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 \( \rho \), and Poisson’s ratio \( \nu \). 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>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>( E )</td>
<td>46,000 kN/m(^2)</td>
</tr>
<tr>
<td>Mass density</td>
<td>( \rho )</td>
<td>1800 kg/m(^3)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>( \nu )</td>
<td>0.25</td>
</tr>
<tr>
<td>Material damping</td>
<td>( \xi )</td>
<td>5%</td>
</tr>
</tbody>
</table>

The unit weight \( \gamma \) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus</td>
<td>( G = E/(2(1 + v)) )</td>
<td>18,400 kN/m²</td>
</tr>
<tr>
<td>Shear wave velocity</td>
<td>( V_s = \sqrt{G/\rho} )</td>
<td>101.1 m/s</td>
</tr>
<tr>
<td>Rayleigh wave velocity</td>
<td>( V_R = \left(\frac{0.87 + 1.12v}{1 + v}\right)V_s )</td>
<td>93.02 m/s</td>
</tr>
<tr>
<td>Rayleigh wavelength</td>
<td>( L_R = V_R/f )</td>
<td>3 m</td>
</tr>
</tbody>
</table>

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: \( d = D \cdot L_R \), \( w = W \cdot L_R \), and \( l = L \cdot L_R \). 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 × 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 10$L_R$ 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](image)

### 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 \( \sigma_n \) and shear stress \( \tau_s \) components absorbed by such dampers are given by:

\[
\begin{align*}
\sigma_n &= -C_1 \rho V_p u_x \\
\tau_s &= -C_2 \rho V_s u_y
\end{align*}
\]

Here, \( \rho \) is the material density; \( V_p \) and \( V_s \) denotes pressure wave and shear wave velocities; \( u_x \) and \( u_y \) 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, \( C_1=1 \) and \( C_2=0.25 \) 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 ($\alpha_\delta$ and $\beta_\delta$) 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 ($\Delta t$) 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 \( \times \) 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](image)

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).

![Convergence study to ensure adequacy of model depth (L_m=35 m)](image)

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

Models of dimension 35 m \(\times\) 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](image)

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.
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>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Range of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized depth</td>
<td>$D$</td>
<td>0.3, 0.4, 0.6, 1.0, and 1.5</td>
</tr>
<tr>
<td>Normalized width</td>
<td>$W$</td>
<td>0.2, 0.4, 0.6, and 0.8</td>
</tr>
<tr>
<td>Normalized distance from source</td>
<td>$L$</td>
<td>1, 2, 3, 4, and 5</td>
</tr>
</tbody>
</table>

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 $W$ ($D=0.3$)](image-url)
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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 $W$ ($D=0.6$)
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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 $D$ ($W=0.4$)
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 ($D\leq0.6$) 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 \( W=0.3 \). 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 $W$ ($D=0.4$)
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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 $D$ ($W=0.2$)
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).

![Graph](image)

**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 $D=1.0$, $W=0.3$. 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
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.