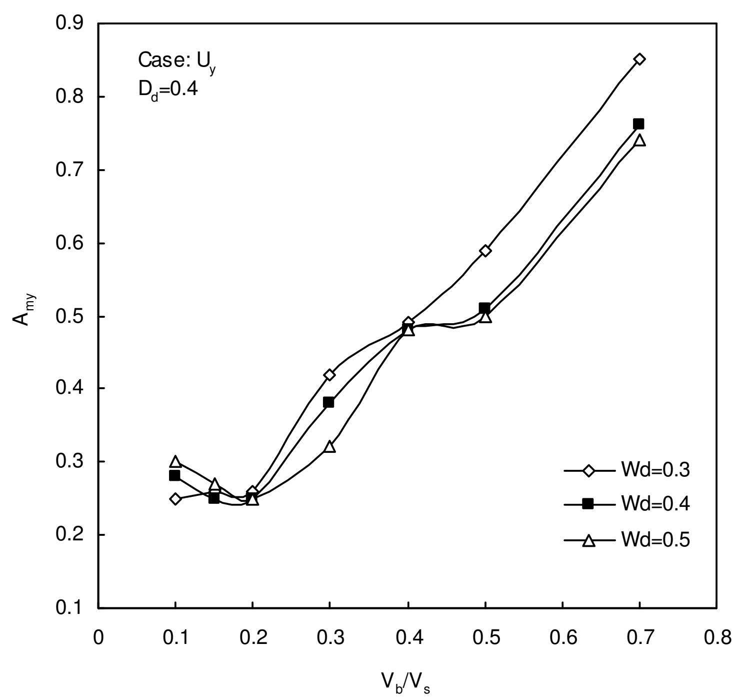

Figure 6.9(c): Variation of A_{my} against W_d and V_b/V_s (D_d=0.4)

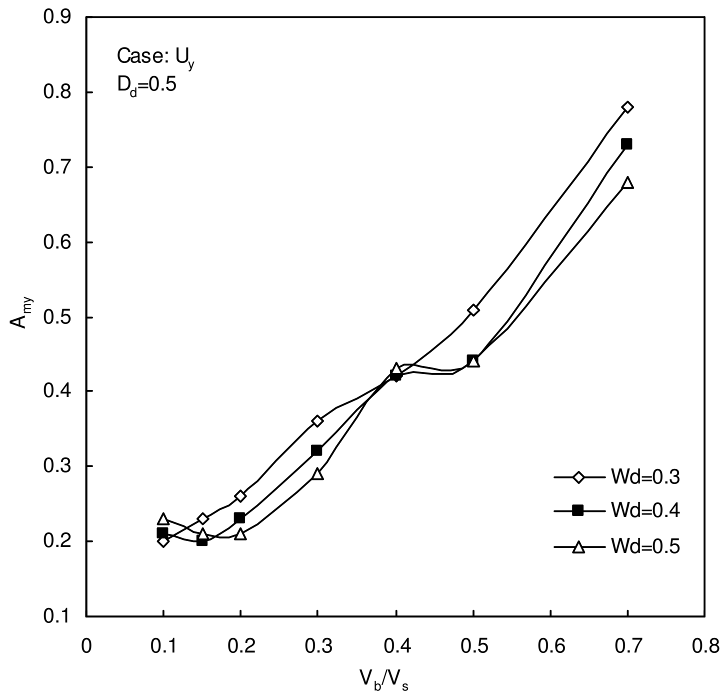

Figure 6.9(d): Variation of A_{my} against W_d and V_b/V_s (D_d=0.5)

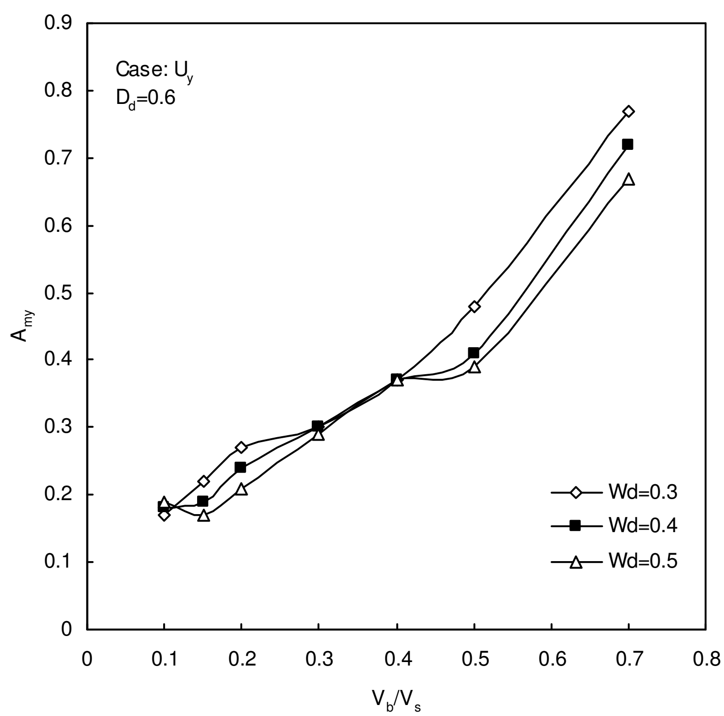

Figure 6.9(e): Variation of A_{my} against W_d and V_b/V_s (D_d=0.6)

