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Analysis and design of open trench barriers in screening steady-state surface vibrations

Ankurjyoti Saikia† and Utpal Kumar Das‡

Department of Civil Engineering, Tezpur University, Tezpur, PIN-784028, Assam, India

Abstract: The problem of vibration isolation by rectangular open trenches in a plane strain context is numerically studied using a finite element code, PLAXIS. The soil media is assumed to be linear elastic, isotropic, and homogeneous subjected to a vertical harmonic load producing steady-state vibration. The present model is validated by comparing it with previously published works. The key geometrical features of a trench, i.e., its depth, width, and distance from the source of excitation, are normalized with respect to the Rayleigh wavelength. The attenuation of vertical and horizontal components of vibration is studied for various trench dimensions against trench locations varied from an active to a passive case. Results are depicted in non-dimensional forms and conclusions are drawn regarding the effects of geometrical parameters in attenuating vertical and horizontal vibration components. The screening efficiency is primarily governed by the normalized depth of the barrier. The effect of width has little significance except in some specific cases. Simplified regression models are developed to estimate average amplitude reduction factors. The models applicable to vertical vibration cases are found to be in excellent agreement with previously published results.

Keywords: finite element; open trench; vibration isolation; wave barrier; non-dimensional

1 Introduction

Ground vibrations induced by vibrating equipment, traffic, pile driving, blasting, etc. 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 the building, while becoming a source of continuous annoyance to the building occupants. Vibration energy propagates in a half-space in the form of body waves (compression and shear waves) and surface waves (Rayleigh waves). It was established that two-thirds of the total vibration energy is transmitted in the half-space in the form of Rayleigh waves (Miller and Pursey, 1955) that propagate exclusively along the surface. These waves are also characterized by much slower amplitude attenuation with distance than body waves. The fact that most of the input energy is transmitted away by Rayleigh waves exclusively along the surface and that it decays much more slowly with distance signify that the Rayleigh wave is of primary concern in vibration isolation problems. Vibration mitigation schemes are commonly known as vibration isolation or screening, which is accomplished by constructing barriers (open or in-filled trenches, sheet piles, solid or tubular piles, etc.) across the line of propagation of surface waves. Installing a wave barrier near the vibration source is known as active isolation, whereas in passive isolation, the barrier is located either at a location remote from the source or in the immediate vicinity of the structure to be protected.

Much research, both experimental and numerical, has been carried out in the last few decades to study the screening of ground-borne vibrations using wave barriers. The first experimental study on the performance of open and in-filled trenches as wave barriers was carried out by Barkan (1962). Woods (1968) conducted a series of field experiments on screening of surface waves by open trenches. Several numerical studies on the performance of wave barriers have been performed using the finite element method (FEM) and boundary element method (BEM). BEM studies of Beskos *et al*. (1986) and Dasgupta *et al*. (1990) on open and in-filled trenches in 2-D and 3-D homogeneous half-spaces are excellent examples of non-dimensional parametric studies. Subsequent BEM studies of Ahmad and Al-Hussaini (1991) on open and in-filled trenches in a 2-D half-space followed by Ahmad *et al*. (1996) on active isolation of machine foundations by open trenches in a 3-D context provide a better insight into the problem. The simplified model developed by Ahmad and Al-Hussaini (1991) for estimating screening effectiveness of open trenches is the only example of such models.

Correspondence to: Ankurjyoti Saikia, Department of Civil Engineering, Tezpur University, Tezpur, PIN-784028, Assam, India
Tel: +91-3712-275955
E-mail: asaikia@tezu.ernet.in
†Assistant Professor; ‡Associate Professor
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However, application of this model is limited to the case of vertical vibration isolation for a passive case. Klein *et al*. (1997) adopted 3-D BEM to study active isolation by open trenches and found reasonable agreement between numerical simulation and experimental data. Kattis *et al*. (1999a) studied vibration isolation by a row of piles replacing the pile row by an effective trench using 3-D BEM. In a continuation of this work, the screening effectiveness of pile wave barriers in contrast to open and in-filled trenches was also investigated in a 3-D context (Kattis *et al*., 1999b). Studies of Hung *et al*. (2004) on open trenches/in-filled trenches/wave impending blocks, Ju (2004) on open trenches/in-filled trenches/ground improvement methods in reducing train-induced ground vibrations, Adam and Estorff (2005) on open and filled trenches in reducing train-induced building vibrations, and Celebi and Schmid (2005) on surface vibrations induced by moving loads; differ in approaches and do not have any one-to-one relevance with this study. Hwang and Tu (2006) experimentally studied the effectiveness of several shallow open trenches in the context of ground vibration caused by dynamic compaction. Tsai and Chang (2009) investigated the effects of open trench sidings (with sheet piles and diaphragm walls on both sides of an open trench) on vibration screening effectiveness using 2-D BEM. This work, although, seems out of context, yet provides a basis of comparison since all the geometric features are made dimensionless with respect to the Rayleigh wavelength and few specific cases are studied without sidings. Ju and Li (2011) studied isolation effectiveness of open trenches filled with water using 3-D FEM. 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 specific case. Recently, Alzawi and El Naggar (2011) conducted a full-scale experimental study supported by 2-D FEM validation on open and geofoam filled trenches in scattering steady-state vibrations induced by machine foundations. Full-scale experimental study is certainly a more convincing approach but possesses some limitations, because the inherent problem of sub-soil stratification cannot be avoided and the number of cases to be investigated for such an extensive analysis is almost impractical to carry out with field experiments. 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).

