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Optimum Geometrical Properties of Active Isolation by Open Trenches to Reduce Vibratory Effects of Shallow Foundations

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ABSTRACT: Vibratory waves generated by dynamic loads subjected to a shallow foundation can be propagated to a noticeable distance having detrimental effects on sensitive structures in the path of wave train, which should be considered in reliability and risk analysis. Reducing the vibration energy, removing the physical environment could be a solution achieved by installing trenches. This paper examines the effectiveness of annular open trenches as wave barrier to mitigate the severity of the vibration energy on a limited soil layer. Three-dimensional Finite Elements Method (FEM) has been utilized to conduct an extensive parametric study on active isolation. Non-Linear Drucker-Prager yielding criterion, harmonic vertical force with a wide range of values and frequencies as well as Time History analyses have been employed to obtain more accurate results. And finally, through comparisons with published laboratory results, the validity of the models and obtained results has been established.

1 INTRODUCTION

For a number of rugged vibratory equipments, the intensity of vibration may be tolerable for the equipment itself. The vibration energy, on the other hand, may not be within a tolerable limit for adjacent structures and sensitive equipments. As a result, it is desirable to isolate the structure from the adverse effects of vibrations by installing suitable wave barriers between the source and the structure to be protected. There are two types of vibration screening by wave barriers, namely active and passive isolations. Active isolation is to reduce the vibrations at the source and should be installed surrounding the vibration source or in the immediate vicinity of it; passive isolation is remote from the vibrating foundation, surrounding the structure to be protected [Das 1993].

Concerning the literature on vibrations screening, Woods (1968-1969) performed a series of field tests to study vibration isolation by open annular trenches at a site with a deep stratum of silty sand (SM). He studied the applicability of open trenches as an active isolation system by defining amplitude-reduction ratio (A_r) examining the influences of the location and depth of an open trench on its effectiveness. He concluded that a minimum trench depth of 0.6 times the Rayleigh wave-length is necessary to achieve a 75% reduction in ground displacement amplitude. Using the lumped mass method, Lysmer and Waas (1972) studied the effectiveness of a trench in reducing the horizontal shear wave motion induced by harmonic load. Beskos et al. (1985, 1986, and 1990) employed the boundary element method (BEM) in the frequency domain to study vibration screening using open and in-filled trenches.

Ahmad and Al-Hussaini (1991, 1996, and 2000) employed simplified design methodologies for wave barriers and vibration screens, focusing on an isolation of machine foundations by trenches using a three-dimensional boundary element algorithm to conduct parametric study on the open and in-filled trenches effectiveness. Other related works to be mentioned here include those of Fuyuki and Matsumoto (1980), May and Bolt (1982), Emad and Manolis (1985), Ni et al. (1994), Yeh et al. (1997). In 1997, Hung examined the effectiveness of both open and in-filled trenches in isolating ground-borne vibrations, due to the passage of trains, using FEM for a range of load frequencies and concluded that the trenches are not suitable for low frequencies.

Kattis et al. (1999a, 1999b) compared the effectiveness of open and in-filled trenches together with pile barriers in vibration screening employing a BEM in the frequency domain. Based on their findings, trenches were appeared to be more effective than pile barriers, except for the vibration with large wavelength where deep barriers are dictated and for that reason, pile barriers are more practical. In 2002, Shrivastava investigated the effectiveness of open and in-filled trenches for screening Rayleigh waves due to impulse loads by FEM with Newmark's method in a 3D model. Adam (2004) conducted a numerical investigation on the effectiveness of open and in-filled trenches in reducing the six-storey building vibrations due to passing trains by a 2D FEM analysis. The results reported that almost 80% reduction in the building vibrations and internal forces could be achieved. El Nagggar (2005) examined the efficiency of both soft and stiff barriers in screening pulse-induced waves for foundations resting on an elastic half-space underlain by rigid bedrock using 2D FEM. He displayed the results by amplitude reduction ratio.

Celebi (2006) presented two mathematical models and numerical techniques for solving problems associated with the wave propagation in a track and an underlying soil due to passing trains. He utilized BEM to investigate the three-dimensional dynamic response of the free field nearby railway lines induced by the moving loads acting on the surface of a homogeneous soil deposit.

