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Finite element study on vibration isolation using dual open trench barriers

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ABSTRACT: *The vibration screening effectiveness of an isolation scheme comprised of a pair of open rectangular trenches of identical cross-sections is numerically investigated in this work. The finite element study is carried out in PLAXIS 2D under plane-strain conditions on a linear elastic, isotropic, and homogeneous half-space subjected to a vertical harmonic excitation. The response of the dual trench barrier in intercepting vertical and horizontal components of vibrations is studied with respect to the variations in its geometric features. The geometric features; i.e. the distances of the trenches from the source, their depths, and widths are made dimensionless by normalizing with respect to the Rayleigh wavelength of vibration. The effects of barrier depths and widths are investigated for active and passive cases separately and results are depicted in non-dimensional forms. The effects of these features and their significance in reducing ground-borne vibrations are discussed and few guidelines are made regarding their optimal selections. Comparison of results obtained with present finite element scheme shows close agreement with published results which justifies its accuracy. A dual trench barrier may be adopted as an effective alternative to a single trench as it requires lesser depth than the latter.*

Keywords – *Vibration isolation, dual trench, open trench, finite element, half-space*

1. INTRODUCTION

Ground vibration induced by traffic, vibrating equipments, construction activities etc. sometimes needs to be screened as it may cause malfunctioning of high-precision instruments, annoyance, and damage of structure and sub-structure in extreme circumstances. Ground-borne vibration propagates in the form of body waves and surface waves (Rayleigh waves). The problem is often handled by constructing barriers across the line of propagation of surface waves as nearly two-thirds of the total vibration energy is transmitted in the form of Rayleigh waves that too within a narrow zone close to the ground surface [1]. Open or in-filled trenches, solid or tubular piles, sheet piles etc. are examples of such barriers. In active isolation scheme the barrier is placed close to the source; whereas in passive case barrier is placed either apart from the source or in proximity of the structure/site to be protected.

Several numerical and experimental studies have been carried out after the experimental study of Woods [1] on screening of surface waves by open trenches. Beskos et al. [2] and Dasgupta et al. [3] conducted two-dimensional (2-D) and three-dimensional (3-D) boundary element studies on vibration isolation using open and in-filled trenches. Simplified models for designing open and in-filled trenches developed by Ahmad and Al-Hussaini [4] and active isolation using open trenches by Ahmad et al. [5] in a 3-D scenario are subsequent contributions. Yang and Hung [6] developed a finite/infinite element scheme to study isolation effectiveness of open/in-filled trenches and elastic foundations in reducing ground vibrations caused by the passage of trains. Few more literatures on isolation of train-induced vibrations are Hung et al. [7] using open/in-filled trenches and wave impeding blocks; Ju [8] using open/in-filled trenches and ground improvement methods; Di Mino et al. [9] using open trenches respectively. Klein et al. [10] adopted a 3-D boundary element code to study the screening effect of open trenches. Adam and Estorff [11] employed coupled boundary element and finite element algorithm to study the attenuation of train-induced building vibrations using open trenches. Alzawi and El Naggar [12] performed full-scale experimental study on open and geofoam filled trenches supported by 2-D finite element approach. The scopes of all these previous works are limited to the study of vibration isolation by single trenches (open or in-filled) except the investigation of Hwang and Tu [13] on the screening performance of several shallow open trenches. The use of single trench is may not be always a feasible solution as it requires unrealistic depth in longer wavelength cases. If the depth of a trench is too large, provision of such a barrier may be difficult or impractical and possesses side wall instability problem too.

In view of the above, the effectiveness of a barrier comprising of a pair of open trenches (having identical cross-sections) is investigated in this study. The response of the barrier in intercepting vertical and horizontal components of vibration is investigated with respect to the variations of its key geometric parameters. In order to perform a dimensionless study, the geometric parameters are normalized with respect the Rayleigh wavelength of vibration. The effect of barrier location, depths, and widths are depicted in the form of non-dimensional design charts. The effect of these parameters and their significance in wave screening process are discussed and few recommendations are made on optimal selection of these parameters. It is observed that a barrier comprised of two open trenches in succession needs lesser depth than a single trench to achieve a certain degree of isolation. This implies that such an isolation scheme can be adopted as an alternative to a single trench in some circumstances where the provision of the latter is difficult or impractical.