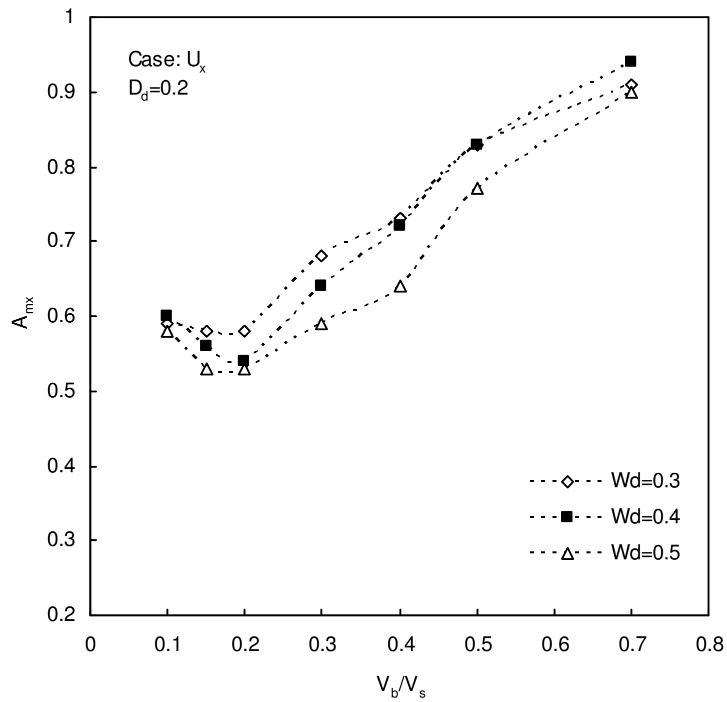

Figure 6.10(a): Variation of A_{mx} against W_d and V_b/V_s (D_d=0.2)

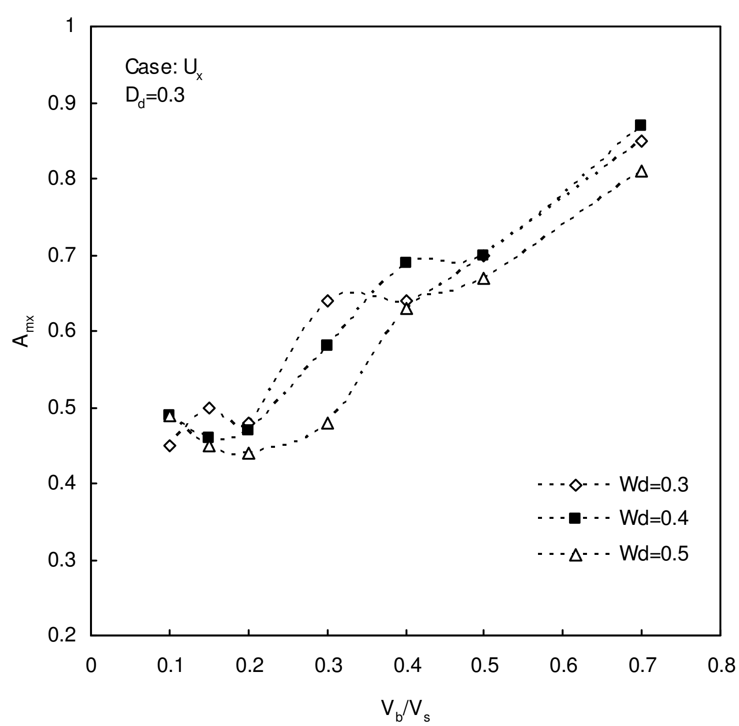

Figure 6.10(b): Variation of A_{mx} against W_d and V_b/V_s (D_d=0.3)

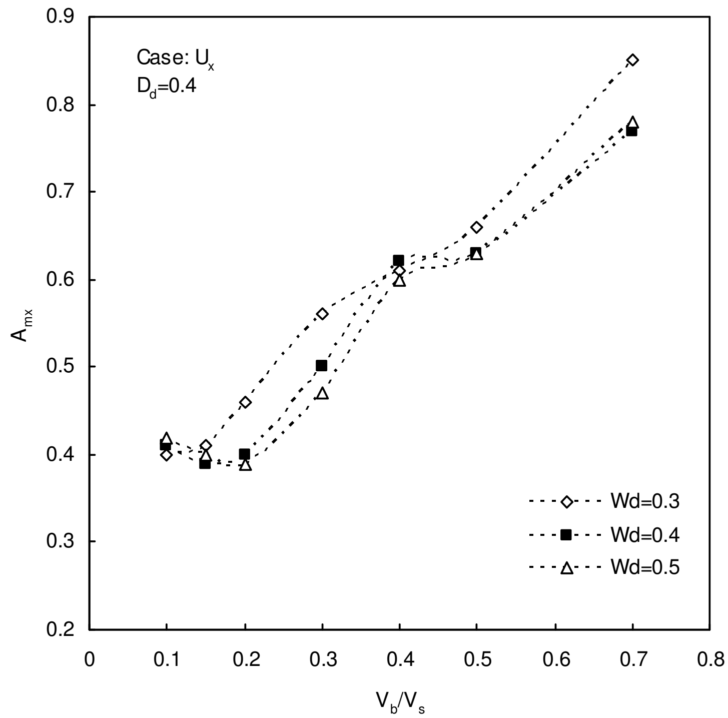

Figure 6.10(c): Variation of A_{mx} against W_d and V_b/V_s (D_d=0.4)

