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RESEARCH ARTICLE

Efficiency of Trenches on Vibration Isolation under Time Dependent Loads

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Abstract

Results from some parametric studies were presented to assess the dynamic response of soil surface and to investigate the effectiveness of trenches in reducing vibrations due to time dependent loads acting vertically on the soil surface for two-dimensional (2-D) problems by coupling finite and infinite elements. The effects of various parameters such as height of the trench, infill materials and location of the trench on screening efficiency have been investigated. It is concluded that using open or in-filled trenches can reduce the vibrations of a structure; especially the use of an open trench provides better isolation than using an in-filled trench. Efficiency of isolation increases with height of trench. The trench height has appeared as the most important parameter on screening vibrations. The location of the trench is also effective on dynamic response of soil surface. Coupling finite and infinite elements can be easily applied to study the isolation problems.

Keywords

Vibration isolation · trench · wave propagation · finite elements · infinite elements

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1 Introduction

Ground vibrations due to heavy traffic, machine foundations, blasting, pile driving or seismic excitations can cause damage to adjacent structures and annoyance to residents. In general, the effect of ground vibrations can be attenuated or prevented by providing a suitable wave barrier between the vibration source and the concerned structure [1–7]. The ground vibration screening systems can be classified into two categories depending on the location of the isolation construction: active isolation system and passive isolation system. The active isolation system, i.e. the "source" isolation is located near to the vibration source and used to reduce the vibrations at around the vibration source. The passive isolation system, i.e. the "receiver" isolation, on the other hand, is constructed close to the area to be protected [4,5,8]. Stationary vibration sources, such as machines working with a certain frequency can be effectively isolated by an active isolation system, whereas a passive isolation system is effective for a wide variety of wave generating sources [4].

In the literature, different types of wave barriers, such as open or in filled trenches, rows of tubular or solid piles, very stiff concrete walls or very flexible gas cushions which diffract those surface waves were studied in detail [1–4, 9, 10]. Among these systems, both open and filled trenches are most common in practical applications since they present effective and low cost isolation measures [4]. In early studies, the vibration isolation problems were examined analytically and some experimental works to investigate the problem by means of trench barriers [11, 12]. However, the closed form solutions confined to simple geometries and idealized conditions. Therefore, various numerical methods were used by many researchers for solving wave propagation and vibration isolation problems. Lysmer and Waas [13] employed the lumped mass method to assess the isolation efficiency of open and bentonite-slurry-filled trenches in a layered soil. Segol et al. [14] studied the same problem by applying finite elements with special non-reflecting boundaries. Fuyuki and Matsumoto [15] studied the scattering of a Rayleigh wavelet by a rectangular open trench by using the finite difference technique. Klein et al. [8], Beskos et al. [16] and Dasgupta et al. [17] investigated the isolation efficiency of countermeasures to incident waves or harmonic point loads by using the boundary element method. Kattis et al. [1] developed a three-dimensional boundary element method and studied vibration isolation by a row of piles in the frequency domain. Kattis et al. [2] constructed an effective trench model to replace a row of piles as passive barriers. Shrivastava and Kameswara Rao [3] examined the effectiveness of open and filled trenches for screening Rayleigh waves due to an impulse load for three dimensional problems. Adam and Von Estorff [4] studied the effectiveness of open and in-filled trenches in reducing the building vibrations due to passing train by coupling finite and boundary elements. Celebi and Schmid [18] employed two different three dimensional numerical methods for the analysis of the propagation of surface vibrations in the soil caused by railway traffic. Gao et al. [5] presented an integral equation governing Rayleigh wave scattering and theoretically studied the efficiency of ground vibration isolation through multi rows of piles as passive barrier in a three dimensional context. Zhang et al. [10] performed three dimensional analyses by using a finite element software to investigate vibration isolation performance cast-in-place concrete thin-wall pipe pile. Wang et al. [19] numerically studied the effect of soft porous layer barriers on the reduction of buried blast-induced ground shock. Cao et al. [7] proposed semi-analytical model to investigate the screening efficiency of trenches to moving load induced ground vibration. It is reported by [1] and [2] that vibration isolation problems can be solved efficiently and accurately only by numerical methods, such as the finite element method. The finite element method has been used for two or three dimensional cases of vibration isolation problems, usually in conjunction with special non-reflecting boundaries. In the published literature, the boundary element method is commonly used as non-reflecting boundary for this kind of problem. Another possibility is by using the infinite element approach employing the displacement shape function with the geometrical decay formulation [20–22]. Yang et al. [23] and Yang et al. [24] concentrated on a coupling of finite and infinite elements applied to study the reduction of train induced vibrations using different types of wave barriers.

In this study, a parametric study was carried out to determine the effectiveness of open and in-filled trenches in reducing vibrations due to time dependent loads for two-dimensional (2-D) problems. A numerical procedure was employed to evaluate whole system response. In the numerical procedure, finite and infinite elements with three wave types [22] were used. The soil region was assumed to be homogeneous, isotropic and viscoelastic layer. Ricker-Wavelet signal was chosen as time dependent load acting vertically on soil surface. The formulation was performed in the Laplace transform domain. Solution in the time domain was obtained by using Durbin's numerical inverse Laplace transform technique [25].

