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An innovative vibration barrier by intermittent geofoam – A numerical study

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Abstract. A new technique is proposed to obtain more effective screening efficiency against the ground vibration using intermittent geofoam (*IF*) in-filled trench. The numerical analysis is performed by employing two-dimensional finite element method under dynamic condition. Vertically oscillated strip foundation is considered as the vibration source. In presence of the ground vibration, the vertical displacements at different locations (pick-up points) along the ground surface are captured to determine the amplitude reduction factor (*ARF*), which helps to assess the efficiency of the vibration screening technique. The efficiency of *IF* over continuous geofoam (*CF*) in-filled vibration barriers is assessed by varying the geofoam density, the location of trench and the frequency of excitation. The results from this study indicate that a significant reduction in *ARF* can be achieved by using intermittent geofoam as compared to continuous geofoam. Further, it is noticed that the efficiency of *IF* increases with an increase in the frequency of the vibrating source. These encouraging results put forward the potential of utilising intermittent geofoam as a vibration screening material.

Keywords: amplitude reduction factor; finite element analysis; geofoam; vertical oscillation; vibration screening

1. Introduction

Vibration barriers are generally provided to mitigate or retard the level of ground vibrations induced by different sources such as road traffic, railways, construction operations, machine foundations, blast activities etc., which might cause unfavourable effects otherwise. Vibration barriers play a major role for changing the wave propagation characteristics of the soil medium. The phenomenon includes both wave scattering as well as diffraction of the surface waves. The efficiency of vibration screening system largely depends on several factors such as the geometry of the trench/barrier and the frequency of the vibration source. A number of studies (Banerjee *et al*. 1988, Dasgupta *et al*. 1988, and Ahmad *et al*. 1994) have indicated that the efficiency of vibration screening system is predominantly dependent on the depth of trench. The vibration barrier may be placed close to or surrounding the source of disturbance (active or near-field isolation) or may be installed away from the source of disturbance (passive or far-field isolation). The demarcation

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between the active and the passive vibration screening is extensively dependent on the Rayleigh wavelength (λ_R) and Poisson's ratio (v) (Gao *et al*. 2014). The efficiency of the vibration barriers in minimising the transmission of waves through the barrier may be increased by maximising the impedance mismatch between the adjacent soil and the barrier. It is well proven by several researchers that the open trench (*OT*) tops the list of effective vibration barrier, since the acoustic impedance of air is pretty low as compared to the mechanical impedance of soil (Woods 1968, Segol *et al*. 1978, Massarsch 2005, Celebi *et al*. 2009, Babu *et al*. 2011, Saikia and Das 2014, Ulgen and Toyger 2015). The acoustic impedance is the product of the density (ρ) of material and the longitudinal wave velocity (V_P) through the same material, which defines how fast the waves propagate through the medium. Therefore, lower the value of the acoustic impedance, lower is the wave propagation through the material. In recent times, several alternative barrier materials such as concrete walls (Woods *et al*. 1974, Kattis *et al*. 1999), flexible gas cushion (Massarsch 2005), soil bentonite (Ahmad and Al-Hussaini 1991), wave impeding blocks (Çelebi and Göktepe 2012, Göktepe *et al*. 2014) and the materials with lower shear wave velocity (Saikia 2014) are being used to retard the ground vibrations; one such is the utilisation of geofoam as an in-filled vibration barrier. Geofoam is basically expanded polystyrene (EPS) or extruded polystyrene (XPS) manufactured into large lightweight blocks. Geofoam has three-dimensional closed cell structural arrangements whose 95% of volume is occupied by air; thus, making it lightweight material (1% of the weight of the traditional earth material) and achieves low acoustic impedance. Geofoam has been considered as the compressible inclusion to reduce the active earth-pressure behind the retaining wall (Zarnani and Bathurst 2007), seismic buffer (Inglis *et al*. 1996) and active in-filled vibration barrier (Davies 1994). Even though it has been reported that geofoam can play an effective role in screening the vibrations (Wang *et al*. 2006, Alzawi and El Naggar 2009, Murillo *et al*. 2009, Alzawi 2011, Ekanayake *et al*. 2014, Zoccali *et al*. 2015), not much attention has been given on the usage optimization of geofoam to achieve the intended purposes. Geofoam in-filled barrier gives flexibility in the design, but the usage of geofoam with large quantity at greater depth seems to be uneconomical. Therefore, in this study, keeping usage optimization in mind, a new screening technique namely intermittent geofoam in-filled trench is devised, where geofoam and air pockets are placed alternately; henceforth will be termed as *IF*. The active vibration screening efficiency of the intermittent geofoam in-filled trench in comparison with the open as well as continuous geofoam in-filled trench is estimated using finite element analysis.