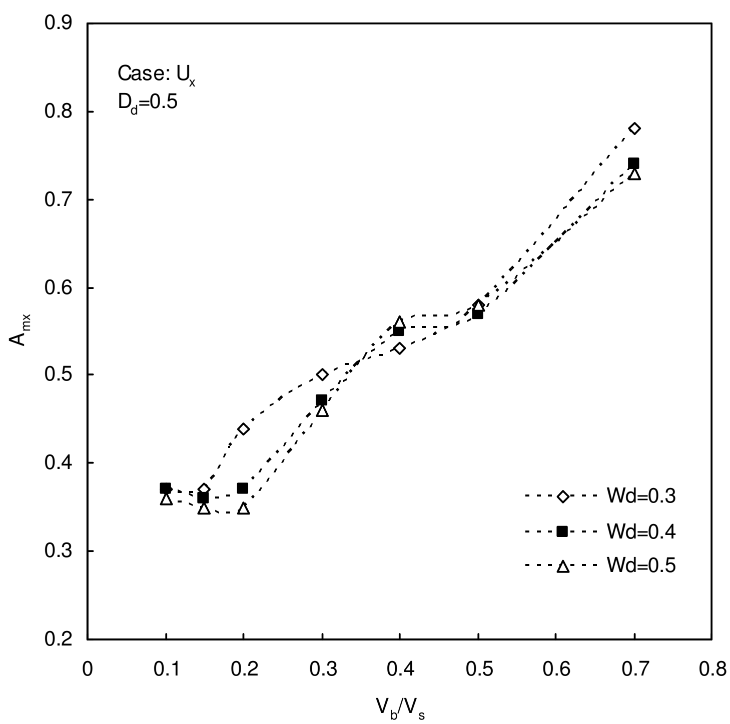

Figure 6.10(d): Variation of A_{mx} against W_d and V_b/V_s (D_d=0.5)

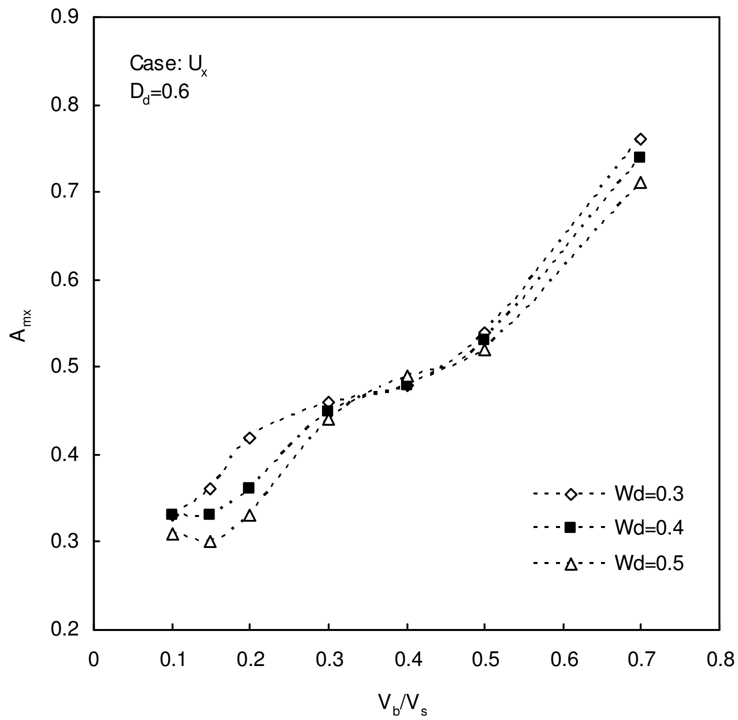

Figure 6.10(e): Variation of A_{mx} against W_d and V_b/V_s (D_d=0.6)

It is difficult to draw any firm conclusion regarding the effect of width of trenches on amplitude attenuation as average amplitude reduction factors (A_{my} and A_{mx}) do not exhibit any regular variation with trench widths (*W*). However, within the range of shear wave velocity ratio, V_b/V_s=0.1 to 0.2, effect of width is little which may practically be ignored. Effects of shear wave velocity ratio on A_{my} and A_{mx} are similar as explained in *Section 6.4.1*.

6.5. ISOLATION EFFECTIVENESS OF DUAL AND SINGLE TRENCH BARRIERS: A COMPARISON

A lateral objective of this study is to explore the feasibility of providing a barrier comprising of two trenches in succession as an alternative to an isolated trench. Provision of a single trench may not always be feasible a solution due to its unrealistic depth requirement, especially in longer surface wavelength cases. This is evident from the preceding sections that a dual trench barrier, open or in-filled, may be used as effective vibration isolation measures. However, it is highly essential to compare screening effectiveness of dual trench barriers over single trenches to justify their usefulness.

In order to compare screening effectiveness of dual open trenches with isolated open trenches, active and passive isolation cases (at location L=1 and 5) by an isolated open trench of width $0.2L_R$ and of varying depths (D=0.3, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.5) are instanced. The screening performance of a dual open trench barrier (each of width $0.2L_R$) is then compared with that of the single open trench of width $0.2L_R$ in *Figures 6.11(a)-6.11(b)*. Variations of A_{my} and A_{mx} are plotted against normalized depths (D_d) of trenches in case of dual trenches or normalized depth (D) of a single trench as appropriate.