Most of the previous works basically studied the isolation of vertical vibration component by open trenches; except the study of Yang and Hung (1997) on active isolation of train-induced vibrations by open and in-filled trenches, where a particular case of vertical and horizontal vibration screening was investigated at varying trench locations. This work, however, does not cover the 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. Current study reveals that horizontal components of vibration attenuate 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 important aspect is the location of the barrier with respect to the source of excitation. In many a such studies, effort is primarily made to study the effects of cross-sectional features of open trenches with respect to 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), a few cases by Beskos *et al*. (1986), and some 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 is not relevant in 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 present study shows that the effect of cross-sectional features of a trench and its efficiency depends on its location from the source of excitation. All the parameters of a trench participating in the wave screening process are normalized with respect to the Rayleigh wavelength of vibration in soil. The variations of amplitude attenuation with respect to the variations in trench geometry and location are presented in the form of non-dimensional design charts, which provide a sound basis to design such barriers. Simplified regression models are developed to estimate amplitude reduction in active and passive cases. Although many studies have been carried out in the recent past, the simplified model developed by Ahmad and Al-Hussaini (1991) is the only example of the solutions as already stated. The regression models applicable to vertical vibration shows excellent agreement with some previously published results, but due to the lack of results, models involving horizontal vibration components cannot be validated.

2 Problem definition and basic assumptions

The screening performance of open rectangular trenches excavated in a homogeneous half-space has been analyzed in this study under the conditions of plane strain. As pointed out by Cakir (2013), 2-D analysis may introduce potential errors since the radiation damping is grossly overestimated in a 2-D model of a 3-D case. Even so, 3-D cases are often reduced to 2-D problems, especially in wave barrier analyses. The plane strain assumption considers only 2-D wave propagation, neglecting the transverse component of vibration (i.e., a circular wave front rather than a spherical one). This assumption overestimates the wave propagation in the directions considered and thus may underestimate the efficiency of the trench (El Naggar and Chehab, 2005), thereby giving conservative results. This may compensate for the aforementioned effect of radiation damping overestimation. Andersen and Jones (2006) performed extensive 2-D and 3-D analyses using FEM and BEM and found that 2-D models provide results that are qualitatively comparable with those of 3-D models in a wide range of frequencies. Previous works of Beskos *et al*. (1986) and Dasgupta *et al*. (1990) for an active isolation case by open trench established that 2-D models give a conservative estimate over 3-D models with an error of 11.54%. In the recent study of Alzawi and El Naggar (2011), 2-D FEM is found to give conservative estimates of isolation effectiveness of open trenches with an average discrepancy of 14.29% compared to full-scale experimental results, which is quite acceptable. In view of the above, 2-D models are considered appropriate for the current study.

Using 2-D finite element models, an extensive analysis has been carried out to determine the effect of key geometrical features of the trenches in the interception of ground-borne vibrations. The geometric features that are considered variables in this analysis are: location of trench from the source of excitation (l), width (w), and depth (d). Axisymmetric models are used in the analysis as the problem is symmetrical about the centreline of the source of excitation. A vertically vibrating source of unit magnitude (P_0 = 1 kN) and frequency (f) of 31 Hz is assumed to act as a distributed load over a massless footing with a width of 1 m (0.5 m for an axisymmetric model). The foundation mass is ignored in the analysis because the isolation effect, and not the foundation response, is the aspect of interest of this work. Previous work by Beskos *et al*. (1986) state that the maximum difference between the isolation efficiencies of a barrier for zero and non-zero foundation masses is only 1.5%. A schematic of the problem of vibration isolation is shown in Fig. 1.

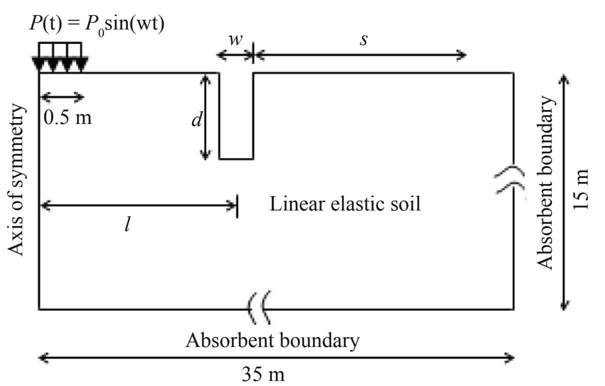

Fig. 1 Schematic of the problem of vibration isolation by an open trench

The half-space soil is considered to be linear elastic, isotropic, and homogeneous. A linear elastic soil is characterized by its elastic modulus (E), density (ρ), and Poisson's ratio (ν). Unless otherwise specified, the elastic modulus, density, and Poisson's ratio are assumed as 46,000 kN/m^2, 1,800 Kg/m^3, and 0.25, respectively. The material damping (ξ) of the soil is assumed to be 5%. The magnitude of the source of excitation (P_0), its frequency (f), and the material parameters of soil are chosen in accordance with previously published literature of Yang and Hung (1997). Using the present data, the shear modulus (G), shear wave velocity (V_S), Rayleigh wave velocity (V_R), and Rayleigh wavelength (L_R) can be calculated as shown in Table 1.