In this research, the foundation, soil, and wave barriers are modeled using 3D finite elements by ANSYS software; results are displayed in the form of dimensionless graphs for a range of trench locations, rate of harmonic loading and frequency of harmonic loads to improve understanding the active isolation by open trenches mechanism.

2 PROBLEM DEFINITION

Figures 1 and 2 illustrate the problem. A rigid circular footing (source) of radius B_f resting on a soil layer of a limited thickness underlain by a hard stratum at a depth H and length L is subjected to a harmonic load $P_0 \sin(\omega t)$ (Figure1). An annular open trench of depth d and width w is installed at a center-to-center distance of r from the foundation (Figure 2). The first step in simulating a real problem by a numerical method is to obtain realistic soil parameters corresponding to the field conditions. Soil type is selected based on the soil properties used in Woods' test field: the soil layer posses a uniform dynamic elastic modulus $E_s = 90100 \text{ KN/m}^3$, Poisson's ratio $\nu_s = 0.35$, mass density $\rho_s = 16.35 \text{ KN/m}^3$, and material damping coefficient $\beta_s = 0.05$, and Rayleigh wave velocity 126.5 m/s (415ft/s).

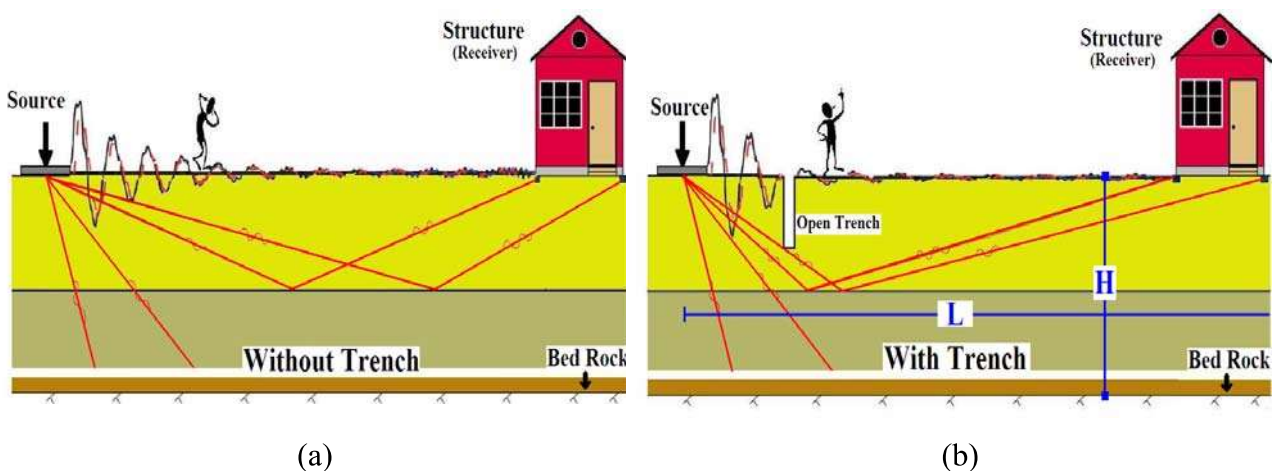


Fig.1 Schematic diagram of trench performance to reduce surface wave energy
 (a) model without trench (b) model with trench

3 ASSUMPTION

The soil is assumed to be isotropic and homogenous with Drucker-Prager yield criterion for plastic deformations and yielding. The soil properties are considered to be uniform throughout the depth of the layer and the hard stratum (the base of the model) is considered to be very rigid compared to the soil layer. Furthermore, a full contact exists between the foundation and the soil beneath. The dynamic response to the harmonic load is merely considered in this research, which means the static response due to the weight of the machine, the foundation, and the soil are not considered in analyses; finally, time-history (Transient) analyses are performed on the FEM.