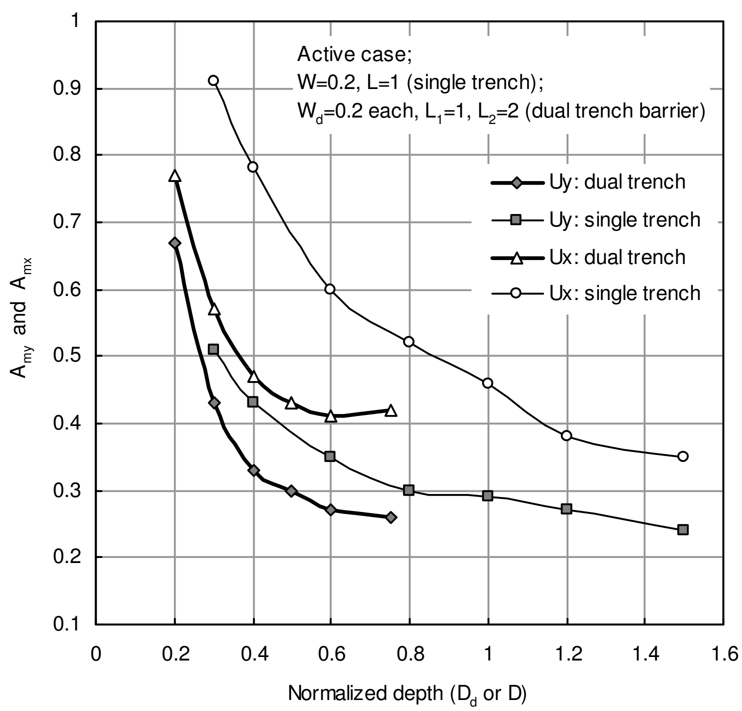

Figure 6.11(a): Dual and single open trench isolation in active case

It is obvious from *Figures 6.11(a)-6.11(b)* that a wave barrier comprising of a pair of open trenches requires much lesser depth than that of a single open trench in order to achieve a targeted degree of isolation. Referring to *Figure 6.11(b)* for illustration, a dual trench barrier, each trench of depth $0.5L_R$ can approximately screen off 80% vertical vibration and 62% horizontal vibration ($A_{my} \approx 0.2$, $A_{mx} \approx 0.38$) which would, otherwise, require a single trench of depth roughly $1L_R$. This fact indicates that a dual open trench barrier may be used as an effective isolation technique in circumstances where the provision of an isolated open trench is impractical because of depth constraint.

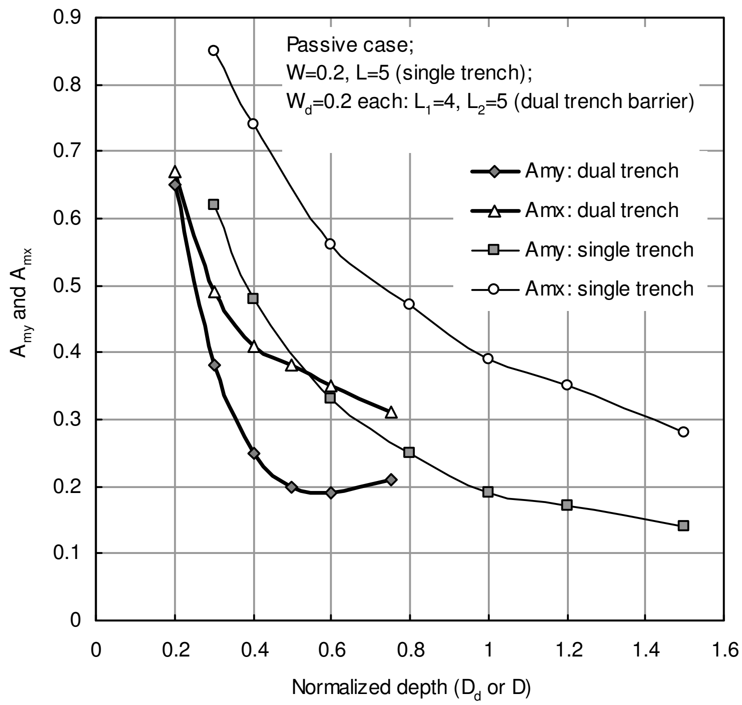

Figure 6.11(b): Dual and single open trench isolation in passive case

Similar comparisons can be made to justify the usefulness of dual in-filled trenches over single in-filled trenches. For this study, passive isolation (L=5) by an isolated in-filled trench against two specific cases of V_b/V_s=0.1 and 0.2 are referenced. The trench is considered to have varying depths (D=0.5, 0.75, 1.0, 1.25, and 1.5) and a constant width (W=0.3). Comparisons depicting screening performance of a dual in-filled trench barrier (each of width $0.3L_R$) for the chosen values of V_b/V_s over the single in-filled trench are presented in *Figures 6.12(a) and 6.12(b)*. These figures depict variations of A_{my} and A_{mx} against normalized depths (D_d) of each trench (in case of dual trench barrier) or normalized depth (D) of an isolated trench as applicable.