To avoid dependency on source frequency and elastic parameters of soil, the geometric parameters are normalized with respect to the Rayleigh wavelength. The screening effect of wave barriers are evaluated in terms of amplitude reduction factor (A_R) defined by Woods (1968) as;

$$A_R = \frac{\text{Displacement amplitude of ground surface with barrier}}{\text{Displacement amplitude of ground surface without barrier}} \tag{1}$$

The amplitude reduction factors are calculated in terms of vertical and horizontal components of surface displacements. Accordingly, the calculation steps of vertical and horizontal amplitude reduction factors are essentially same; except one considers the vertical component, while the other considers the horizontal component of surface displacements with and without barrier. The amplitude reduction factor is not uniform over a range (s). The effectiveness of an isolation system is, therefore, expressed in terms of average amplitude reduction factor (A_m) by numerically integrating the amplitude reduction factors obtained at various distances from the source (x) over the range of investigation. The amplitude reduction factor can also be calculated in terms of horizontal and vertical velocities. Obviously, a smaller value of A_m indicates that a better isolation effect has been achieved by the barrier.

$$A_m = \frac{1}{s}\int_0^s A_R(x)\mathrm{d}x \tag{2}$$

Table 1 Calculation of relevant soil parameters

Parameter	Formula	Value
Shear modulus	$G = E/2(1+\nu)$	18400 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

The amplitude reduction factors are calculated beyond the barrier and up to a distance of $10L_R$ (30 m) at intervals of $0.5L_R$. The average amplitude reduction factors are obtained using Eq. (2).

3 Finite element model and validation

The problem is simulated in PLAXIS using a 2-D axisymmetric model with fifteen nodded triangular mesh elements. The model dimension is kept as 35 m × 15 m. The appropriate model dimension required for this study is decided on the basis of convergence studies. Standard fixities are assigned to the model boundaries. Special boundary conditions have to be defined to account for the fact that in reality, the soil is a semi-infinite medium. Without special boundary conditions, the waves will be reflected at the model boundaries, causing perturbations. To avoid spurious reflections, absorbent boundary conditions are specified at the bottom and right side boundaries. The absorbent boundary conditions in PLAXIS use Lysmer and Kuhlemeyer (1969) dampers. The wave absorption on the absorbent boundaries is improved by introducing wave relaxation coefficients C_1 and C_2. The coefficient C_1 improves the wave dissipation in a direction normal to the boundary and C_2 does in the tangential direction. In the present analysis, PLAXIS default values C_1 = 1 and C_2 = 0.25 are used. Research findings show that C_1 = 1 and C_2 = 0.25 results in reasonable wave absorption at the boundaries (Brinkgreve and Vermeer, 1998). A typical finite element model is shown in Fig. 2. The length of the model is kept somewhat higher than the crucial zone of screening (30 m). Although special measures are adopted to avoid spurious reflections, there is always a chance of small influence and it is a good practice to keep the model boundaries away from the region of interest.

A harmonic load of magnitude 1 kN/m and frequency of 31 Hz is considered to act over a width of 0.5 m to simulate the source of excitation. A linear elastic material model is used in the analysis with the parameters already explained. The material type is considered as drained. Material damping of 5% is introduced into the soil by assigning Rayleigh $\alpha = 0.9$ and $\beta = 0.000488$ to satisfy the relationship, $\alpha + \beta\omega^2 = 2\xi\omega$ between these two parameters with angular frequency of excitation (ω) and material damping (ξ). The mesh discretization is done with very fine elements. Local refinements are done along the surface and around the edges of the trenches and load to ensure higher accuracy. The time interval (Δt) for dynamic analysis is taken as 0.5 s, which is sufficient to permit the complete passage of dynamic perturbations in the zone of investigation. The input vibration completes fifteen and half cycles of sinusoidal motion within the time interval chosen. The default values of additional steps (n) and dynamic sub-steps (m) are 250 and 4 respectively, for which the time-step of integration ($\delta t = \Delta t / mn$) is 0.0005 s. The peak displacement amplitudes are calculated from displacement-time histories at selected nodes in both vertical and horizontal directions. The ratio of peak displacement amplitudes with and without barrier at a certain point gives the amplitude reduction factor at that point.