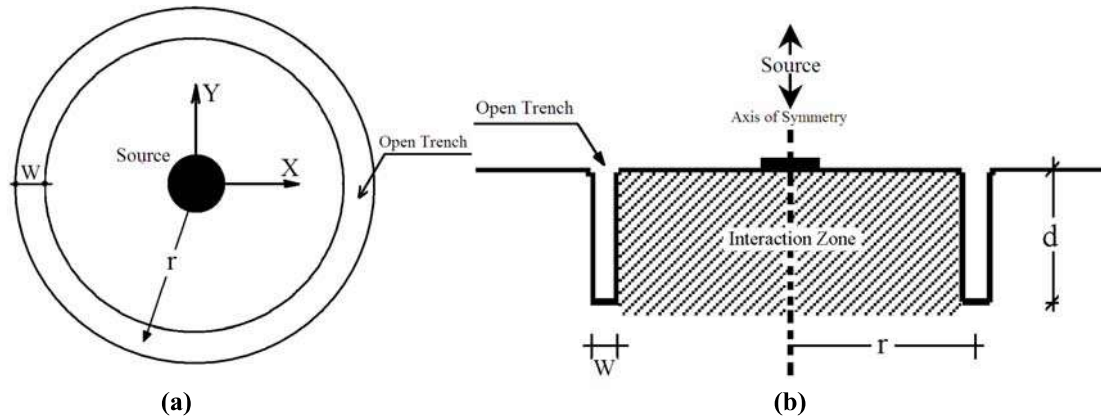


Fig.2 Problem definition active isolation by open trench (a) plan, (b) elevation

4 FINITE ELEMENT MODELS

4.1 The geometry of model

The problem is symmetrical, therefore only 1/4 of the actual model with proper boundary conditions is considered in the analysis. Soil as the basic material with natural material damping is used in stimulating the half space (Wolf and Song, 1996). By selecting the model dimensions large enough, it is possible to prevent the wave reflection from the boundaries. Thus, the response of soil in interaction zone is similar to the half space. Owing to the fact that two-third of energy of vibrations transmits by surface waves, on selecting appropriate model dimensions not to reflect the surface wave, other waves are claimed to be damped. Equation 1 is used to estimate the appropriate model dimensions:

$$A = A_1 \sqrt{\frac{x_1}{x}} \exp(-\alpha(x - x_1)) \quad (1)$$

Where:

A = computed or measured amplitude at distance x from vibration source.

A₁ = amplitudes at distance x₁.

α = coefficient of attenuation

Taking the value of α as 0.05 (Barkan 1962) with the ratio of A₁/A as 0.025 and x₁= 15m (the longest radial distance from the source studied in this paper), x can be computed as:

$$0.025 = \sqrt{\frac{15}{x}} \exp(-0.05(x - 15)) \Rightarrow x \approx 72 \text{ m} \quad (2)$$

Considering the body waves propagation with the noticeable soil damping, the depth of model to prevent any wave reflection from the boundaries, is computed through trial and error as 30m. Accordingly, a homogeneous, isotropic, non-linear soil cylinder with radius of 72m and height of 30m is utilized in this research.

4.2 Boundary Condition:

Symmetry boundary, loading and geometry of model conditions are applied along the axis of symmetry by restraining the displacement in the x and y directions: the y displacements in x direction together with x displacement along y axis are restrained. Having selected the appropriate model dimensions to avoid wave reflecting from the boundaries, the freedom degrees are restrained in x and y directions. The hard stratum underlying the soil layer could be bedrock, hard clay till, or very dense sand, which is much stiffer than the overlying soil would practically reflect all incident waves. Therefore, it is reasonable to assume that this stratum represents a rigid boundary and the base of the model is assumed to be fixed. The geometry of FEM, meshing method and boundary conditions are shown graphically in Figure 3.