2 Equation of motion in Laplace transform domain

In plane elasticity (plane stress/plain strain) problems, equilibrium equations are given by

$$\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + f_x - \rho \frac{\partial^2 u}{\partial t^2} &= 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y - \rho \frac{\partial^2 v}{\partial t^2} &= 0 \end{aligned} \tag{1}$$

where u and v are displacement components. Applying Laplace transformation [22] to Eq. (1) and integrating over an element multiplying by weighting factors, afterwards Galerkin's approach is employed; the governing differential equations are expressed in integral form as:

$$\begin{aligned} & h_e \int_{A_e} \{\delta\overline{\varepsilon}\}^T \{\overline{\sigma}\}\, dA_e + s^2 h_e \int_{A_e} \rho \begin{Bmatrix} \delta\overline{u}_r \\ \delta\overline{v}_r \end{Bmatrix}^T \begin{Bmatrix} \overline{u}_r \\ \overline{v}_r \end{Bmatrix} dA_e = \\ & h_e \int_{A_e} \begin{Bmatrix} \delta\overline{u}_r \\ \delta\overline{v}_r \end{Bmatrix}^T \begin{Bmatrix} \overline{f}_x \\ \overline{f}_y \end{Bmatrix} dA_e + h_e \int_S \begin{Bmatrix} \delta\overline{u}_r \\ \delta\overline{v}_r \end{Bmatrix}^T \begin{Bmatrix} \overline{t}_x \\ \overline{t}_y \end{Bmatrix} dS - \\ & h_e \int_{A_e} \rho \begin{Bmatrix} \delta\overline{u}_r \\ \delta\overline{v}_r \end{Bmatrix}^T \begin{Bmatrix} \overline{a}_{gx} \\ \overline{a}_{gy} \end{Bmatrix} dA_e \end{aligned} \tag{2}$$

where h_e is element thickness, ρ is mass density and s is Laplace transform parameter. Overbar represents the Laplace transform of related quantity. Eq. (2) is the usual virtual work principle in the Laplace transform domain. In the numerical treatment, by using finite element approximation, the system equations of motion in the Laplace transform domain are obtained as:

$$\left(\left[\overline{K}\right] + s^2\left[\overline{M}\right]\right)\left\{\overline{U}\right\} = \left\{\overline{P}\right\} \tag{3}$$

in which $\left[\overline{K}\right]$ and $\left[\overline{M}\right]$ are system stiffness and mass matrices, $\left\{\overline{P}\right\}$ is system load vector and $\left\{\overline{U}\right\}$ is system displacement vector that contains all of the nodal displacements. In the presence of viscous damping in the material, the material constants in the material matrix are to be multiplied by $(1 + \zeta\ s)$. Where, ζ is damping coefficient.

3 Formulations of finite and infinite elements

In this study, a standard eight-node isoparametric, quadratic plane element was used as the finite element. Fig. 1 shows the eight-node isoparametric, quadratic finite element. The chosen finite element's formulations are well-known. For this reason, the formulations need not be discussed in detail, only interpolation functions are given as [26]:

$$\begin{aligned} N_i &= \frac{1}{4}(1+\xi\xi_i)(1+\eta\eta_i)(\xi\xi_i+\eta\eta_i-1) \quad \text{(corner nodes)} \\ N_i &= \frac{1}{2}(1-\xi^2)(1+\eta\eta_i) \quad (\text{side nodes}, \xi_i = 0) \\ N_i &= \frac{1}{2}(1+\xi\xi_i)(1-\eta^2) \quad (\text{side nodes}, \eta_i = 0) \end{aligned} \tag{4}$$

Infinite elements with three wave types have been used as non-reflecting boundary. This infinite element type includes

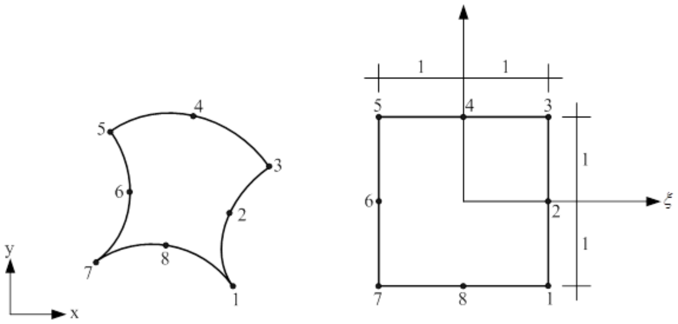

Fig. 1. Eight-node isoparametric finite element

three different wave (pressure, shear and Rayleigh) characters [22]. Fig. 2 shows the infinite elements adequate to represent the propagation of three wave types.

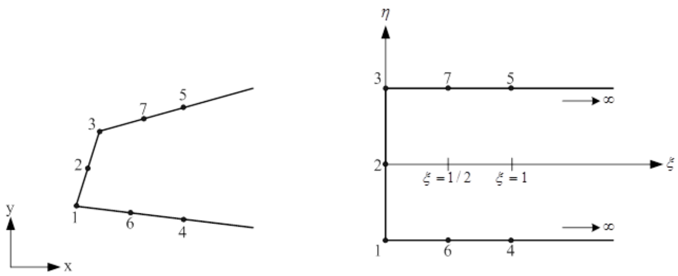

Fig. 2. Infinite element with three wave types

The shape functions of dynamic infinite elements are constructed by using a wave-propagation function that represents the amplitude attenuation and phase delay in the direction extending to infinity. The mapping functions of the infinite elements are given as [27]:

$$
\begin{aligned}
M_1 &= \frac{1}{2}(\xi - 1)(\eta - 1) \\
M_2 &= 0 \\
M_3 &= \frac{1}{2}(1 - \xi)(\eta + 1) \\
M_4 &= \frac{1}{2}\xi(1 - \eta) \\
M_5 &= \frac{1}{2}\xi(1 + \eta)
\end{aligned}
\tag{5}
$$

