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 ($D\leq0.6$) 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>
<thead>
<tr>
<th>Case</th>
<th>Vibration component</th>
<th>Trench location</th>
<th>Expression</th>
<th>Range of (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>Vertical</td>
<td>(L = 1)</td>
<td>(A_{my} = 0.28D^{-0.44})</td>
<td>(W \leq 0.6)</td>
</tr>
<tr>
<td>Passive</td>
<td>Vertical</td>
<td>(L = 5)</td>
<td>(A_{my} = 0.18D^{-0.95})</td>
<td>(W \leq 0.6)</td>
</tr>
<tr>
<td>Active</td>
<td>Horizontal</td>
<td>(L = 1)</td>
<td>(A_{mx} = 0.43D^{-0.59})</td>
<td>(W \leq 0.4)</td>
</tr>
<tr>
<td>Passive</td>
<td>Horizontal</td>
<td>(L = 5)</td>
<td>(A_{mx} = 0.37D^{-0.71})</td>
<td>(W \leq 0.6)</td>
</tr>
</tbody>
</table>

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 $V_b/V_s=0$. 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 $L \approx 2$ 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.
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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.