2. METHODOLOGY

The problem is studied in a 2-D half-space using a finite element tool, PLAXIS 2D. In vibration isolation studies in particular, realistic 3-D cases are often simplified to 2-D problems as the latter is simpler yet provide results qualitatively comparable to 3-D models [14] and full-scale experiments [12]. 2-D analysis is hence considered suitable for the current study. The geometric features that are treated as variables are; locations of the trenches from the source of excitation (l_1 and l_2), depths (d_d) and widths (w_d). A schematic of the isolation scheme is depicted in Fig. 2.

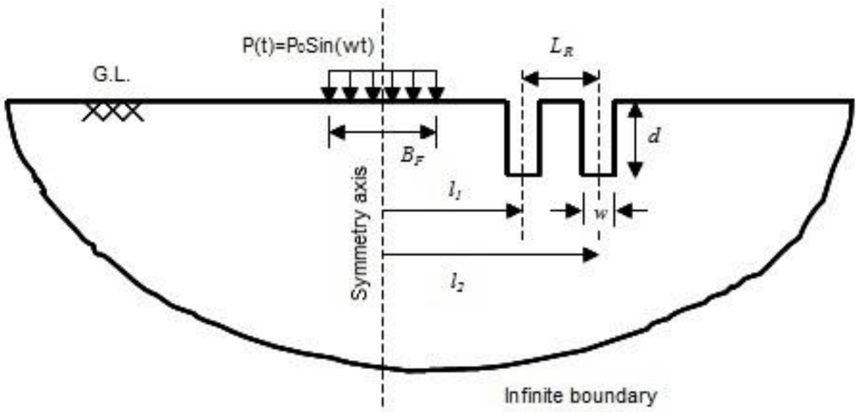

Figure 1: 2-D schematic of the vibration isolation scheme on an elastic half-space

The elastic modulus (E), density (ρ), and poisson's ratio (ν) of the linear elastic half-space are assumed to be 46000 kN/m^2, 1800 Kg/m^3, and 0.25 with material damping (ξ) as 5%. A steady-state harmonic load of unit magnitude (P_0=1 kN) and frequency (f) 31 Hz is assumed to act as distributed load over an imaginary footing of width (B_F) of 1 m. The source magnitude, its frequency, and elastic parameters of the half-space are assumed in accordance with Yang and Hung [6]. For the parameters chosen, the shear wave velocity (V_s), Rayleigh wave velocity (V_R), and Rayleigh wavelength (L_R=V_R/f) of vibration in soil are respectively 101.1 m/s, 93.02 m/s, and 3 m. The geometric parameters are normalized with respect to the Rayleigh wavelength (L_R) in order to avoid dependency on the source frequency and elastic parameters of soil. The screening effect of the barrier is measured in terms of amplitude reduction factor (A_R) defined by Woods [1]. The amplitude reduction factor (A_R) is not uniform over a range of investigation (s). It is, therefore, logical to express the degree of isolation in terms of average amplitude reduction factor (A_m). Lesser the value of A_m better is the screening effect and vice-versa.

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

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

2.1 Finite Element Scheme

The problem is analyzed using 2-D axisymmetric models of dimension 35 m $\times$ 15 m with fifteen nodded triangular mesh elements. Horizontal fixities (u_x=0) are assigned to the symmetry edge and the rightmost boundary of the model. The bottom boundary is restrained in both vertical and horizontal directions by applying total fixities (u_x=u_y=0). To account for the fact that soil is semi-infinite medium, special boundary conditions need to be imposed on the rightmost and bottom boundaries. Without special boundary conditions the waves will be reflected at the model boundaries, causing interference. Absorbent boundary conditions are accordingly assigned to the bottom and right hand side boundaries to avoid spurious reflections. A typical finite element model showing dimensions and boundary conditions etc. is depicted in Fig. 2.