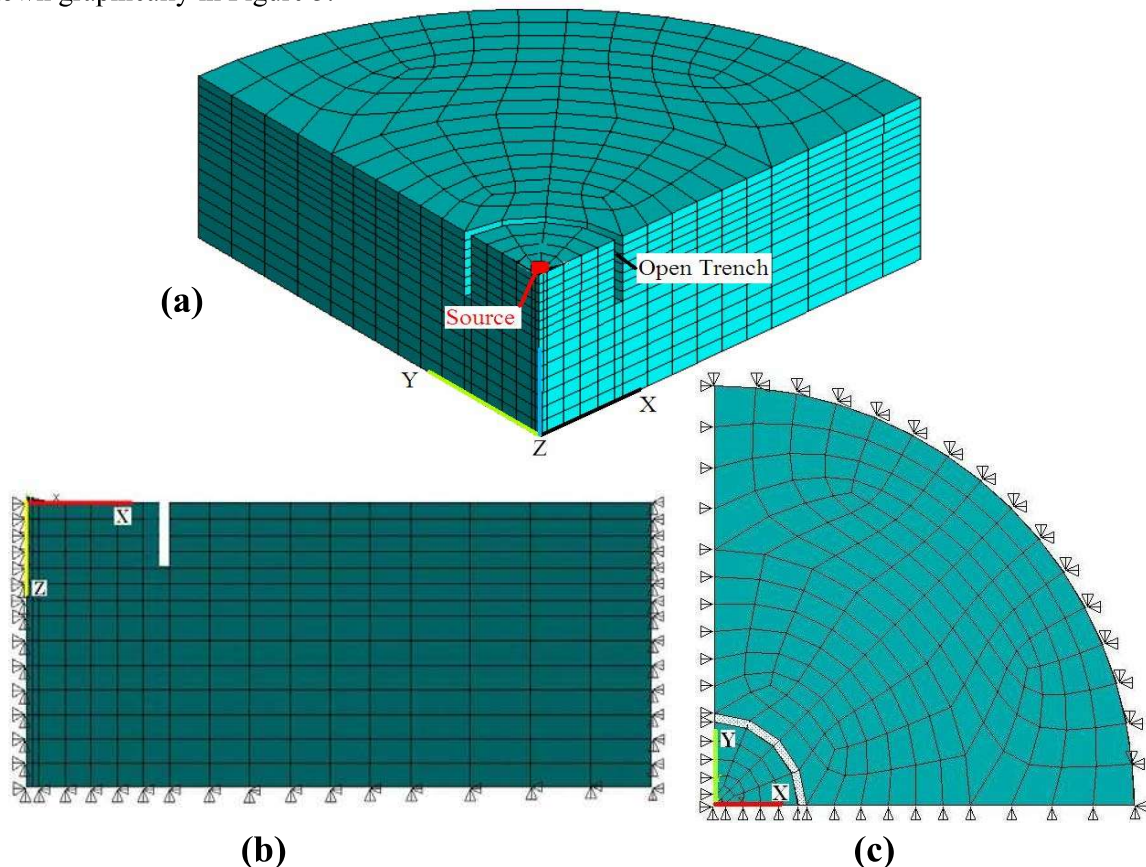


Fig.3 The geometry of finite element model
a) 3D model, b) elevation, c) plan

4.3 Element type

SOLID45 is used for 3D modeling of foundation and soil, defined by eight nodes and three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, as well as large strain capabilities (Figure 4).

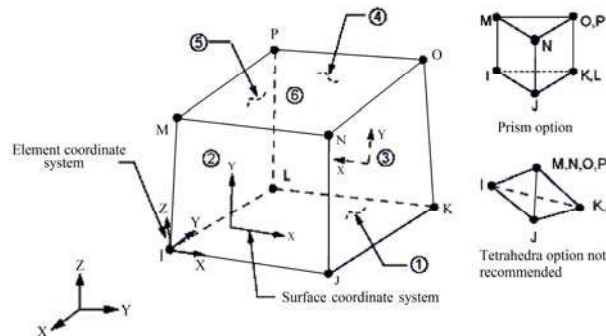


Fig.4 Three-dimensional eight-noded element used in the finite element mesh

4.4 Foundation Model:

The foundation is merely to transmit the forces from source to the soil and its performance is not examined. Therefore, very high stiffness is assigned to the solid elements; it is restrained against horizontal displacement and rotation to ensure that the foundation, as a rigid body, moves in the vertical direction only. The foundation elements are glued to the soil elements at the nodes, assuming full contact along the foundation–soil interface.