2. Methods and materials

2.1 Problem formulation

In this study, rigid dynamically loaded strip foundation is considered (Triandafilidis 1965, Richart *et al*. 1970), which is commonly used in factories, large machine foundations and offshore platforms. The foundation subjected to a vertical dynamic excitation of $P(t) = P_0 \sin(\omega t)$ is placed on dry homogeneous soil deposit with an embedment factor (D_f/B) of 1.0. Considering a moderately high-speed machine, constant force amplitude of sinusoidal dynamic load, P_0 of 1 kN with an operating frequency, F of 5 Hz for a duration, t of 10 seconds is applied on the foundation. In addition, a static working load intensity of 10 kN/m^2 is considered as the self-weight of the machine and other accessories, which is found to be well below the ultimate failure load of the foundation under static condition. An active vibration isolation system is devised adjacent to the machine foundation using a combination of air pockets (void space) and geofoam arranged

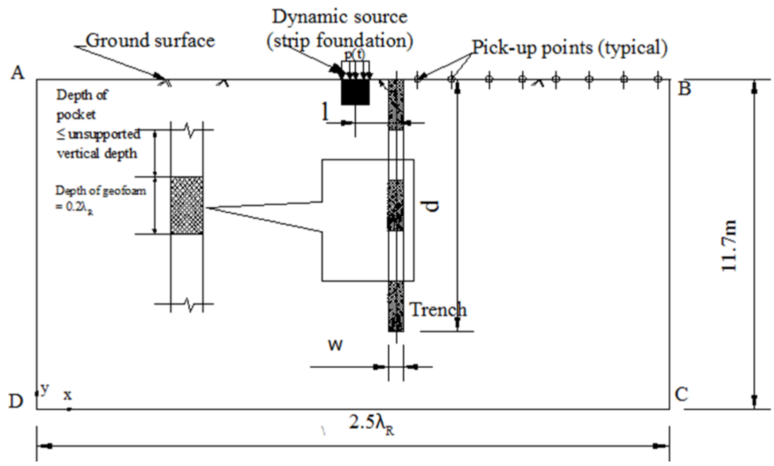


Fig. 1 Schematic diagram of influence domain and its geometric parameters

alternately throughout the depth of the trench.

Fig. 1 shows the schematic representation of the influence domain with trench at one side, geometric parameters of *IF*, typical locations of pick-up points on the surface adjacent to the trench. The efficiency of *IF* over the open trench (*OT*) and the continuous geofoam in-filled trench (*CF*) considering dynamically loaded strip foundation is studied using two-dimensional plane strain finite element analysis.

Fig. 2 shows the two dimensional pictorial view of the influence domain along with *IF*. In addition, the influence of distance between the vibration source and the barrier, the material properties of geofoam and the frequency of the dynamic excitation on the screening efficiency of *IF* is also studied.

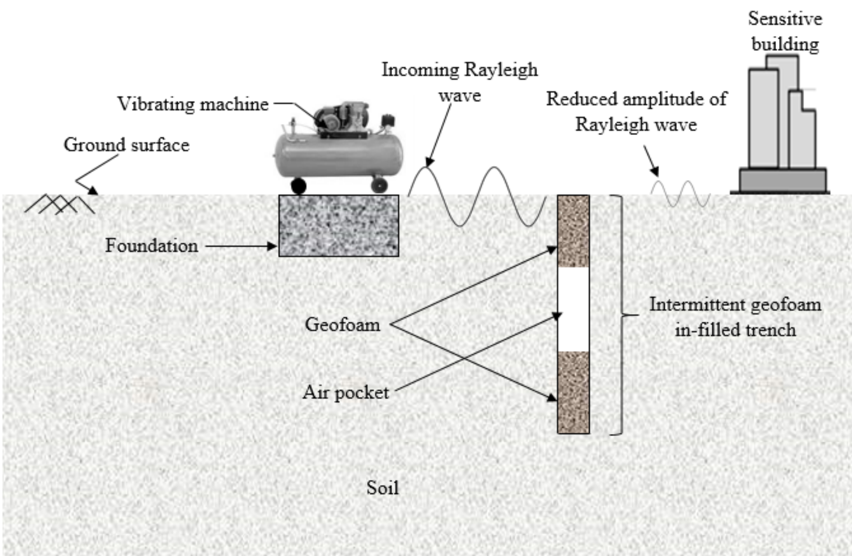


Fig. 2 Pictorial view of influence domain

Table 1 Properties of EPS geofoam (ASTM D6817)