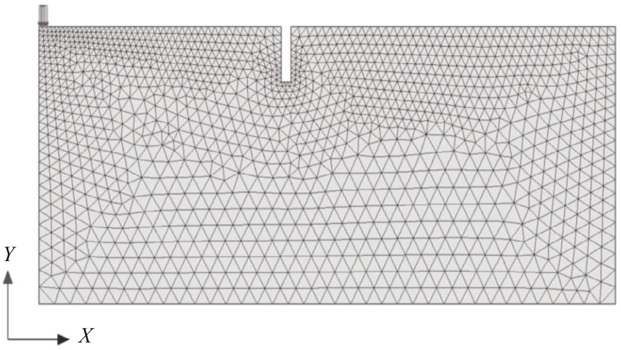

Fig. 2 Typical FEM model

Few previous studies on vibration screening by wave barriers indicate that the crucial zone that needs screening lies within a distance of $10L_R$ from the source (Ahmad *et al*., 1996; Al Naggar and Chehab, 2005; Yang and Hung, 1997). In the present analysis, L_R = 3 m and therefore, the length of this crucial zone amounts to 30 m. However, the distance of the right model boundary from the source should be somewhat greater to avoid any possibility of undue reflection despite the fact that an absorbent boundary condition is assigned. In order to decide a suitable overall length of the model, a convergence study is carried out taking trial lengths as 35 m, 40 m, and 50 m. A trial model depth (H) is taken to be $5L_R$ = 15 m for all these analyses. An undisturbed half-space (without barrier) with the assumed soil parameters is subjected to a steady-state harmonic disturbance of magnitude and frequency as stated earlier. The amplitudes of vertical and horizontal components surface displacements are plotted against normalized distances from the source ($X = x/L_R$) as shown in Fig. 3. Here, x denotes the absolute distance of a point from the source and X is its dimensionless distance (normalized with respect to the Rayleigh wavelength of vibration in soil) from the source. For example, normalized distance X = 2 implies that actual distance of the point from source (x) is $2L_R$, which is equal to 6 m in this study. It is observed that the displacement amplitudes for these three cases show convergence. Therefore, the right side model boundary is kept at a distance of 35 m from the source for all subsequent analyses. After deciding the model length, a convergence study is further carried out to determine the suitable depth of the model with depth, $H = 5L_R$, $6L_R$, $8L_R$, and $10L_R$. The variations of vertical and horizontal components of surface displacement against normalized distances from the source up to a distance of $10L_R$ for these four cases are found to be identical and exactly similar plots as shown in Fig. 3 are obtained (hence, they are not included

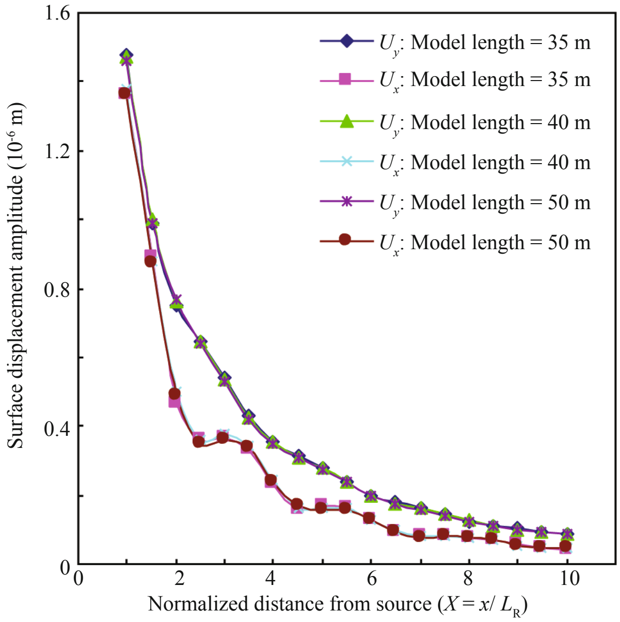

Fig. 3 Convergence study to determine model length

in this study). A model of dimension 35 m × 15 m is, therefore, considered adequate for all subsequent studies. It is apparent that the displacement amplitudes at a distance of $10L_R$ are negligible and will be reduced further until the right side boundary is reached; if a small portion of it undergoes reflection, although not likely; it is not expected to cause any problem of interference. If this were the case, the study undertaken to determine the model length would not have shown convergence. This also justifies the use of absorbent boundaries and the wave relaxation coefficients introduced provide sufficient wave absorption at the boundaries. Contour maps showing vertical and horizontal components of displacements are presented in Figs. 4(a) and 4(b) for a particular case of isolation by an open trench of depth $1L_R$ and width $0.2L_R$ located at a distance of $5L_R$ from the source.

In order to validate the model, a 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 subjected to a harmonic excitation is taken as a reference. The plot of vertical vibration amplitude reduction factors versus normalized distance from the source ($X = x/L_R$) obtained in this study are compared with previous works of Ahmad and Al-Hussaini (1991) and Di Mino *et al*. (2009) and found to be in close agreement. A schematic representation of the comparative study is shown in Fig. 5. With reference to this example, one can have a clear understanding of how the average amplitude reduction factors are being calculated. It is simply the weighted average of all amplitude reduction factors over the zone of investigation (the distance beyond the barrier and within $10L_R$ from source).

4 Parametric study

The parameters that govern the isolation efficiency of an open trench barrier are its depth (d), width (w), and distance (l) from the source of excitation. These parameters are expressed as functions of Rayleigh wavelength (L_R) as: $d = DL_R$, $w = WL_R$ and $l = LL_R$, where D, W, L are dimensionless multipliers and are termed as normalized depth, width, and distance of trench from source, respectively. The average amplitude reduction factors for vertical and horizontal vibrations (A_{my} and A_{mx}) are calculated for various trench dimensions, i.e., D = 0.3, 0.4, 0.6, 1.0, 1.5 and W = 0.2, 0.4, 0.6, 0.8 at trench locations varied from active (L = 1) to passive cases (L = 5). The results of this parametric study along with the simplified models are presented in non-dimensional graphical forms in Figs. 6(a) to 6(e), 7(a) to 7(c), and 8(a) to 8(d), which are discussed in the following subsections. 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 of L = 1 or close. Active isolation primarily represents screening of body waves, which are predominant near the source. Whereas in passive