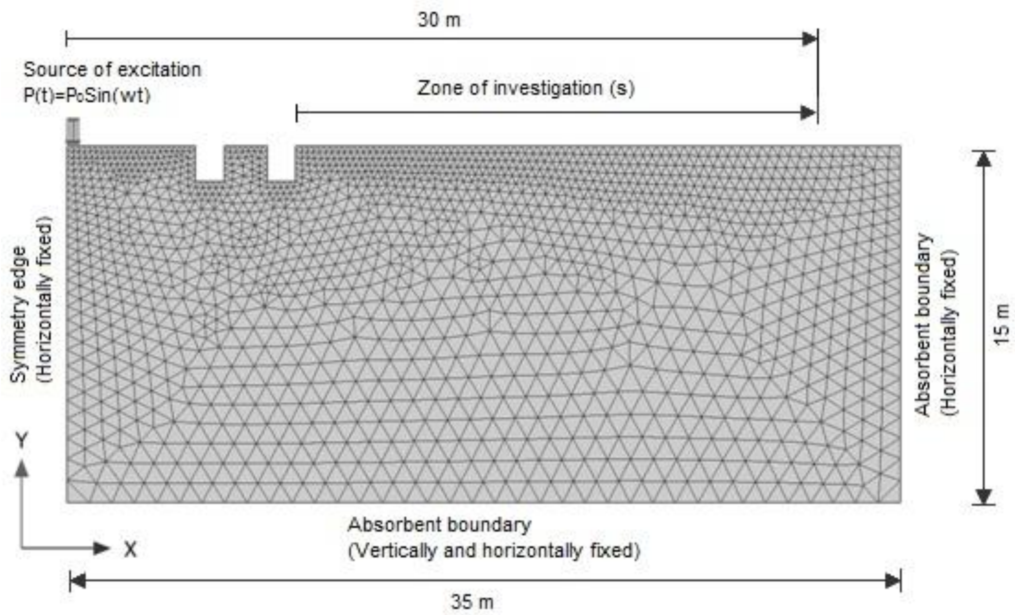

Figure 2: A typical finite element model

The absorbent boundary conditions in PLAXIS employ dampers given by Lysmer and Kuhlmeyer [15]. The normal and shear stress components absorbed by such dampers are expressed as; $\sigma_n = -C_1\rho V_p \dot{u}_x$ and $\tau_n = -C_2\rho V_s \dot{u}_y$. Here, ρ is the material density; V_p and V_s denotes the velocity of pressure wave and that of shear wave respectively; $\dot{u}_x$ and $\dot{u}_y$ are the particle velocities in the normal and tangential directions (*x* and *y* directions as shown in Fig. 2) respectively. C_1 and C_2 are the wave relaxation coefficients introduced to improve the wave absorption at boundaries. The coefficient C_1 improves the wave absorption in a direction normal to the boundary and C_2 does in the tangential direction. Past literatures indicate that C_1=1 and C_2=0.25 provides reasonable absorption of waves at boundaries [16, 17]. In the present analysis, the wave relaxation coefficients are, therefore, taken as C_1=1, and C_2=0.25. A vertically vibrating steady-state harmonic load of magnitude 1 kN/m and frequency 31 Hz is considered to act over a width of 0.5 m; i.e. half the width of the imaginary footing ($B_F/2$) as axisymmetric models are used. Linear elastic material model is used in the analysis with the previously stated parameters. The material type is considered as drained. Material damping of 5% is assigned to the soil by adapting Rayleigh mass and stiffness matrix coefficients (α and β) according to the applied frequency of excitation. The finite element model is discretized with extremely finer elements with local refinements along the surface and around the edges of the trenches. The use of local refinement tool divides the mesh elements to an extent further, thereby ensuring high precision. The dynamic analyses are performed choosing a time interval (Δt) of 0.5 sec. which is sufficient to allow the complete passage of dynamic disturbance in the zone of investigation. The time-step of integration (δt) is taken to be 0.0005 sec. Review of past studies [6, 18] reveals that a zone extending to $10L_R$ from the source is adequate enough for such analyses to be performed. In this particular study, this crucial zone amounts to 30 m. The right hand side boundary is, however, placed at a distance somewhat more (35 m) to eliminate any possibility of interference despite of assigning absorbent boundary conditions. The adequacy of the model dimension is further ensured by conducting convergence studies.