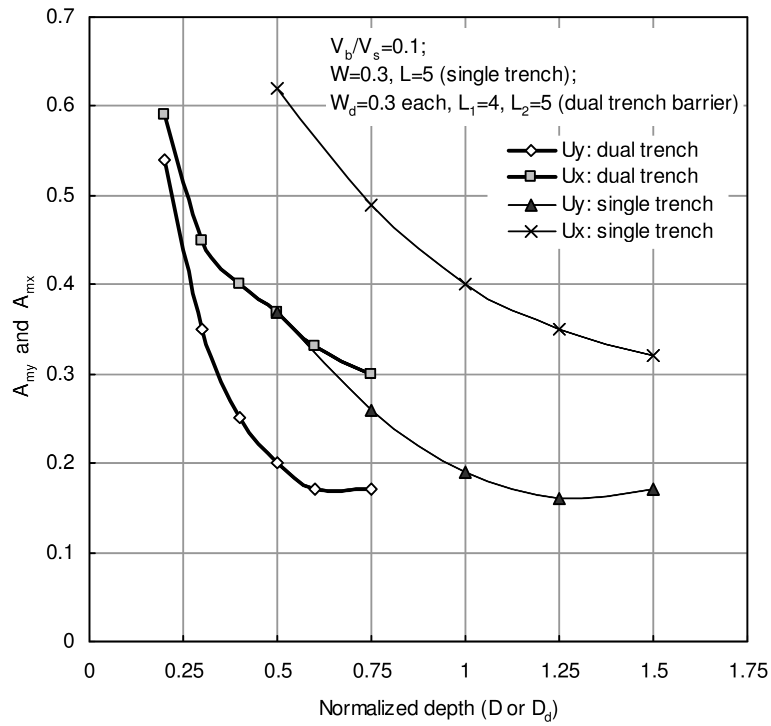

Figure 6.12(a): Dual and single in-filled trench isolation (V_b/V_s=0.1)

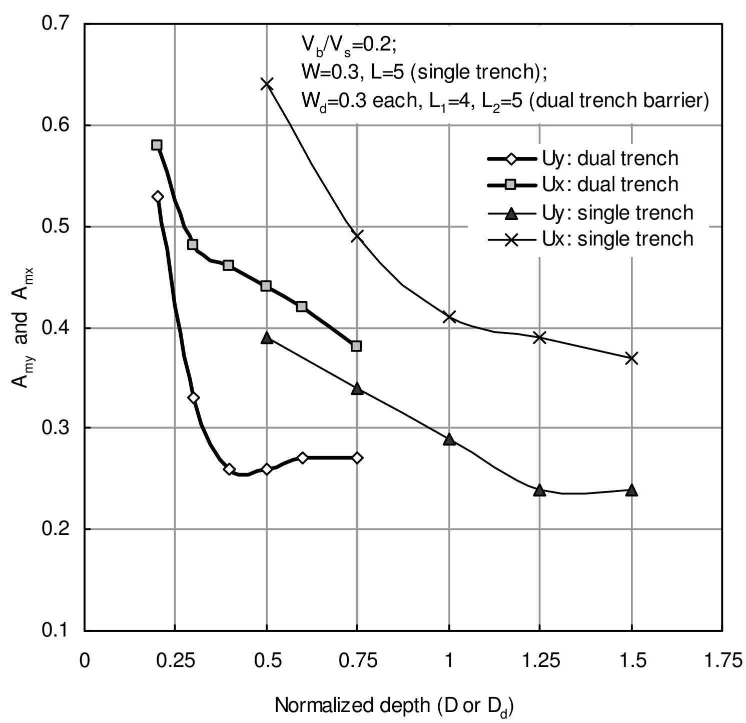

Figure 6.12(b): Dual and single in-filled trench isolation (V_b/V_s=0.2)

It can be seen from *Figures 6.12(a)* and *6.12(b)* that depth requirement by a dual in-filled trench barrier to achieve a certain degree of isolation is much less compared to isolated in-filled trenches. With reference to *Figure 6.12(a)* for instance, it is apparent that degree of isolation that can be achieved by a dual trench barrier, each trench of depth as low as $0.6L_R$ is nearly same to that of an isolated in-filled trench of depth nearly $1.25L_R$.

The comparative studies imply that dual trench barriers, open or in-filled, may be adopted as effective alternatives of isolated trenches in circumstances where provision of the latter is impractical or difficult.

6.6. SUMMARY

Screening effectiveness of a dual open trench barrier is lowest in active isolation case and increases by some extent with increase in barrier distance from source. However, from L_1=2 and L_2=3 onwards A_{my} remains practically unaffected. Horizontal vibration attenuation pattern is somewhat irregular; yet showing least isolation effect in active case. Such barriers are more effective in reducing vertical vibration than horizontal.

The screening performance increases with depth of trenches up to a depth of $0.5L_R$ to $0.6L_R$ and thereafter remains nearly unaltered or adversely affected (in some cases). In general, increase in trench widths has no favourable effect on barrier effectiveness. In order to achieve optimum efficiency, the widths of the trenches should be less; preferably between $0.2L_R$ to $0.3L_R$.

Screening effectiveness of dual in-filled (softer) trench barriers remains practically unaffected against barrier location. Barrier effectiveness significantly increases with decrease in backfill shear wave velocity ratio (V_b/V_s). However, there exists a limiting value of V_b/V_s below which further decrease of the same either adversely affects the barrier effectiveness or does not have any beneficial effect. The optimal value of V_b/V_s mostly lies within a range of 0.1 to 0.2. Dual in-filled trench barriers are found more effective in screening the vertical component of vibration than horizontal.