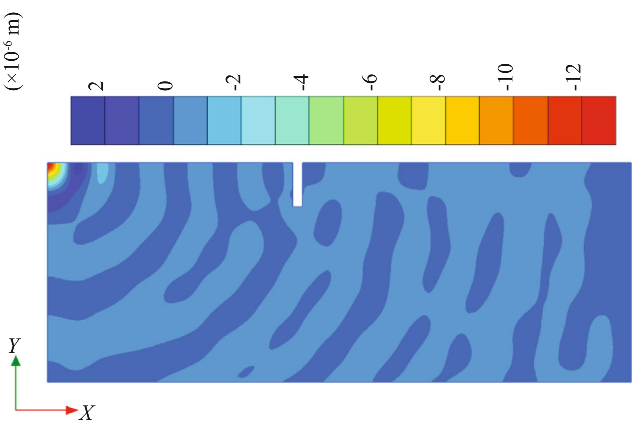

Fig. 4(a) Contour map showing vertical displacement component

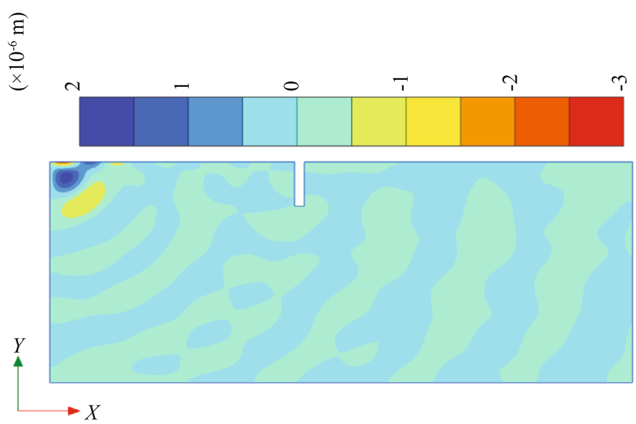

Fig. 4(b) Contour map showing horizontal displacement component

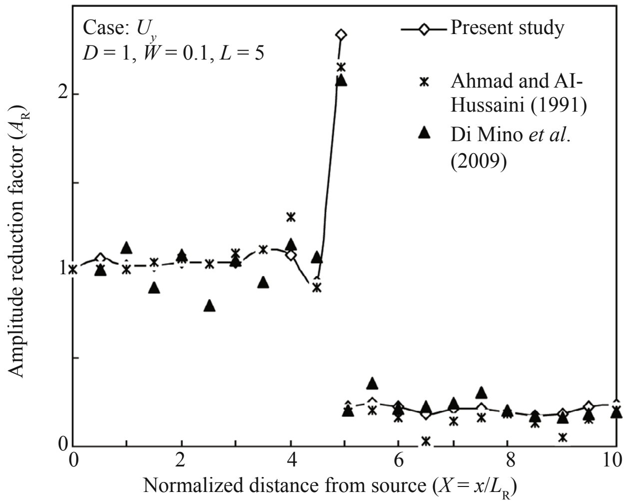

Fig. 5 Comparative study on vibration isolation by open trenches

case, the incident waves principally consist of Rayleigh waves. Dasgupta *et al*. (1990) investigated a passive isolation case for $L = 2$. A subsequent study of Yung and Hung (1997) indicates that from $L \geq 2$, the influence of the body wave decreases and the surface wave starts predominating body waves. However, several previous works considered $L = 5$ as the true passive isolation cases (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 represents a true picture of the effects of geometric features of the barrier on vibration screening with respect to a particular case. The variation of amplitude reduction factors against trench locations and widths for some specific depths are shown in Figs. 6(a) to 6(e). The variation of the same versus barrier locations and depths for a few constant widths are depicted in Figs. 7(a) to 7(c). The vertical and horizontal vibration cases are denoted by U_y and U_x, respectively, and the meaning of the other notations has already been explained.

4.1 Vertical vibration

As can be seen from Figs. 6(a) to 6(e) and Figs. 7(a) to 7(c), it is the normalized depth of an open trench that primarily governs the amplitude reduction factor for vertical vibration (A_{my}), with its normalized width a secondary parameter. For example, it is apparent from Fig. 7(a) that A_{my} for a trench of normalized width, $W = 0.2$ in the 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. On the other hand, Fig. 6(a) clearly 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, and therefore results in a better isolation. However, A_{my} is not directly proportional to the trench depth.

A_{my} decreases marginally as the normalized widths of open trenches increases. The effect of normalized width is somewhat more in cases where the trench is located far-off from the source, i.e., passive cases ($L = 5$). However, too large a width ($W > 0.6$) adversely affects the screening efficiency of shallow trenches ($D \leq 0.6$) for active isolation cases ($L = 1$) in particular. The adverse effect of wider trenches diminishes with its depth and distance from the source of excitation. This is because as the trench is located close to the source, body waves play a more important role than surface waves. A trench of shallow depth ($D \leq 0.6$) close 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, provide 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 over body waves. This is the reason why adverse effects of wider trenches are negligible 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 and the rapid decrease of surface waves as they travel down a wider trench. However, irrespective of all locations and depths, $W = 0.6$ 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 unaffected (passive cases).

An open trench of normalized depth 0.6 or larger gives the lowest A_{my} for passive cases. This is in accordance with Yang and Hung (1997), in which the variation in A_{my} was studied against varying trench locations (from $L = 1$ to $L = 5$) for an open trench of dimensions $D = 1.0$ and $W \approx 0.3$. Nevertheless, the same is not applicable 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, refer Fig. 7(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 the same width gives $A_{my} = 0.29$ and 0.19 at $L = 1$ and 5, respectively, showing a diminishing trend.