In the Laplace transform domain, the horizontal ($\overline{u}$) and vertical ($\overline{v}$) displacement fields of the infinite element can be written as:

$$
\begin{aligned}
\overline{u} &= \sum_{i=1}^{7} \overline{N}_i \overline{u}_i \\
\overline{v} &= \sum_{i=1}^{7} \overline{N}_i \overline{v}_i
\end{aligned}
\tag{6}
$$

where N_i: displacement shape functions of the infinite element, and they can be expressed as:

$$
\begin{aligned}
\overline{N}_1(\xi,\eta,s) &= \overline{P}_1(\xi,s)\left[\frac{1}{2}\eta(\eta-1)\right] \\
\overline{N}_2(\xi,\eta,s) &= \overline{P}_2(\xi,s)(1-\eta^2) \\
\overline{N}_3(\xi,\eta,s) &= \overline{P}_3(\xi,s)\left[\frac{1}{2}\eta(\eta+1)\right] \\
\overline{N}_k(\xi,\eta,s) &= \overline{P}_k(\xi,s)\left[\frac{1}{2}(1-\eta)\right] k = 4,6 \\
\overline{N}_k(\xi,\eta,s) &= \overline{P}_k(\xi,s)\left[\frac{1}{2}(1+\eta)\right] k = 5,7
\end{aligned}
\tag{7}
$$

where $P_k(\xi, s)$ is the wave-propagation function. Based on the derivation for the harmonic infinite elements given by [27], the wave-propagation functions can be approximately represented by the superposition of plane waves. Thus, their general form in the Laplace transform domain is expressed by [22] as:

$$
\begin{aligned}
P_k(\xi,s) &= a\,e^{-(\alpha+\beta_1)\,\xi} + b\,e^{-(\alpha+\beta_2)\,\xi} + c\,e^{-(\alpha+\beta_3)\,\xi} \\
\beta_k &= \frac{s}{c_k}L
\end{aligned}
\tag{8}
$$

where α: decay parameter; c_k: wave velocities and a, b, c are undetermined constants. The constants a, b and c were determined using Eq. (6) which details were given in [22].

Calculation of the infinite element stiffness and mass matrices was performed numerically. For the finite direction, the usual Gauss-Legendre integration technique was used. But infinite integrals were evaluated by using Newton-Cotes numerical integration scheme [20].

4 Model verification by comparison with published results

A study carried out by Von Estorff and Kausel [29] to investigate numerical solution procedures of complex soil-structure interaction problems by using finite and boundary elements. In order to represent the efficiency of open and in filled trenches on vibration isolation, a halfspace which divided into two subregions was taken into account. One of them which discretized with 35 square finite elements of 10 m x 10 m, was a region of 50 m x 70 m including the location of the load, the trench, and the observation point A. The other part of halfspace was modelled by 21 boundary elements of length 10 m. A time dependent distributed load, acting vertically, was applied over one finite element. Its time function was a rounded impulse over $5.\Delta t(= 0.125\,\text{sec})$ as given Fig. 3

At first, a trench of width $b = 10$ m, not filled with any material, was considered and it was investigated the effect of trench depth on displacements of the surface at a distance 40 m from the distributed load (point A). Three different depths (T) of the trench ($T/b = 2, 3, 4$) were considered and compared to the halfspace solution ($T/b = 0$). Secondly, in order to determine how to the displacements were influenced by filling the trench, two

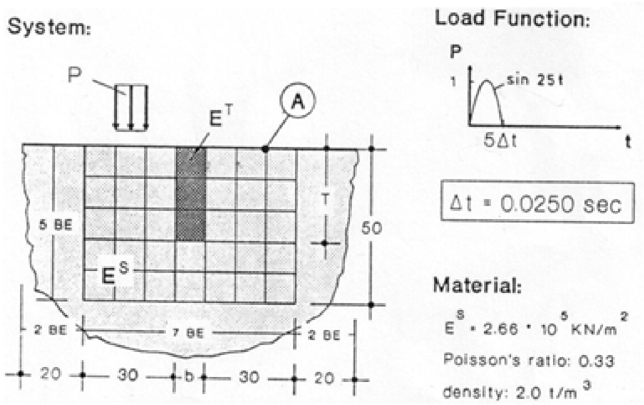

Fig. 3. Elastic halfspace with a trench presented by Von Estorff and Kausel [29]

different material stiffnesses (E_T) were assigned to the corresponding finite elements for $T/b = 3$. The ratio $E_T/E_S = 0.1$ describes the filling material which is much softer than the surrounding soil, while $E_T/E_S = 6$ represents a very stiff filling material. Fig. 4 presents a comparison of the results by using finite-infinite elements model presented in this study with the results from Von Estorff and Kausel [29]. Fig. 4 reflects that the solution by using finite and infinite elements agrees well with the Von Estorff and Kausel's [29] results.

5 Parametric studies

The effectiveness of open and filled trenches in reducing vibrations for two-dimensional (2-D) problems was investigated and evaluated subjected to time dependent loads. A numerical procedure was employed. In the numerical treatment, finite and infinite elements with three wave types [22] were used. In the coupling system of finite and infinite elements, infinite elements have been used at boundaries since they satisfy the radiation conditions at infinity [20–22]. Typical finite-infinite element discretization of the systems is shown in Fig. 5

A series of parametric studies were carried out. Schematic representation of the numerical models is shown in Fig. 6, where, "O" is vibration source point, "A" is point just before and point "B" is just after the trench. Points "C" and "D" are located far away from the trench. The soil region was assumed as homogeneous, isotropic and viscoelastic layer. Soil properties were considered as mass density $\rho_s = 2.0\ t/m^3$, Poisson's ratio $\upsilon = 0.35$ and modulus of elasticity $E_s = 200$ MPa. Because of the viscous damping effect was not under particular interest, it was assumed that soil media has 5% constant viscous damping ratio. The height of soil layer was assumed constant in all simulations. Underlying rock was considered as rigid base. It is noted that in all simulations, no relative displacement was allowed at the soil-rock interface. On the other hand, the material properties were not crucial because it was carried out a comparative study.

For the time dependent load data acting vertically on the soil surface, Ricker-Wavelet was chosen. The input signal is shown in Fig. 7. Its equation in time is given as

$$f(t) = A_0 \left(1 - 2a^2\right) e^{-a^2} \tag{9}$$

where $a = (t - t_s)/t_0$; t_s is the time at which the maximum occurs; A_0 is the amplitude and fixed to 1, t_0 corresponds to the dominant period of the wavelet. In this study, t_0 was set to $1/\pi$, which corresponds to a dominant frequency of the wavelet near 1 Hz. The time lag t_s was taken equal to $3t_0$ ($t_s = 3/\pi$) same as chosen in [28].