4.5 Drucker-Prager yielding criterion

One of the most important parts of numerical analysis is to simulate the actual soil behavior under subjected loads. In almost every published papers, linear behavior of materials was investigated. In this research, however, non-linear behavior of material under subjected loads is studied. As mentioned earlier, non-linear Drucker-Prager (DP) yielding criterion is applied to study the trench performance [Drucker and Prager, 1952]. The DP option is applicable to granular (frictional) material such as soils, rock, and concrete using the outer cone approximation to the Mohr-Coulomb law defined by the following constants:

C: The cohesion value; $C = 34.33 \text{ KN/m}^2$.

Φ : The angle of internal friction; $\Phi = 38^\circ$.

Ψ : The dilatancy angle; $\Psi = 8^\circ$.

It should be noted that the amount of dilatancy (the increase in material volume due to yielding) could be controlled with the dilatancy angle. If the dilatancy angle is equal to the friction angle, the flow rule is associative. If the dilatancy angle is zero (or less than the friction angle), there is no (or less of an) increase in material volume when yielding and the flow rule is nonassociated.

4.6 Damping

Referring to the software manual (ANSYS), the damping matrix (C) is calculated by multiplying the following constants to the mass matrix (M) and stiffness matrix (K):

$$[C] = \alpha_r [M] + \beta_r [K] \quad (3)$$

The Rayleigh damping is material-dependent damping (β_s) calculated by Equation 4.

$$\beta_s = \frac{\alpha_r}{2\omega_i} + \frac{\beta_r \omega_i}{2} \quad (4)$$

Where ω_i is the natural circular frequency of mode i.

In many practical soil related problems, alpha damping is ignored $\alpha_r = 0$ (Idriss and Seed, 1974) since it can lead to undesirable results if a large mass has been introduced into the model. By selecting $\beta_s = 0.05$, α_r and β_r could be evaluated as following:

$$\beta_r = \frac{0.05}{\pi f} \approx 5 * 10^{-3}, \quad \alpha_r = 0 \quad (5)$$

5 MODEL VERIFICATION

Assuring the accuracy of the FE model, the Woods' field study (test AF6-300) and BEM (Ahmad 1996) are simulated numerically. Woods' soil profile with the following properties is used for FE model verification: $D = 0.6096\text{m}$ (2ft), $R = 0.3048\text{m}$ (1ft), $B_i = 0.0508\text{m}$ (2in), $W = 0.0762\text{m}$ (0.25ft), $L = 3.65\text{m}$ (12ft). A vertical load $P_0 = 80.1 \text{ N}$ (18lb) with frequency of 300Hz exerting on the foundation. Amplitude Reduction Ratio (A_{rr}) was established by Woods to investigate vibration isolation:

$$A_{rr} = \frac{\text{Vertical displacement amplitude of ground surface with the barrier}}{\text{Vertical displacement amplitude of ground surface without the barrier}} \quad (6)$$

Figure 5 presents a comparison between the results of Woods's tests, Ahmad's and the FEM solution. In an average sense, the FEM solution agrees reasonably well with Woods's and Ahmad's test results.