4.2 Horizontal vibration

It is quite evident that irrespective of all locations and widths, A_{mx} decreases as the normalized trench depth increases. It can be seen from Figs. 7(a) to 7(c), where the variations of A_{my} and A_{mx} against L and D are shown for a few specific widths.

In most of the observations, an increase in normalized width results in a noted decrease in A_{mx}, with the trend being more pronounced for active isolation cases. For example, from Fig. 6(a) it is evident that A_{mx} drops from approximately 0.9 to 0.63 as W increases from 0.2 to 0.8 at barrier location $L = 1$. An increase in normalized

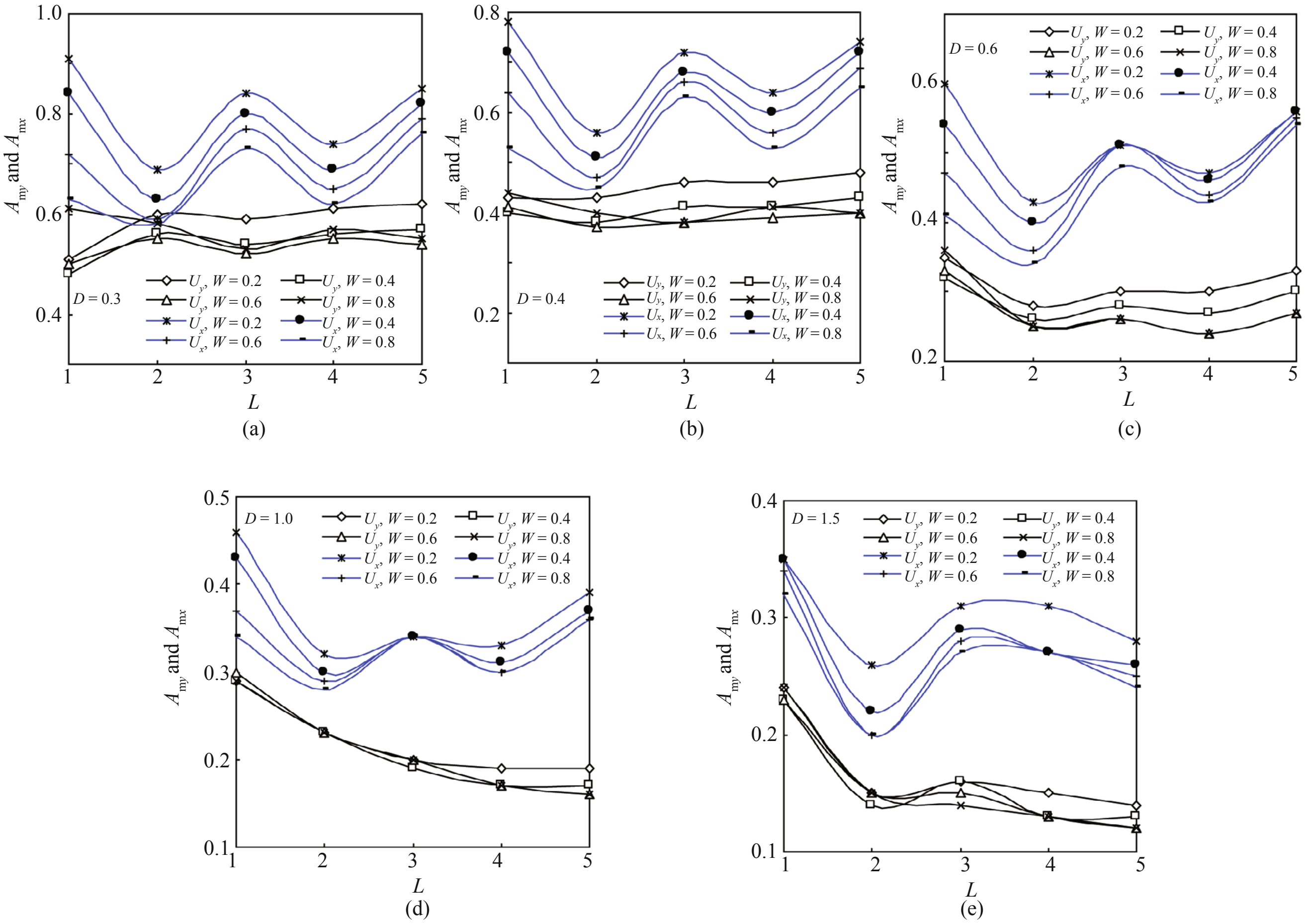

Fig. 6 Variation of A_{my} and A_{mx} versus normalized location and width

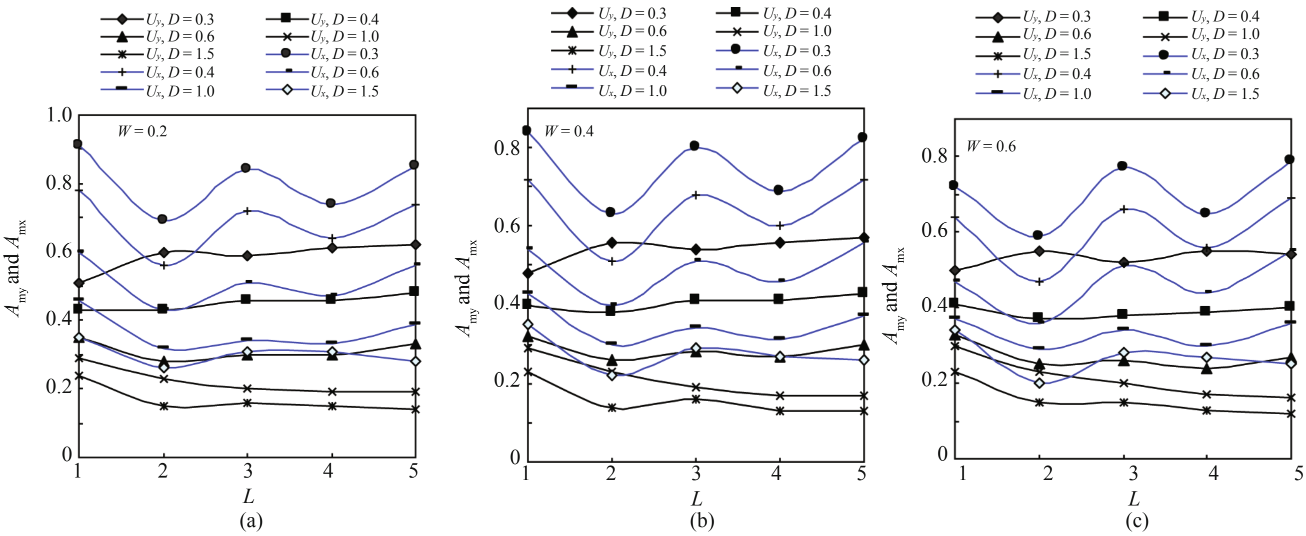

Fig. 7 Variation of A_{my} and A_{mx} versus normalized location and depth

width causes a consistent decrease in A_{mx} and hence, no upper limit of W is observed for horizontal vibration.

No generalized conclusion can be drawn regarding the trench location, as A_{mx} varies with the normalized distance of trench (L) in an irregular pattern.

It can also be concluded that open trench barriers are more effective in isolating the vertical vibration component than the horizontal. As illustrated in Fig. 6(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, which implies that it is capable of reducing 71% of the vertical vibration compared to 54% of the horizontal vibration. This is because an open trench reflects the vertical component of vibration into the half-space and not the horizontal. The horizontal component, therefore, does not participate much 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 as the normalized widths increase, but A_{my} is adversely affected in some specific cases.