3. PARAMETRIC STUDY AND RESULTS

The parameters governing the isolation efficiency of the barrier are the depths (d_d) and widths (w_d) of each trench and their distances (l_1 and l_2) from the source of excitation. 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 the normalized distances of the first and second trench from the source respectively.

3.1 Effect of Barrier Location

In order to investigate the effect of barrier locations, the trench pairs are placed at varying distances from the source of excitation and the average amplitude reduction factors are calculated at each location as shown in Fig. 3. The distance between the trenches is, however, kept constant as $1L_R$ for this study (refer Fig. 1). The depths and widths of each trench are taken as $0.5L_R$ and $0.2L_R$. The term U_x and U_y are used to denote horizontal and vertical components of vibration whereas A_{mx} and A_{my} refer the average amplitude reduction factors in the respective directions. The variation 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. This can be seen from Fig. 3, the isolation efficiency is worst when the trenches are located close to the source; i.e. at $L_1=1$ and $L_2=2$. This implies that the 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 the source. From $L_1=2$ and $L_2=3$ onwards the screening efficiency remains practically unaltered for vertical vibration case. For horizontal vibration case, however, such conclusions are difficult to make as the amplitude attenuation pattern is somewhat irregular. When the trenches are located close to the source, the body waves play a more important role than the surface waves. A significant portion of body waves can still pass through below the trenches which subsequently converts into surface waves; thereby making the screening effect less significant. On the other hand, passive scheme is more effective due to smaller influence of body waves at larger distances. The results also demonstrate that dual trench barriers can isolate vertical vibration more effectively than horizontal.

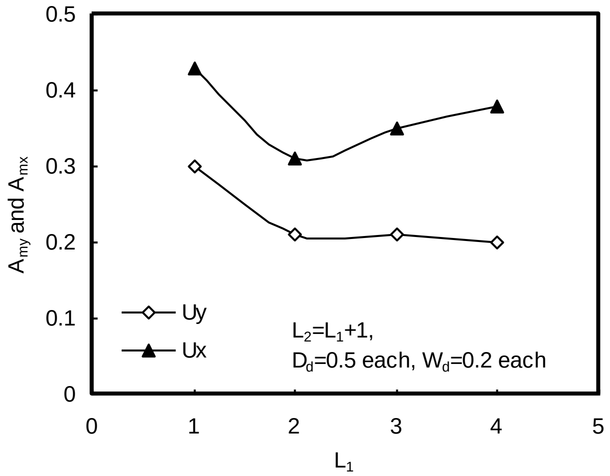

Figure 3: Effect of location of trenches

3.2 Effect of Width and Depth of Trenches

The effect of normalized widths and depths of trenches is studied for two distinct cases; active and passive case. In active case (barrier close to the source) trench locations are taken as L_1=1 and L_2=2; whereas in passive case (barrier placed apart from source) 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) of each trench are taken to be 0.2, 0.3, 0.4, and 0.5. The effects of normalized depths and widths in attenuating vertical and horizontal vibrations in active and passive cases are depicted in Fig. 4(a)-4(b) and Fig. 5(a)-5(b) respectively.