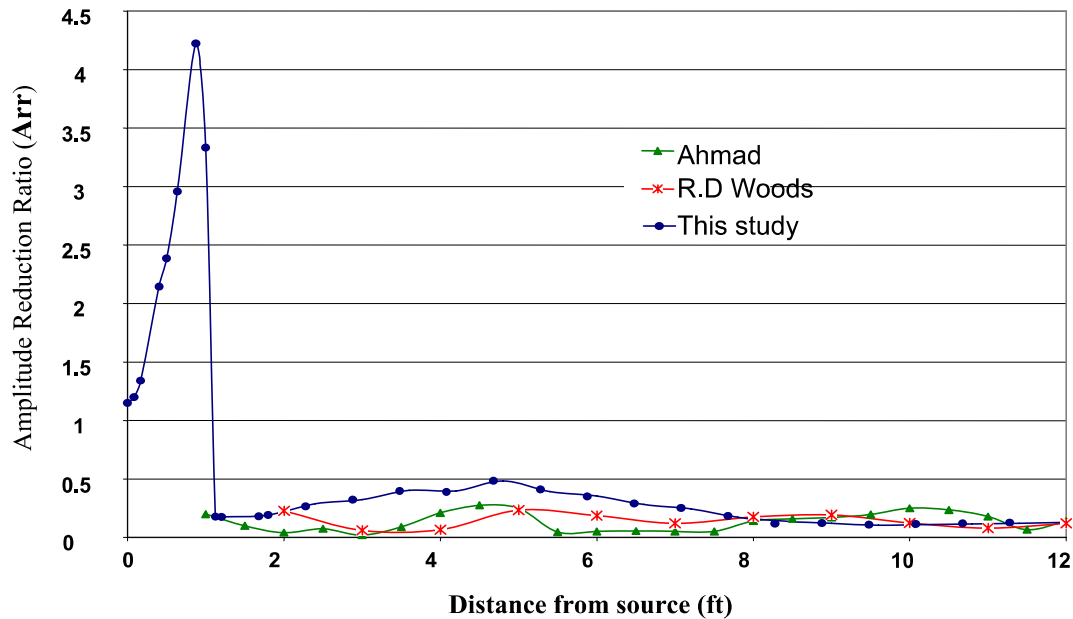


Fig.5 Comparative study of active isolation by open trench [Hamissi (2007)]

6 RESULTAND DISCUSSIONS

For the sake of generalization, the geometric parameters and the results are presented in a dimensionless form. Generally, the foundations with constant radius have the similar behavior under dynamic loads. For this reason, the geometric parameters are normalized by the radius of foundation (B_f) (Equation 7 and table 1). The vertical displacements of several nodes at different locations on the soil surface are obtained through time history analyses in front of and behind the trench. The maximum vibration amplitude is computed from each time history. The vibration amplitudes for different nodes are tabulated for the with-trench and without-trench cases. The with-trench amplitudes are normalized by that of the without-trench cases and are plotted as a vibration-reduction factor versus the radial distance, to be normalized by B_f .

$$D = \frac{d}{B_f} \quad , \quad R = \frac{r}{B_f} \quad , \quad W = \frac{w}{B_f} \quad (7)$$

6.1 The effects of trench location

Studying the applicability of trenches, various radial trench locations have been examined for a single trench with the depth of 12m ($D/B_f=8$) and width of 1.5m ($W/B_f=1$). From the diagram of A_{tr} plotted against the radial distance from the source, two different zones can be observed: the first, in front of the trench, is the zone between the vibration source and trench; the second zone is beyond the outer edge of the trench. Amplitude magnification (indicated by $A_{tr} > 1.0$) is observed in front of and near the end of the trench, caused by wave reflection, demonstrating a critical situation due to trench installation, which should be considered in geotechnical design. However, regarding second zone, the magnitude of A_{tr} is less than 1.0 showing desired situation (Figure 6).

Figure 7 shows the effects of average amplitude reduction \bar{A}_{tr} (the average of A_{tr} from outer edge of trench to the boundary) against the normalized distances of trench from the source. In case of middle distances ($R \approx 6$), the effectiveness of trenches is observed to be improved; however, in case of farther distances the A_{tr} appears to increase showing a reduction in trench efficiency. In addition to the shorter distances, reflected waves from trench boundaries have more adverse effects due to creating stronger peaks and valleys. Lastly, it is reasonable to conclude that the middle distances ($R \approx 6$) can be the optimum trench location [Hamissi (2007)].

Table 1. Open trench geometric parameters

	Trench Depth	Trench Location			Trench Width
Real Size (m)	12	4.5	9	15	1.5
Normalized by B_f	8	3	6	10	1