4.3 Simplified design formulae

In order to develop simplified design expressions, the variations of A_{my} and A_{mx} against normalized depths and widths are sorted out for two distinct locations; i.e., active (L = 1) and passive (L = 5). In addition to the previous normalized depths, D = 0.8 and 1.2 cases have also been studied at these two locations. As noted earlier, the normalized depth (D) is the primary parameter and normalized width (W) has little significance on the screening effectiveness of open trenches. The vertical vibration isolation 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 for the horizontal amplitude reduction factor (A_{mx}) in an active case (L = 1) is developed for trenches of $W \leq 0.4$ because, in this case, the increase in W has a prominent effect on A_{mx}. The simplified models are shown in Figs. 8(a) to 8(d). The simplified formulae and their applicability are discussed in Table 2. Although the regression models are developed for two particular barrier locations, L = 1 and L = 5, indicating active and passive cases, respectively, the expressions involving A_{my} are still applicable for L within this range. As can be seen from Figs. 7(a) to 7(c), average vertical amplitude reduction factors (A_{my}) show marginal variation with barrier locations from L = 2 onwards in most of the observations. This implies that the expression deduced for A_{my} in the passive case holds for barrier locations $L \geq 2$. But the expression involving A_{my} in the active case is exclusively applicable for L = 1. When L is between 1 and 2, linear interpolation may be used. As far as the horizontal component is concerned, it is difficult to make such recommendations because the variation of A_{mx} with L is irregular by a considerable