The geometric parameter that chiefly governs the isolation effectiveness is the depth of each trench. Within the optimum range of V_b/V_s, barrier efficiency consistently increases with depths up to $0.6L_R$. Further increase in depths shows little to no effect on amplitude reduction. No conclusion can be drawn regarding trench widths as amplitude reduction shows inconsistent variation with barrier widths. Nevertheless, within the range of shear wave velocity ratio 0.1 to 0.2, the effect of width is little which can be ignored from practical standpoint.

Usefulness of dual open/in-filled trench barriers over isolated open/in-filled trenches are justified with examples and found that their depth requirement is much less than isolated trenches to achieve a desired degree of isolation.

CHAPTER 7
SUMMARY AND CONCLUSIONS

An extensive numerical investigation is carried out in PLAXIS 2D on vibration isolation by four different barriers; open trench, in-filled trench, dual open trenches, and dual in-filled trenches in a 2-D context. Axisymmetric finite element models are used in the numerical computations. The half-space and backfill soils are assumed to be linear elastic, isotropic, and homogeneous. The half-space is subjected to a steady-state vertical excitation at the surface. Effects of barrier features are analyzed in terms of amplitude reduction of vertical and horizontal components of vibrations. The key results and crucial observations of this study are summarized in this chapter.

7.1. OPEN TRENCH BARRIERS

In case of open trenches, overall amplitude reduction factors of vertical and horizontal vibration components, A_{my} and A_{mx} are primarily governed by normalized depth of a trench with the former always being more affected. Irrespective of any location and width, A_{my} and A_{mx} decreases with increase in D; however, not in a linear fashion. On the other hand, width of an open trench is found to be a less significant parameter as compared to its depth.

Effects of normalized width on A_{my} and A_{mx} are case-specific. Increase in W up to 0.6 causes marginal decrease in A_{my}. The trend is somewhat more in passive cases. W=0.6 can be considered as an upper limit of normalized width beyond which further increase in W adversely affects A_{my} of shallow trenches ($D \leq 0.6$) for active isolation cases (L=1) in particular. In all other cases, increase in W beyond 0.6 does not have any appreciable effect on A_{my}. In general, the effect of width has little significance in vertical vibration screening. However, above conclusions are not applicable for the horizontal component of vibration. Increase in W results in a noticeable decrease in A_{mx} especially in active isolation cases. In passive cases, however, the effect is less significant. A_{mx} consistently decreases with normalized widths and therefore, no upper limit of W is observed in horizontal vibration cases.

In case of vertical vibration, deeper trenches ($D \geq 0.6$) provide better isolation effect (lower A_{my}) in passive cases, whereas trenches shallower than D=0.6 are more effective in active isolation cases. Variation in A_{my} with L mostly occurs up to L=2 and thereafter remains virtually constant. In case of horizontal vibration component, no conclusion can be drawn regarding the trench location as A_{mx} shows inconsistent variation with L. However, this can be concluded that variation of A_{mx} with L decreases for higher depths ($D \geq 1.0$). It is also observed that open trenches are more effective in screening vertical vibration component than horizontal.

The simplified design models are deduced based on best-fit curves drawn through the average data points in case of narrow open trenches in active and passive cases (L=1 and 5). The models are deduced for $W \leq 0.6$ except the expression of A_{mx} in active case which is limited to $W \leq 0.4$ because width, W shows a prominent effect in such cases. The regression models applicable to vertical vibration cases are found to be in close agreement with some published results. However, the models involving horizontal vibration component cannot be validated owing to the lack of published results. *Table 7.1* summarizes the simplified models and their applicability.

Table 7.1: Simplified design formulae and their applicability

Case	Vibration component	Trench location	Expression	Range of W
Active	Vertical	$L=1$	$A_{my}=0.28D^{-0.44}$	$W \leq 0.6$
Passive	Vertical	$L=5$	$A_{my}=0.18D^{-0.95}$	$W \leq 0.6$
Active	Horizontal	$L=1$	$A_{mx}=0.43D^{-0.59}$	$W \leq 0.4$
Passive	Horizontal	$L=5$	$A_{mx}=0.37D^{-0.71}$	$W \leq 0.6$

The expression involving A_{my} in passive case is applicable for $L \geq 2$, whereas the same for active case is solely applicable for L=1. This is so because variation of A_{my} mostly occurs up to L=2 and is almost negligible from L=2 onwards. In cases where L lies in between 1 and 2, one may use linear interpolation. For the set of expressions involving A_{mx}, it is difficult to make such recommendation as A_{my} does not exhibit any regular variation with L. If it is required to estimate A_{mx} for any intermediate value of L between 1 and 5, one may refer the dimensionless chart solutions presented in *Sections 4.4.1* and *4.4.2*.

This has to be noted that the simplified models give only approximate values of A_{my} and A_{mx} for a given value of D. This is because the models reflect only the average effect of width and do not take the effect of locations other than L=1 and 5 into account. In circumstances where the applications of these models are restricted, the dimensionless graphical solutions may be referred to.

7.2. IN-FILLED TRENCH BARRIERS

In the analysis of in-filled trench barriers, softer barriers (trenches filled in with softer backfill) are considered as such barriers are found to provide markedly better screening effectiveness than stiffer barriers.

It can be conceived that an open trench is a special case of an in-filled trench of $V_b/V_s \approx 0$. Vibration attenuation is caused only when the backfill is either softer or stiffer than the surrounding half-space. In order to achieve a good degree of isolation, the backfill shear wave velocity ratio, V_b/V_s should be around 0.3 or preferably less. It can also be concluded that in-filled trenches can isolate the vertical vibration component to a better extent than the horizontal.