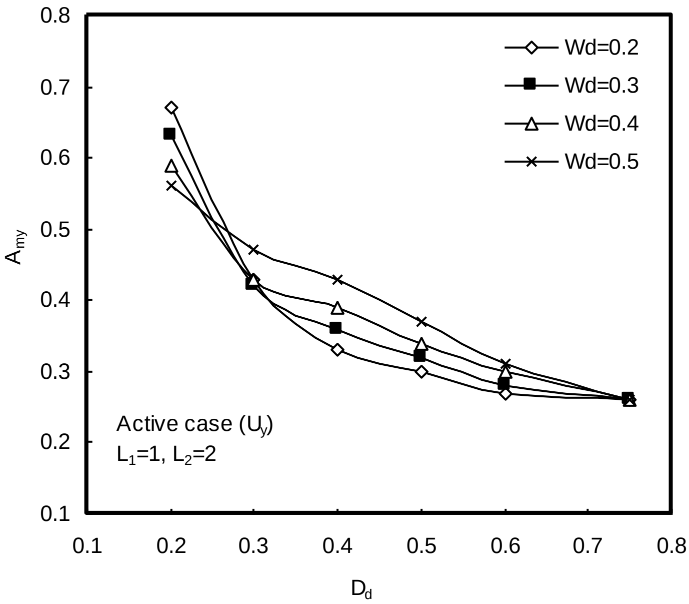

Figure 4(a): Effect of depth and width of trenches on reducing vertical vibration (active case)

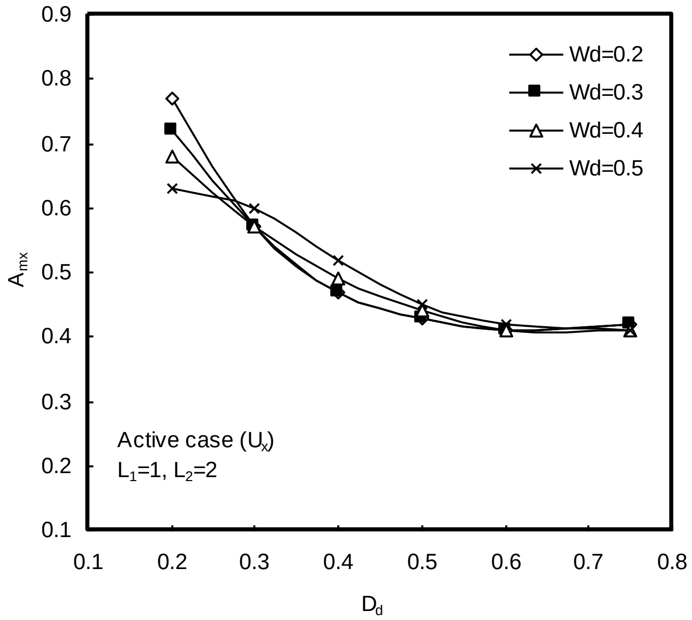

Figure 4(b): Effect of depth and width of trenches on reducing horizontal vibration (active case)

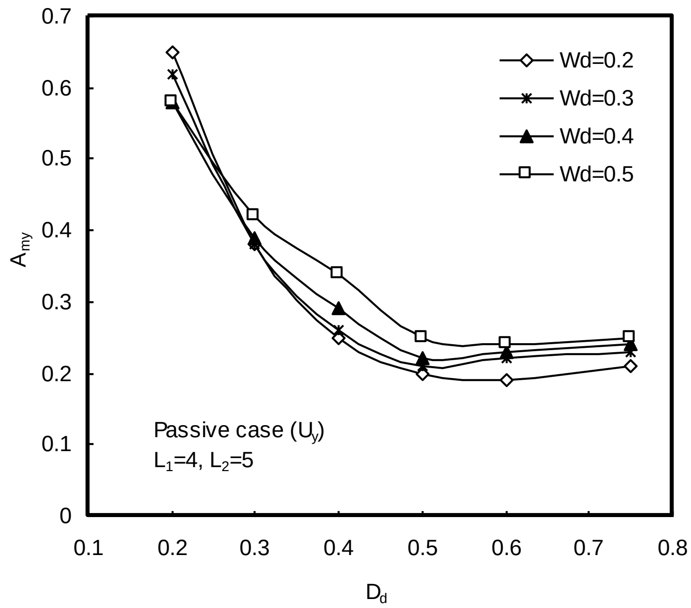

Figure 5(a): Effect of depth and width of trenches on reducing vertical vibration (passive case)