The parametric studies were carried out in three stages: at first, an open trench taken into account to determine the effectiveness of trench height in reducing vibrations at soil surface. Three different H/b ratios ($H/b = 1$, $H/b = 3$ and $H/b = 5$) considered, where H represents height of the trench. Secondly, considering the H/b ratio equals 3, the trench is filled with different materials. It was assumed that mass density and Poisson's ratio of the infill material were the same as that of soil. Various values of the elasticity modulus of the infill materials (E_f), ($E_f = 0.5E_s$, $E_f = E_s$, $E_f = 5E_s$, $E_f = 10E_s$ and $E_f = 100E_s$) were studied to investigate the effect of infill materials on vibrations. Finally, considering again the H/b ratio equals 3, the effects of location of the trench in reducing vibrations were studied. Aiming at this goal, four different distances "L" were selected ($L = 0.5b$, $L = b$, $L = 2b$ and $L = 5b$), where L is the distance between the vibration source and the trench. It is noted that the width of the trench (b) was kept constant at 10 m [28, 29] in all simulations. It was reported that the trench width did not have much effect on isolation efficiency, except for narrow trenches [3]. For the finite and infinite elements presented earlier, a computer program coded in FORTRAN90 programming language was prepared. The efficiency and accuracy of the program code were published in [30]. The solutions were obtained in the Laplace domain. Then using Durbin's numerical inverse Laplace transform technique [25], solutions were transformed into time domain.

6 Results and discussion

Effectiveness of open and filled trenches on dynamic response of the soil surface has been studied and results were presented for time dependent loads acting vertically. Ground vibrations and their propagation from the source through geological formations and their interaction with structures in or on the ground is a complex problem. The fundamentals of wave propagation in soils have been described extensively in the literature [9, 31–35]. It was reported by Massarsch [9] that soil stratification, the ground water and the dynamic properties of soils have great influence on the dynamic response. Special phenomena occur at geometric irregularities or across in homogeneities. At the interface between two elastic bodies, body waves are partly reflected and refracted. The wave amplitudes depend on the angle of incidence and the ratio of the wave propagation velocity of the two materials. At a free surface, full reflection occurs.

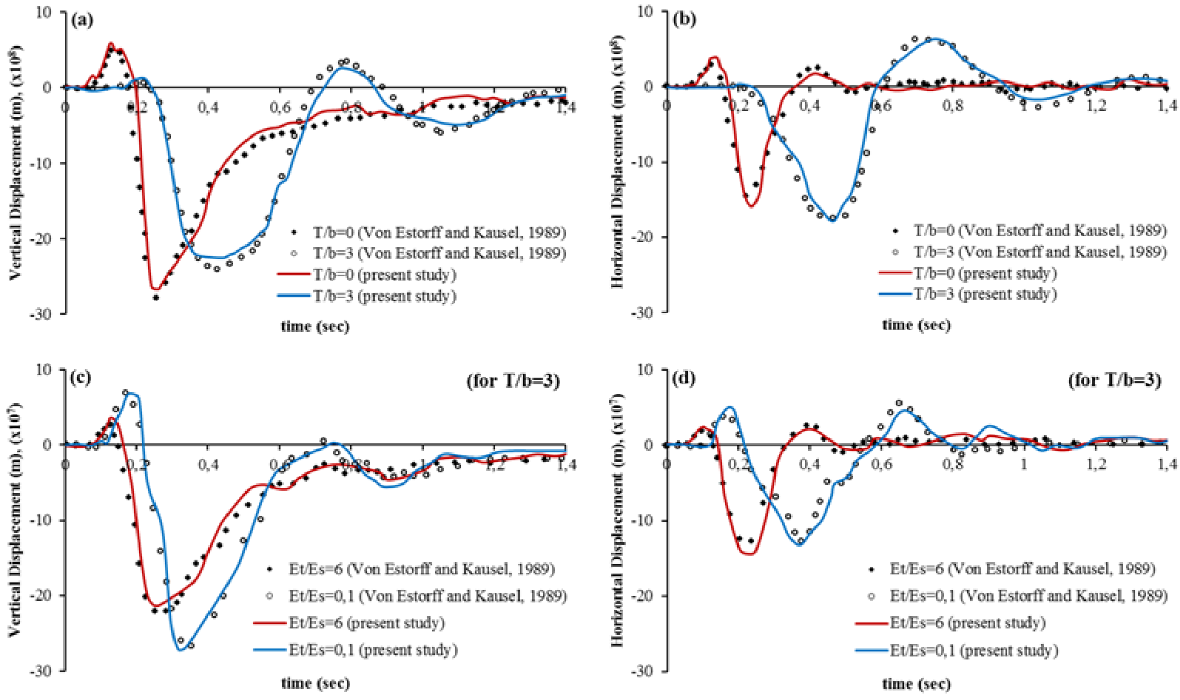

Fig. 4. Comparison of the present results with the results from Von Estorff and Kausel [29], (a) and (b) represent vertical and horizontal displacements, respectively (for $T/b = 0$ and $T/b = 3$); (c) and (d) represent vertical and horizontal displacements, respectively (for $Et/Es = 6$ and $Et/Es = 0.1$)

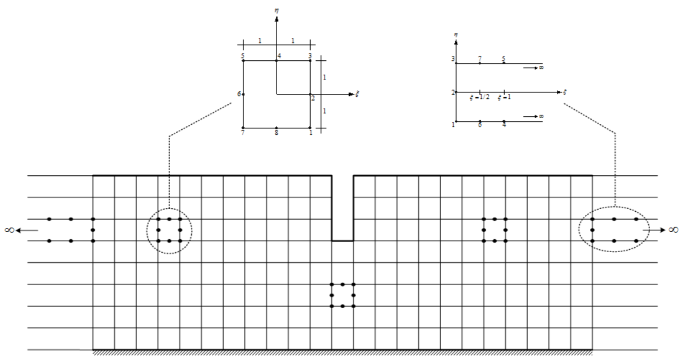

Fig. 5. Typical finite-infinite element discretization of the soil-trench systems