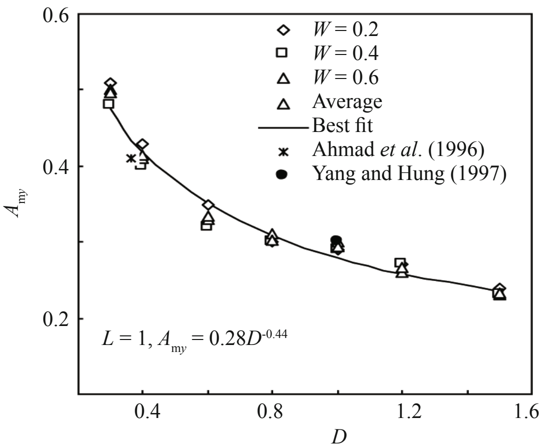

Fig. 8(a) Simplified model for estimating A_{my} in active case

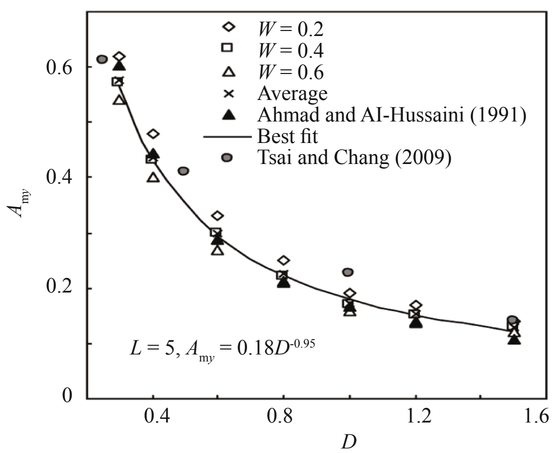

Fig. 8(b) Simplified model for estimating A_{my} in passive case

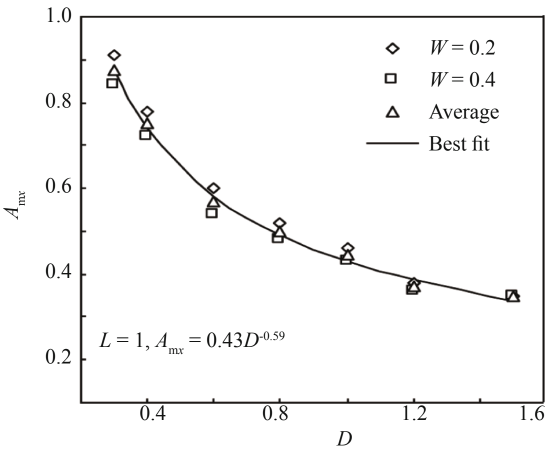

Fig. 8(c) Simplified model for estimating A_{mx} in active case

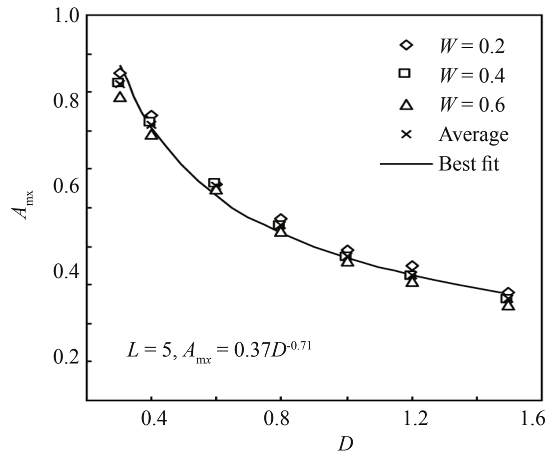

Fig. 8(d) Simplified model for estimating A_{mx} in passive case

Table 2 Simplified design formulae and their applicability

Case	Vibration component	Trench location	Formulae	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	$L = 5$	$A_{mx} = 0.37D^{-0.71}$	$W \leq 0.6$

margin. If these cases are encountered, the dimensionless chart solutions presented in Figs. 6(a) to 6(e) and Figs. 7(a) to 7(c) can be consulted.

The model developed for the vertical vibration amplitude reduction factor in the active case (L = 1) is compared with earlier works 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 using a trench of D = 1.0, $W \approx$ 0.3. The present and previous results are found to be in good agreement as depicted in Fig. 8(a).

The simplified model developed to estimate A_{my} in passive case (L = 5) for narrow ($W \leq$ 0.6) open trenches shows close agreement with the previously developed model of Ahmad and Al-Hussaini (1991) and a few results obtained by Tsai and Chang (2009) for an open trench of varying depths and a specific width, W = 0.2 in passive case as shown in Fig. 8(b). Due to a lack of previous results, the simplified design formulae developed for horizontal vibration cases cannot be validated.

5 Conclusions

An extensive numerical study is carried out to study the effects of different geometric features of open rectangular trenches and their effectiveness in reducing vertical and horizontal vibrations in a homogeneous half-space under the conditions of plane strain. The important observations of this study can be summarized as follows.

A_{my} and A_{mx} are primarily governed by the normalized depth of an open trench with the former always being more affected. Irrespective of any location and width, A_{my} and A_{mx} decrease as D increases; however, not in a linear fashion.

The effect of normalized width on A_{my} is case specific. An increase in W up to 0.6 causes a marginal decrease in A_{my}. The trend is somewhat greater in passive cases. W = 0.6 can be considered as an upper limit of normalized width beyond which a further increase in W adversely affects A_{my} of shallow trenches ($D \leq$ 0.6) for active isolation cases (L = 1) in particular. For all other cases, an increase in W beyond 0.6 does not have any beneficial effect on A_{my}. In general, the effect of normalized width has little significance in attenuating vertical vibrations and can be ignored in all practical cases. However, these conclusions are not applicable for horizontal vibration cases. An increase in W results in a noted decrease in A_{mx}, especially in active isolation cases. A_{mx} consistently decreases with normalized widths and therefore, no upper limit of W is observed in the horizontal vibration cases.

In case of vertical vibration, deeper trenches ($D \geq$ 0.6) provide a better isolation effect (lower A_{my}) in passive cases, whereas trenches shallower than D = 0.6 are more effective in active isolation cases. For horizontal vibration, no conclusion can be drawn regarding the trench location as the variation of A_{mx} with L is irregular. It is also observed that open trenches are more effective in screening the vertical vibration component than horizontal.

The simplified design formulae and their applicability are thoroughly discussed. The models applicable to vertical vibration cases are in close agreement with previously published results but those for the horizontal vibration cases could not be validated due to a lack of such results. In circumstances where the applications of these models are restricted, the dimensionless graphical solutions presented in Section 4 may be referenced.

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