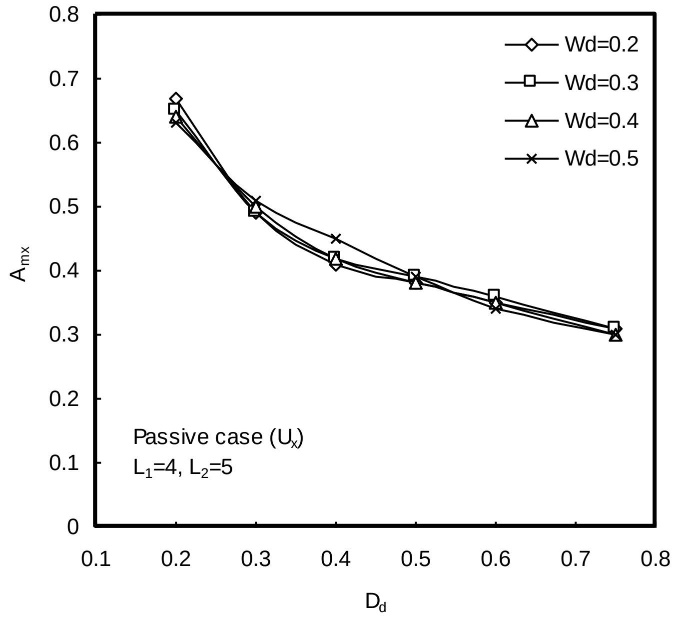

Figure 5(b): Effect of depth and width of trenches on reducing horizontal vibration (passive case)

It is apparent from Fig. 4(a)-4(b) and Fig. 5(a)-5(b), the vertical vibration component attenuates with increase in normalized 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 case, increase in depths beyond this is observed to have 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 a dual open trench barrier.

Similar conclusions can be made on the effects of widths and depths in reducing the horizontal component of vibration. 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. It can be seen from Fig. 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 so the upper limit of depth of each trench can be considered as $0.6L_R$ for all practical aspects. The adverse effect of increased width is less pronounced for horizontal vibration case. In either case, increase in trench widths has virtually no beneficial role on the screening effectiveness of the barrier.

4. DISCUSSION

The objective of this study is to explore the feasibility of providing a barrier comprising of two open trenches in succession as an alternative to an isolated trench. Provision of a single trench may not always be feasible due to unrealistic depth it requires especially in longer surface wavelength cases. This is evident from the preceding sections that a dual open trench barrier may be used in vibration isolation schemes as an alternative to a single open trench barrier. It is, therefore, essential to compare the screening effectiveness of a dual trench barrier with that of a single trench. For this comparative study, a passive isolation case (at location *L*=5) by a single open trench of width $0.2L_R$ is investigated for varying depths (*D*=0.3, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.5). The notations; *L*, *D*, and *W* used here refer to the location, depth, and width of the trench, normalized with respect to the Rayleigh wavelength (as done in case of dual trenches). The isolation efficiencies are evaluated in terms of average amplitude reduction factors for vertical and horizontal components of vibration in a way similar to dual open trenches. The screening performance of a dual trench barrier (each of width $0.2L_R$) is then compared with that of the single open trench of width $0.2L_R$ in Fig. 6. The variation of A_{my} and A_{mx} are plotted against the normalized depths (D_d) of trenches in case of dual trenches or the normalized depth (D) of a single trench as applicable.