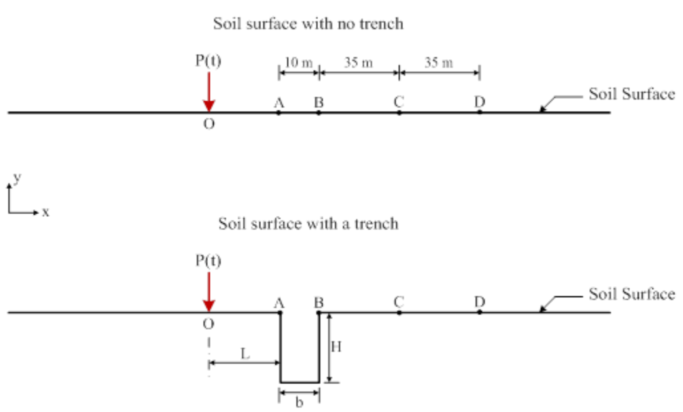

Fig. 6. Configurations of wave barrier systems

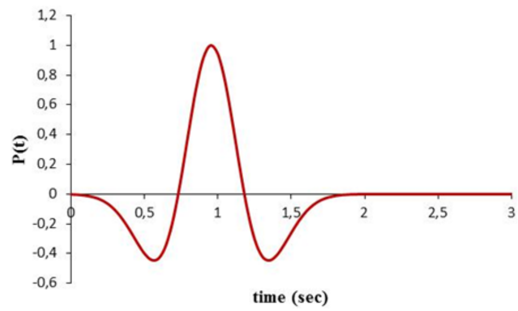

Fig. 7. Ricker-Wavelet signal

For vibration problems, the surface waves (i.e., Rayleigh waves or R-wave) have greatest practical importance. The Rayleigh wave propagates along the free surface of the half space and consists of vertical and horizontal vibration. The screening wave mechanism by a wave barrier is that the ground motion from a vibration source in an undisturbed half space is principally due to Rayleigh wave energy [12, 16, 17]. Placing a wave barrier means creating a finite discontinuity for the wave field in undisturbed half space. After a Rayleigh wave incident on a trench at soil surface, it gives rise to (a) reflected R-wave; (b) body waves (i.e., P and S) that radiate outwards from the obstacle; and (c) transmitted R-waves. Body waves can be subdivided in two groups: reflected body waves that radiate downwards and transmitted body waves that propagate other side of the obstacle. The energy contained within transmitted R-wave and transmitted body waves cause smaller vibrations at the other side of the trench [3].

Effect of the trench height is shown in Figs. 8 to 10. It is shown that the trench height has a great influence on the dynamic response of the soil surface especially in the vertical di-