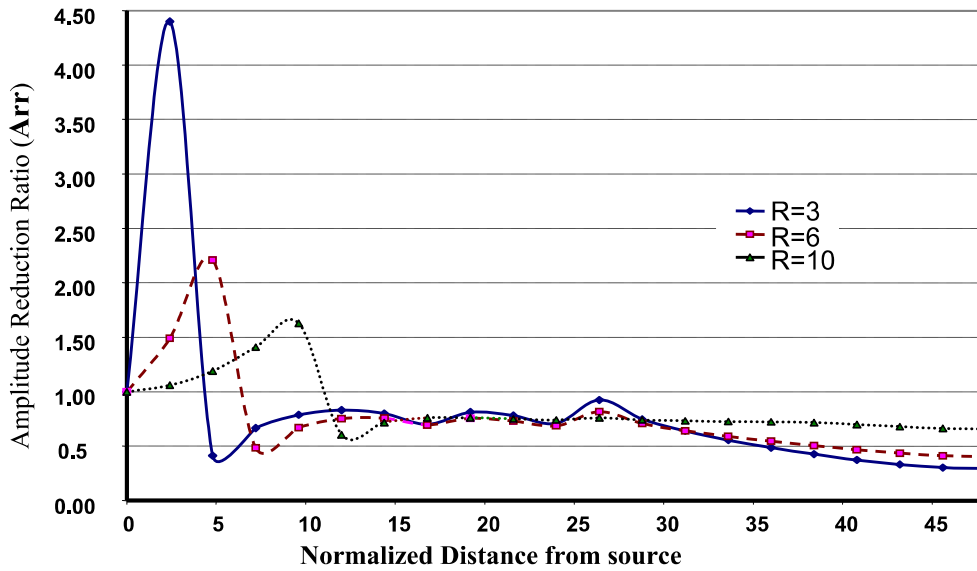


Fig.6 Comparative A_{rr} trends against distance from source for the various trench locations

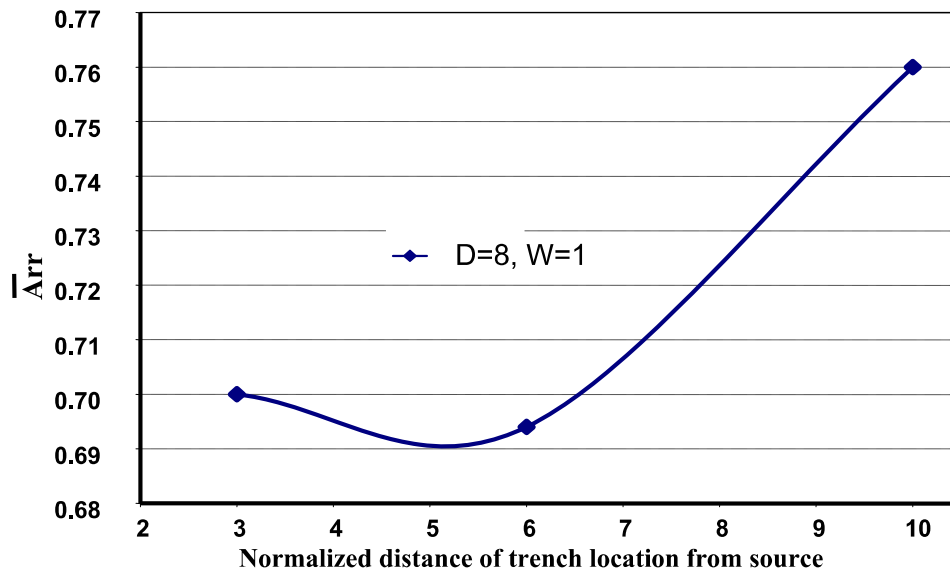


Fig.7 Comparative A_{rr} trends versus various trench locations

6.2 The effects of applied loads

Loading is one the parameters considered in estimating trench effectiveness. Trenches were concluded to be inefficient to reduce vibration energy for shock producing equipment [El Naggar (2005)]. In this paper, the foundation is subjected to a harmonic vertical load, $P_0 \sin(\omega t)$ with wide range of magnitudes ($P_0=25, 50, 75, 100, 200$ KN) and frequencies ($\omega=10, 100, 200, 300$ Hz). Figure 8 represents the A_{rr} diagram plotted against the radial distances for several load magnitudes highlighting the fact

that the P_0 (magnitude of the force) has no effects on amplitude reduction (A_{rr}). Contrary to the load magnitudes, frequency plays more significant role in amplitude reduction, to put it more simply, in case of higher frequencies trenches have more efficient performance and the poorer performance is measured for the lower frequencies (Figure 9) [Hamissi (2007)].