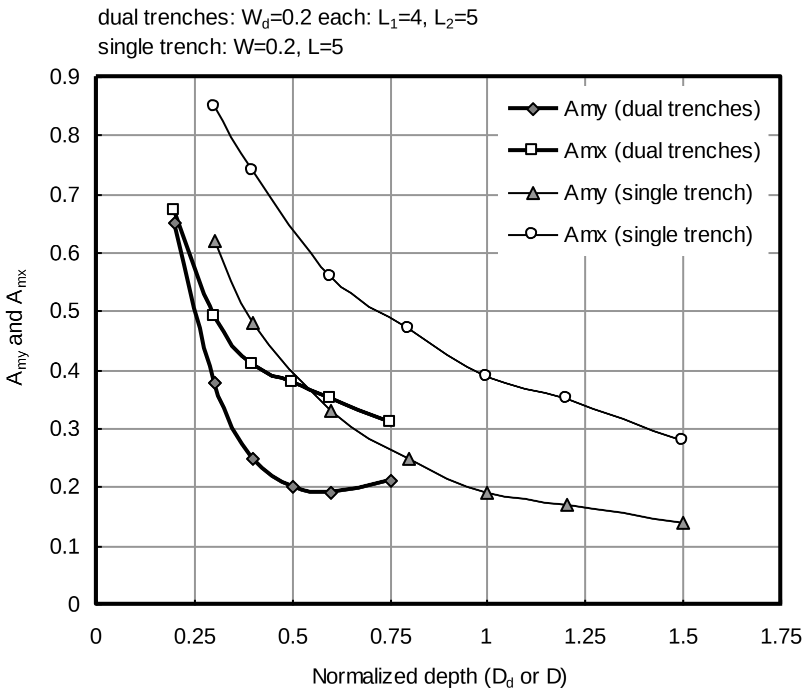

Figure 6: Comparison of screening effectiveness of dual trench barrier over a single trench

It is apparent from Fig. 6 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. For instance, a dual trench barrier each 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 trench barrier may be used as an effective isolation technique in circumstances where the provision of a single trench is impracticable because of depth constraint.

4.1 Model Validation

The problem of vibration isolation by a pair of open trenches was not attempted in any of the previous studies. But there are documented results of surface wave isolation by single open trenches which provides a scope of validating the present modeling scheme. A particular case of vertical vibration isolation by an open trench of depth $1L_R$ and width $0.1L_R$ placed at a distance of $5L_R$ from the source is analyzed with the present scheme. The plot of vertical amplitude reduction factors versus normalized distances from source ($X=x/L_R$) is in excellent agreement with a previous study [9] as presented in Fig. 7. This justifies that the current modelling scheme provides reasonable accuracy for wave barrier analysis.

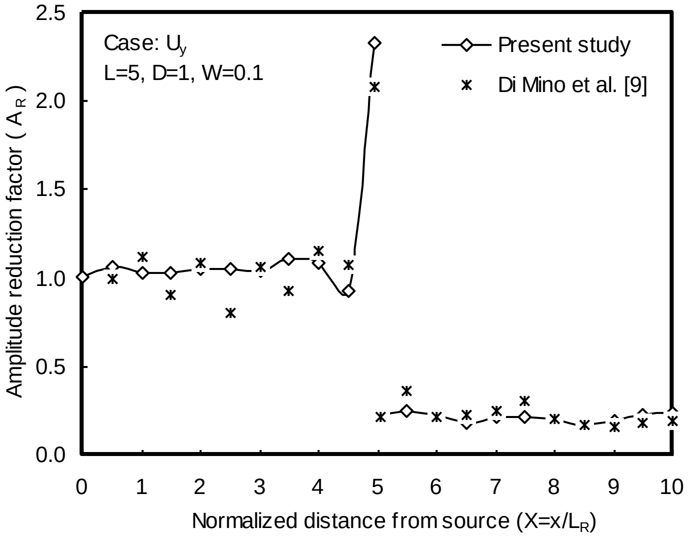

Figure 7: Comparative study on vibration isolation by an open trench

5. CONCLUSIONS

The screening performance of a pair of open rectangular trenches of identical dimensions excavated in a homogeneous, elastic, and isotropic half-space is investigated in this work. Following conclusions may be drawn regarding the vibration isolation effectiveness of such barriers.

The screening performance of a dual open trench system is worst 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 worst 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 pair of trenches is primarily governed by their depths. The efficiency increases up to a depth of 0.5L_R-0.6L_R and remains unaltered thereafter. In fact, in some cases increase in depths beyond this is seen to have adverse effect on the 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 trench pairs 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 should be kept in between 0.2L_R to 0.3L_R.

The depth requirement of a dual trench system is much less compared to that of a single trench to achieve a certain degree of screening. This indicates that a dual trench barrier may be used as an alternative to a single open trench in some circumstances where the provision of the latter is either difficult or unrealistic. Comparison with a published study on vibration isolation by an open trench is showing excellent agreement which substantiates the accuracy of the present finite element scheme. An experimental investigation may be pursued as a future scope of this study.

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