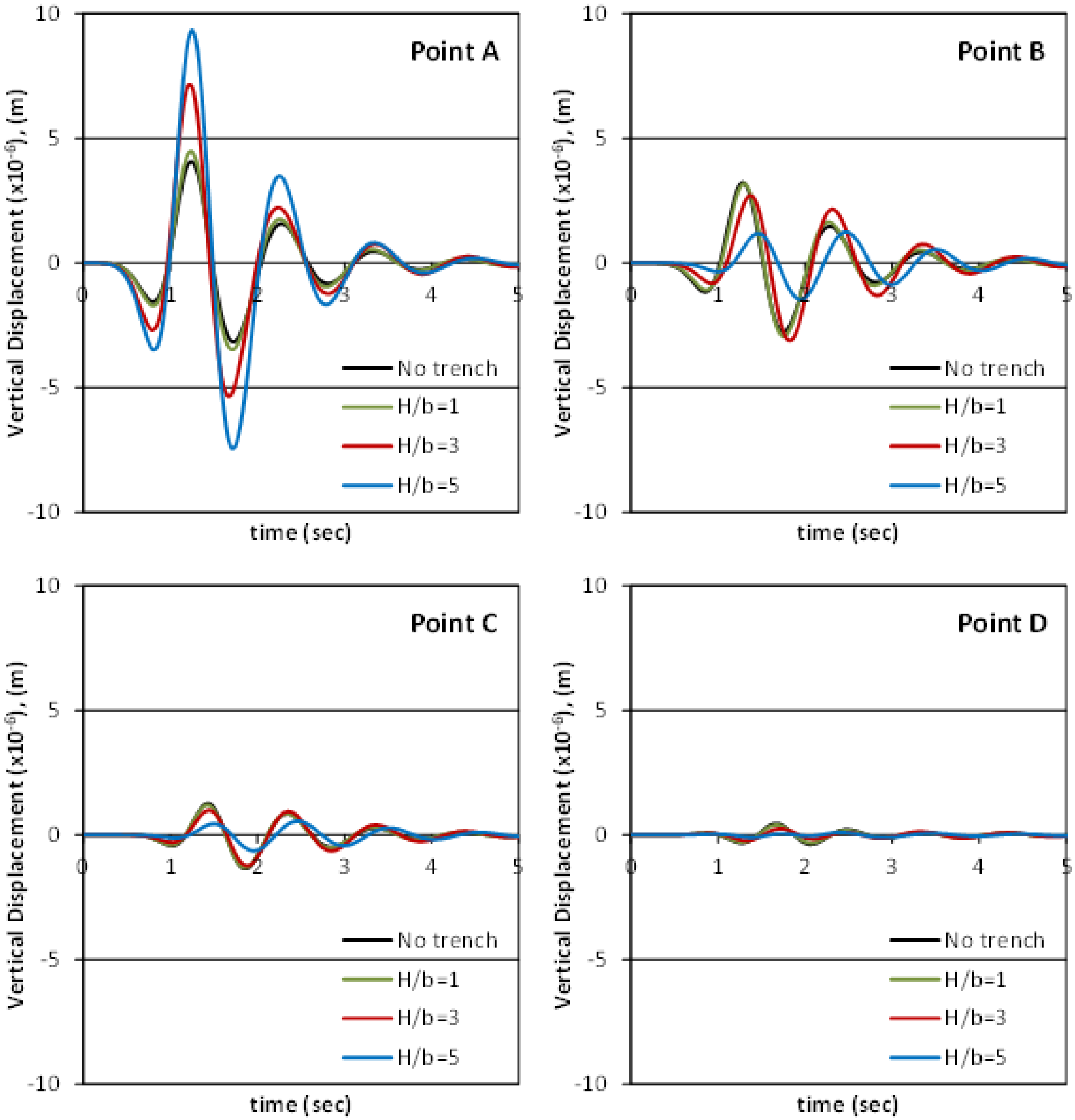

Fig. 8. Influence of trench height on vertical displacements

rection. Vertical displacements are mainly affected when the H/b ratio increases. When H/b ratio gets greater: (i) greater amplification occurs at the points before the trench. Maximum amplification occurs at Point A, located just before the trench. Increase in vertical displacements reaches up to 130% for $H/b = 5$. Similar results are obtained by [36] and [37]. This amplification is due to the interaction between incident and reflected waves [34], (ii) the vertical displacements systematically decrease at the points after the trench. Decrease in the vertical displacements reaches up to nearly 55% at the points B, C and D for $H/b = 5$. Similar observations have been made by [3, 12, 28, 29, 38], (iii) a time delay occurs in the maximum vertical displacements. Physically this indicates that the waves travel around the trench to reach the points after the trench [39]. In an experimental study carried out by Woods [12] to define screening effects of trench barrier systems, it was shown that if the trench height is increase, greater displacements occur at the points before the trench, but the displacements systematically decrease at the points after the trench in both active and passive isolation tests. Shrivastava and Kameswara Rao [3] indicated that increase in the trench depth cause more reduction in displacements after the trench. Gao et al [40] pointed out that the trench depth is an important variable of practical concern for the vibration isolation. An increase of the isolation effectiveness is obtained at the points after the trench, when the trench depth increases. Adam and Von Estorff [4] determined that when the trench depth increases, attenuation occurs in acceleration. Since the time dependent load acting vertically on the soil surface, the horizontal displacements naturally occur smaller than those of the vertical direction. According to the results, the trench height has no distinctive effect on the horizontal displacements.

A non-dimensional parameter, which is called "amplitude ratio" at any point of time, expressed as the ratio of amplitude of the soil surface with trench to that of the system without trench