The effect of barrier location on its screening effectiveness depends on the barrier depth and width and also on the component of vibration under consideration. In case of the vertical vibration component, deeper ($D \geq 0.75$) barriers are more effective in passive cases. However, variation in screening effectiveness from active to passive cases decreases as the trench width increases from W=0.3 to 0.5. The exceptions are the cases of shallow (D=0.5) trenches where variation of A_{my} is inconsistent with L and no firm conclusion can hence be made. In most of the observations, other than D=0.5, the screening effectiveness increases up to L=2 to 3 and thereafter remains virtually constant.

So far as the horizontal vibration component is concerned, better isolation effect is noted in passive cases when the trench is narrow (W=0.3). In these cases, amplitude reduction factor decreases with L, roughly up to 2 and remains constant thereafter. However, for wider trenches (W=0.5) the trend is highly irregular and such conclusions are difficult to make.

Increase in barrier depth not necessarily decreases A_{my}. To obtain optimum screening effect in vertical vibration case, a specific trench depth must be accompanied by a specific width and vice-versa. There exists a certain value of D/W at which a softer barrier provides optimum isolation efficiency irrespective of the cases whether active or passive. In most of the observations, this critical D/W value lies roughly within a range of 1.2 to 1.6. So far as the horizontal component is concerned, no such relationship exists between D and W. There is consistent decrease in A_{mx} with increase in either D or W. However, the effect of W is pronounced only in active cases and has little significance in passive cases. In all cases, irrespective of the component of vibration, W=0.8 can be considered as a limiting value of barrier width beyond which increasing the same has little to no effect on A_{my} and A_{mx}.

Non-dimensional charts are developed for designing such barriers in actual engineering practice. It is observed that an ideal backfill should have shear wave velocity within a range of 0.1 to 0.2 times of that of the surrounding soil to achieve optimum screening effect. The design charts are validated with some previously published results on wave isolation by softer barriers and good agreements is obtained.

7.3. DUAL OPEN TRENCH BARRIERS

The screening performance of a dual open trench barrier is lowest in active isolation case; i.e. when the barriers are located close to the source (at L_1=1 and L_2=2). Screening efficiency can be enhanced by placing the barriers some distances apart from the source. However, from L_1=2 and L_2=3 onwards the screening efficiency remains practically unaltered for vertical vibration case. Horizontal vibration attenuation pattern is somewhat irregular but it can still be concluded that the isolation effect is least when the barriers are placed close to the source. It is also evident that a pair of open trenches is more effective in reducing vertical vibration than horizontal.

The isolation efficiency of a dual open trench barrier is chiefly governed by the depths of each trench. The efficiency increases up to a depth of $0.5L_R$ to $0.6L_R$ and thereafter remains nearly unaltered. In fact, in some cases increase in depths beyond this is seen to have adverse effect on isolation effectiveness of the barrier. Increasing the trench widths not necessarily increases the screening effectiveness. For very shallow trenches (depths not exceeding $0.25L_R$) some benefit can be realized by increasing the widths of trenches. Nevertheless, to achieve a successful isolation the depths of the trenches must be greater than $0.25L_R$ for which increasing the trench widths adversely affects the isolation efficiency. It may, therefore, be concluded that increase in trench widths have virtually no beneficial effect on the screening efficiency of the barrier. In order to achieve optimum efficiency, the widths of the trenches should be less, preferably to be kept in between $0.2L_R$ to $0.3L_R$. The dimensionless charts presented in *Section 6.3.2* would serve as design guidelines in practical application of such barriers.

It has been justified with examples that a dual open trench barrier requires much lesser depth in comparison to isolated open trenches to achieve a targeted degree of isolation. This implies that a barrier comprising of two open trenches in succession may be adopted as effective alternatives of isolated trenches where provision of the latter is impractical or difficult due to excessive depth requirement.

7.4. DUAL IN-FILLED TRENCH BARRIERS

Distances of the trenches from source of excitation do not have any appreciable effect on isolation efficiency of the barrier. This implies that regardless of the trench locations, the amplitude reduction remains virtually unaffected.

The shear wave velocity of in-fill material of trenches with respect to the parent soil has significant effect on screening effectiveness of the barrier. Decrease in shear wave velocity ratio results in marked decrease in average amplitude reduction factors and vice-versa. However, there exists a certain limiting shear wave velocity ratio (V_b/V_s) below which further decrease of the same does not increase the screening effectiveness. Rather, barrier screening effectiveness is adversely affected to some extent with decrease in V_b/V_s beyond this limit, especially when the trenches are shallow. For trenches of depth less than or equal to $0.5L_R$, the optimum efficiency is observed for V_b/V_s within a range of 0.15 to 0.2. For trenches deeper than this depth, the optimum efficiency is achieved at V_b/V_s lying within 0.1 to 0.15. It may be concluded, in general that the backfill should have shear wave velocities within 0.1 to 0.2 times that of surrounding soil in order to achieve optimum screening effectiveness by the barrier. It is also evident that dual in-filled trench barriers are more effective in screening vertical component of vibration than the horizontal one.