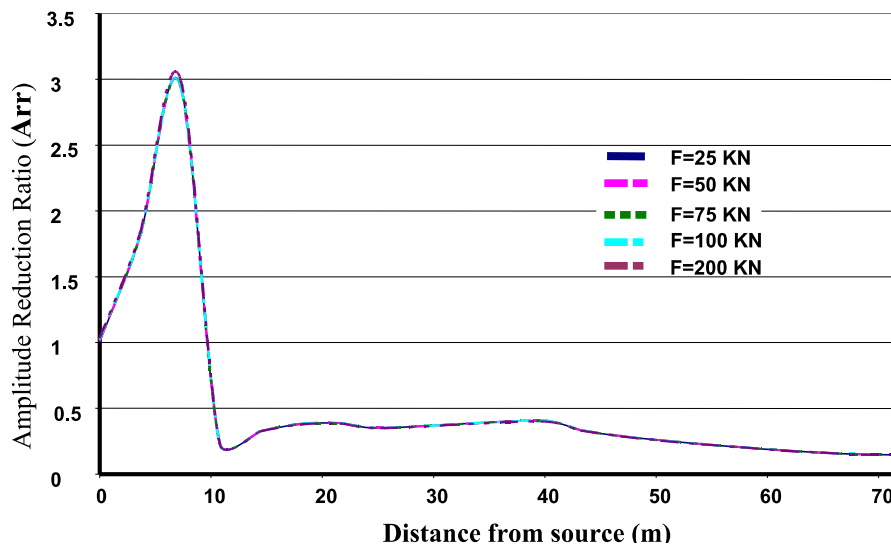


Fig.8 The effects of harmonic load magnitudes on trench efficiency

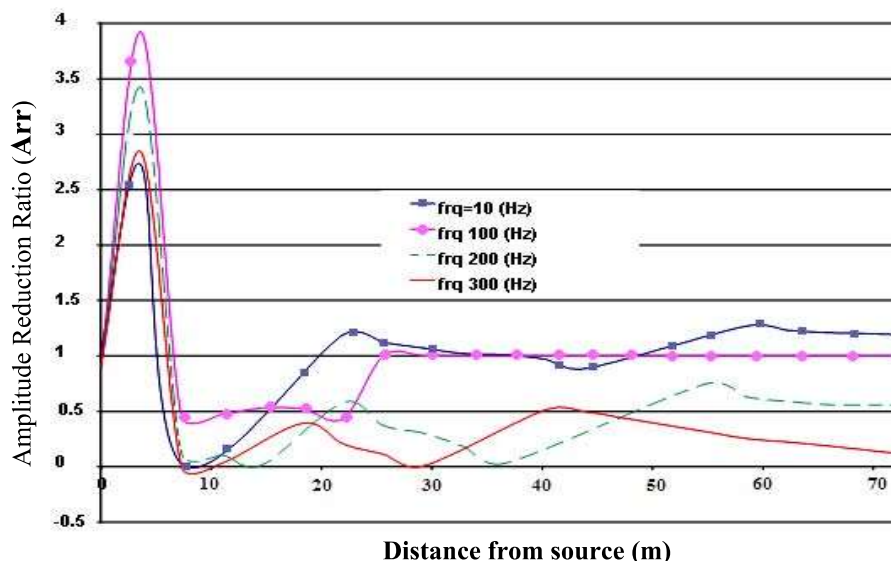


Fig.9 The effects of harmonic frequencies on trench efficiency

7 CONCLUSIONS

A three dimensional Finite Element Method is employed to study active isolation for shallow foundations by an open annular trench employing transient analyses with the computer program ANSYS. Taking into the account the obtained results with the pertinent soil properties, the following conclusions are drawn:

1. Two different zones can be seen by excavation of trench, the first zone is critical zone; however, the second zone is screened zone.
2. The magnitude of harmonic loads is inefficient in vibration screening.
3. The effectiveness of open trench as wave barrier increases as the frequencies of harmonic load increase.
4. The reflected waves from the wave barrier have more adverse effects as the distance from the source becomes shorter.

5. The normalized middle distances ($R \approx 6$) are concluded to be the optimum trench location.

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