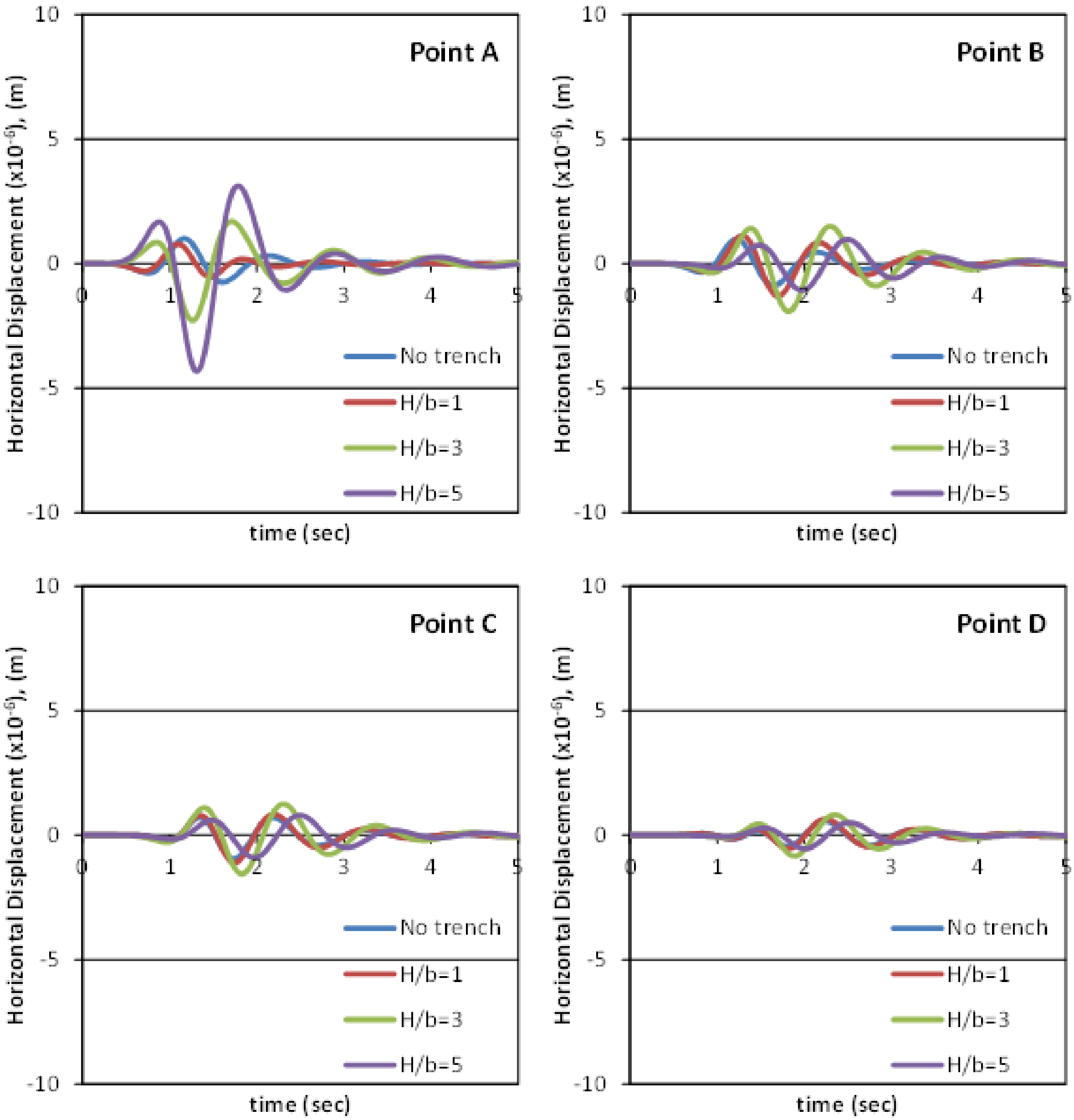

Fig. 9. Influence of trench height on horizontal displacements

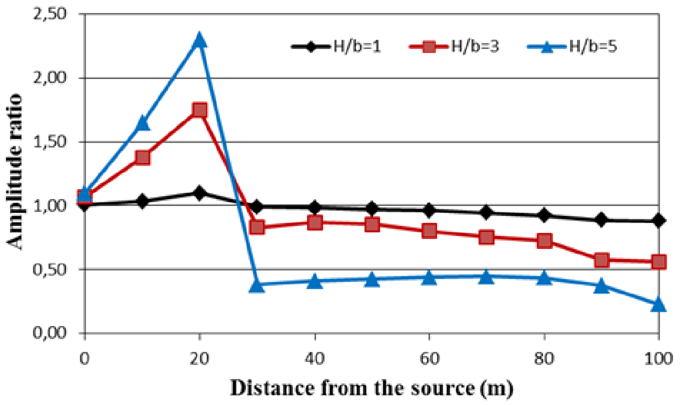

Fig. 10. Effect of H/b ratio in vertical direction

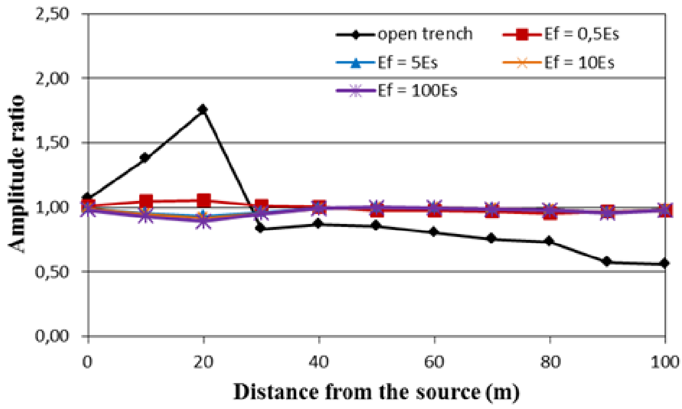

Fig. 11. Effect of infill materials in vertical direction

has been used to express the isolation efficiency. Amplitude ratio of maximum displacement is that ratio which corresponds to maximum displacement with trench to that of the case without trench at the same instant time. It is a measure of the reduction in maximum response. When the trench height increases, the amplitude ratio in vertical direction increases at points between vibration source and the trench; whereas it decreases drastically at points after the trench.