The geometric parameter that primarily governs the isolation effect of a dual in-filled trench barrier is the depth of each trench. It is observed that within the optimum range of V_b/V_s specified above, barrier efficiency consistently increases with increase in depths up to $0.6L_R$. Further increase in trench depths beyond $0.6L_R$ does not result in an enhanced screening performance for vertical vibration case, in particular. For horizontal vibration cases, marginal increase in screening efficiency are still observed beyond a depth of $0.6L_R$. In all practical purposes, a depth of $0.6L_R$ may be considered as an upper limit of depth of each trench beyond which the screening efficiency either remains unaltered or marginally increases with further increase in trench depths. No conclusion can be drawn on the effect of trench widths on vibration attenuation as amplitude reduction shows inconsistent variation with barrier widths. Nevertheless, within the range of shear wave velocity ratio 0.1 to 0.2, the effect of width of trenches is little which can practically be ignored.

Similar to dual open trenches, the usefulness of dual in-filled trench barriers over isolated in-filled trenches are justified with examples and found that their depth requirement is much less than isolated in-filled trenches to achieve a desired degree of isolation.

7.5. GENERAL REMARK

Provision of isolated open or in-filled trench is restricted to cases involving high to medium frequency vibrations as it may require unrealistic depth in low frequency vibrations. In case of low frequency vibrations, dual trench barriers may be adopted as alternate isolation techniques as already discussed. However, the provision of such barriers should be viewed from the aspect of feasibility of construction. The frequency of excitation, elastic parameters of half-space and backfill (in case of in-filled trenches) must be determined prior to adopting an effective isolation measure.

For example, in order to adopt a suitable dimension to an open trench isolation scheme, the parameter required is the Rayleigh wavelength of vibration which in turn, requires the determination of frequency of source of excitation and elastic parameters of half-space. Knowing the Rayleigh wavelength of vibration, one can decide the dimension of an open trench required to achieve a desired degree of isolation based on the simplified regression models shown in *Section 4.4.3* or the design charts presented in *Sections 4.4.1* and *4.4.2*. If depth requirement is excessive, feasibility of providing dual open trench barriers may be looked at. For dual open trench barrier design, the non-dimensional charts incorporated in *Section 6.3.2* may be referred to.

In case of in-filled trenches, in addition to the Rayleigh wavelength of vibration, one must know the shear wave velocity of backfill to determine V_b/V_s. Hence the elastic parameters of backfill need to be determined apart from the frequency of excitation and half-space elastic parameters. Knowing the Rayleigh wavelength and V_b/V_s, the dimension required by the in-filled trench barrier to achieve a desired degree of isolation can be decided from the non-dimensional charts presented in *Section 5.3.4*. For the design of dual in-filled trenches, the charts presented in *Section 6.4.2* need to be referred to.

It is worth mentioning that in case of dual open trenches and isolated in-filled trenches, the design charts are formulated representing two cases, active and passive, considering L=1 and 5 respectively. For any intermediate value of L, both active and passive case may be looked at and whichever gives conservative estimate of overall amplitude reduction factors (A_{my} and A_{mx}) may be considered. The study is performed assuming a homogeneous half-space as there are numerous possibilities of sub-soil stratification and it is impractical to analyze all such cases. The conclusions regarding the selection of optimal parameters, design charts etc. would certainly provide some generalized guidelines from theoretical standpoint. However, in stratified deposits that are generally encountered in practice, the results may vary depending on the extent of sub-soil stratification.

This has to be noted that linear elastic material model is used in this work for analyzing both parent and backfill soil. Linear elastic assumption holds good for very small strain problems such as machine induced vibrations. In small or large strain problems, soil may exhibit elasto-plastic or completely plastic behaviour and present analyses may not be appropriate in such cases.

Unit weights of soil do not vary by a great extent and this study, therefore, assumes that the unit weights of parent and backfill soils of in-filled trenches are comparable. However, for low density materials (e.g. geofoam) this may not be the case. Accordingly, results of this study are limited only for soft soil barriers (e.g. bentonite) and not for geofoam barriers.

7.6. CONTRIBUTIONS

In the context of open trench isolation, the non-dimensional charts are significant findings where variation of amplitude reduction is shown against barrier cross-sectional features and its location in a manner more exhaustive than any of the previous studies. The investigation unfolds several unaddressed issues regarding the effects of barrier features on its screening effectiveness. The simplified design models incorporating all possible cases of open trench isolation are entirely new contributions to the field.

Concerning in-filled trench isolation, investigation regarding the effects of barrier features explores several new aspects of softer barrier isolation. Recommendations regarding the selection of optimal parameters are novel contributions which would be highly useful in practical application of such barriers. In addition, design charts are contributed in non-dimensional form which would provide a sound basis in designing such barriers in actual engineering practice.

Vibration isolation with a pair of open/in-filled trenches is entirely a new approach in the domain. Effects of different parameters on amplitude reduction are presented in the form of non-dimensional charts and recommendations are made for their optimal selection, which would provide valuable guidelines in practical application of such barriers. Dual trench barriers may prove to be an effective alternative in circumstances where provision of isolated trenches is impractical due to excessive depth requirement.

7.7. SCOPE OF FUTURE STUDY

This study explores some new areas of barrier isolation, particularly the use of dual trenches which would be highly effective in longer surface wavelengths cases. Investigations on vibration screening by a barrier comprising of an open and in-filled trench (two trenches in succession; one open and the other in-filled) may be viewed from future standpoint. Vibration isolation by a partially filled trench, which would give a combined effect of open and in-filled trench, may also be studied in continuation with this study. There is also a scope of investigating the effect of soil layering (under some ideal conditions) on barrier isolation effectiveness. A small-scale or full-scale experimental study may also be pursued as a future scope of this study.