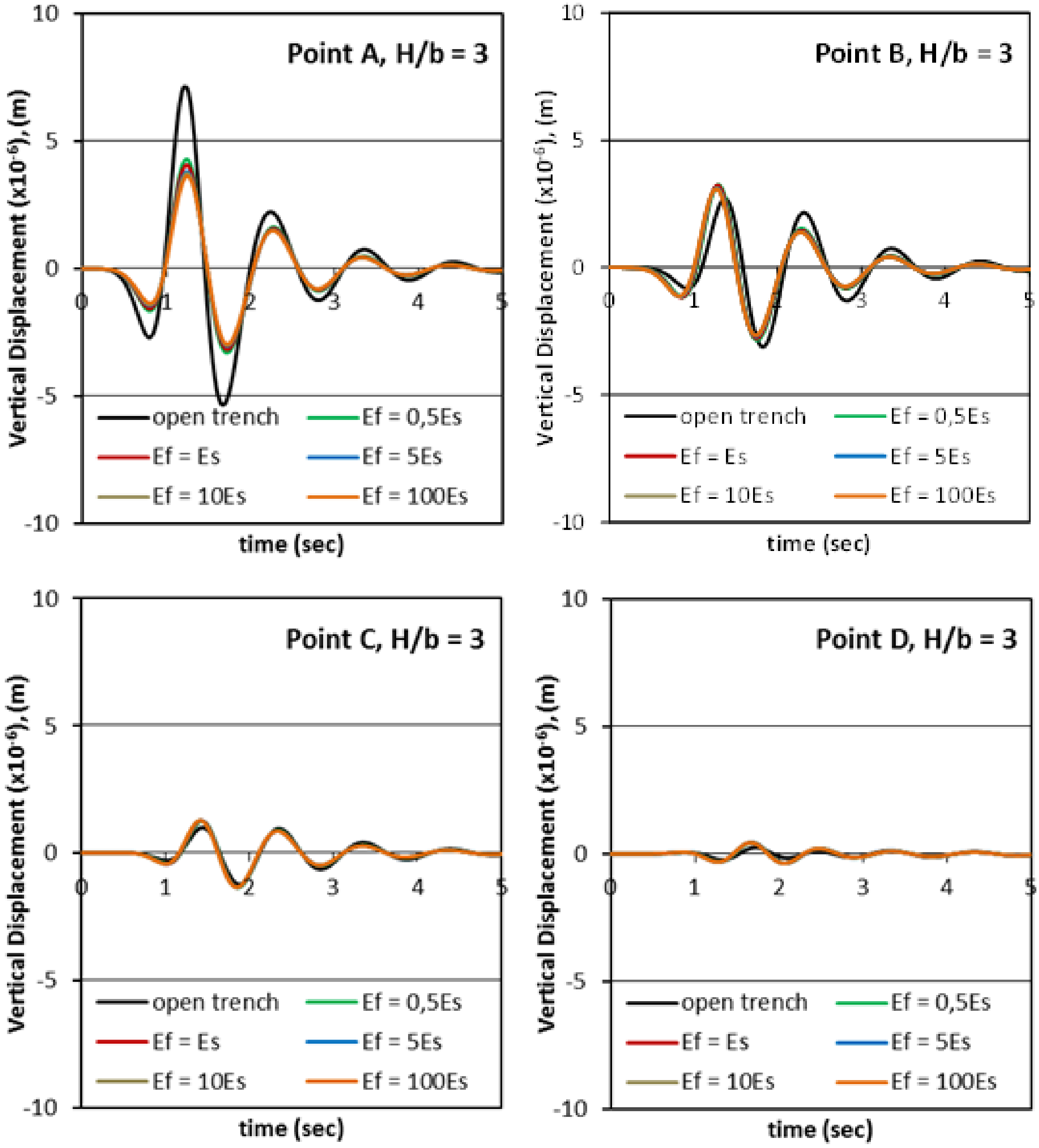

Fig. 12. Effect of infill materials in vertical displacements

Effect of the infill materials is shown in Figs. 11 to 12. It is shown that the infill materials have minor effect on the dynamic response of the soil surface. The amplitude ratio is always higher for open trench than filled trench at the points between vibration source and the trench, on the other side, the amplitude ratio is always smaller for open trench than filled trench at the points after the trench. The reason behind that is, in case of trench filled with a filling material, there is always some possibilities for Rayleigh wave to adopt shortcut path cross the trench along width through the filling material, and reach at the points after the trench. But in case of open trench, there is no filling material, width wise, and waves are bounded to move downwards and then reach to the points after the trench [3, 39]. When a comparison is made between open and filled trench, it is shown that open trench is a better option than filled trench in screening vibrations. A parametric study conducted by Shrivastava and Kameswara Rao [3] reported that an open trench provides better vibration isolation than the trench which filled with different materials. Also Çelebi et al [41] which carried out a series of field tests on wave propagation and vibration isolation using trenches indicated that the use of an open trench is more effective than using an in-filled trench, but its practical application is limited to relatively shallow depths.

It was observed that the location of the trench was also effective on dynamic response of soil surface. The results are summarized in Figs. 13 to 14. According to the results, when the trench gets closer to the vibration source, greater displacements occur in both vertical and horizontal direction at the points between vibration source and the trench. But at the point B, located just after the trench, the displacements drastically decrease, especially in vertical direction. Maximum decrease in the displacements occurs in the case of that the trench is located closest distance to the vibration source ($L = 0.5b$). The other points after the trench were slightly influenced by location of the trench. Thai and Chang [42] indicated that the distance from vibration source to the trench is insignificant parameter on vibration isolation efficiency.

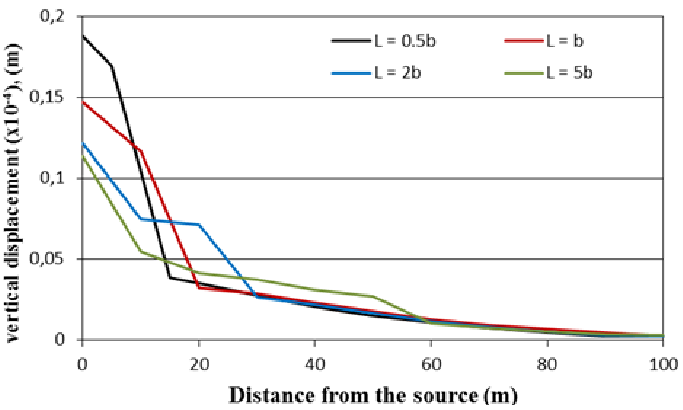

Fig. 13. Effect of location of the trench on vertical displacements

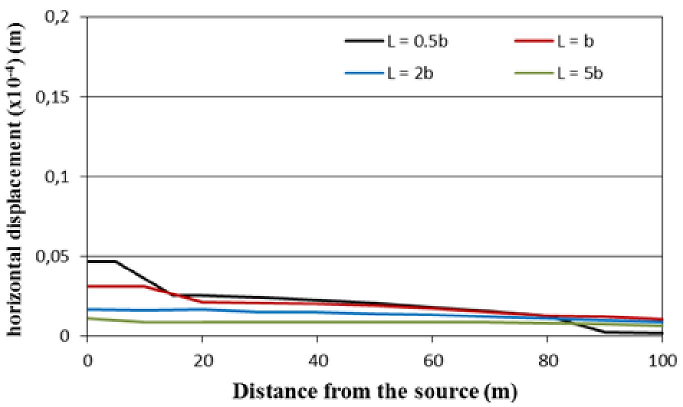

Fig. 14. Effect of location of the trench on horizontal displacements

7 Conclusions

A parametric study was carried out to evaluate the dynamic response of soil surface and to investigate the effectiveness of open and filled trench in vibration screening due to time dependent loads acting vertically on the soil surface. The effects of various parameters such as height of the trench, infill materials and location of the trench on isolation efficiency have been investigated.

The results obtained in this study correspond with those in the literature. According to the results, it was shown that;

1 Using open or filled trenches can reduce the vibrations of a structure; especially the use of an open trench provides better isolation than using an in-filled trench but its practical application is limited to relatively shallow depths.

2 Efficiency of vibration isolation increases with height of trench for time dependent loading. The trench height was seemed as the most important parameter on screening vibrations.

3 Filling the trench by different materials has minor effect in reducing vibrations.

4 The location of the trench is also effective on dynamic response of soil surface. When the trench gets closer to the vibration source, greater displacements occur in both vertical and horizontal direction at the points between vibration source and the trench. On the other hand, at the point, located just after the trench, the displacements drastically decrease. Maximum decrease in the displacements occurs when the trench is located closest distance to the vibration source.

5 Excavation of trench changes displacements significantly at the points between vibration source and the trench.

6 A coupling of finite and infinite elements can be easily applied to study the vibrations isolation problems.

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