Properties	EPS12	EPS15	EPS19	EPS29
Density (ρ) (kg/m^3)	11.2	14.4	18.4	28.8
Elastic modulus (E_G) (MPa)	3.3	5.5	8.8	16.5
Poisson's ratio (v)	0.1	0.1	0.1	0.1
Acoustic impedance (Z_G) (kN-s/m^3)	7.72	9.96	12.61	17.26

2.2 Material properties

In the present analysis, expanded polystyrene (EPS) geofoam is considered as a potential vibration barrier material. As per ASTM D6817, the properties of EPS geofoam are shown in Table 1.

It is worth noting that due to very low stiffness value, the geofoam may squeeze under large confining pressure offered by the side soil, which can be however, prevented by providing some lateral stiffener during the installation process. The installation and serviceability aspects of geofoam in-filled trench in the field are beyond the scope of the present study. An idealised homogeneous subsoil strata extending up to a depth of 11.7 m followed by bedrock is considered in the present study (Ghosh and Kumari 2012). Table 2 lists the static and dynamic material properties of the soil deposit, adopted from the layer one of subsoil used by Ghosh and Kumari (2012).

The water table is assumed to be at great depth and hence, it is assumed to have no significant impact on the dynamic response analysis. The embedded concrete foundation has the bulk and the shear modulus of 1.39×10^7 kN/m^2 and 1.04×10^7 kN/m^2, respectively. As mentioned earlier, the intermittent geofoam is formed by alternate arrangement of geofoam and air pockets. The height of each pock*et al*ong the depth of the trench is determined based on the concept of unsupported vertical cut in soil. The unsupported vertical height of the adopted soil deposit is determined as 2.6 m. By keeping the pocket height lesser or equal to the unsupported vertical depth, the intermittent

Table 2 Static and dynamic properties of soil layer

Properties	Soil deposit
Bulk unit weight, γ (kN/m^3)	17
Undrained cohesion, c_u (kN/m^2)	19.4
Internal friction angle, ϕ (°)	24.7
Static elastic modulus, E_s (kN/m^2)	2.06×10^3
Dynamic elastic modulus, Ed (kN/m^2)	4.20×10^4
Shear modulus, G (kN/m^2)	1.61×10^4
Shear wave velocity, V_s (m/s)	96.57
Rayleigh wave velocity, V_R (m/s)	89.52
Rayleigh wavelength ($\lambda_R = V_R/F$) corresponding to F = 5 Hz (m)	17.9
Acoustic impedance ($Z_S = \rho \times V_P$) (kN-s/m^3)	306.85
α (Rayleigh damping coefficient)	0.146
β (Rayleigh damping coefficient)	2.215×10^{-3}

geofoam is placed within the trench in three layers with a depth of 0.2 times λ_R of the soil deposit (Fig. 1). It is worth noting here that the total volume ($0.03\lambda_R^3$) of geofoam is kept constant along the depth of the trench by varying the height of void space without violating the concept of unsupported vertical depth. Fig. 3 represents the details of geometry of the air pockets as well as the intermittent geofoam used in the trench.

2.3 Numerical modelling

The failure domain is discretized with six-noded triangular elements using *PLAXIS V8.5* (PLAXIS 2002), which are found to generate fairly accurate solution in standard deformation problems (Fig. 4). The distance between the vibration source and the vibration barrier (l), the width (w) and the depth (d) of the vibration barrier are reported as non-dimensional terms by normalising with respect to λ_R of the soil deposit. Eventually, the vertical displacements at different pick-up points along the ground surface (Fig. 1) are captured during the dynamic analysis. The soil and foundation nodes are connected by the interface element of virtual thickness. Generally, the interface is considered weaker and more flexible than the associated soil layer for the real soil-structure interaction. Therefore, throughout the analysis, the strength reduction factor (R_{inter}) is assumed in the order of 0.67 for the interface. However, the problem is associated with very low strain level ($< 10^{-3}$ %) and therefore, no strength reduction factor is used at the interface

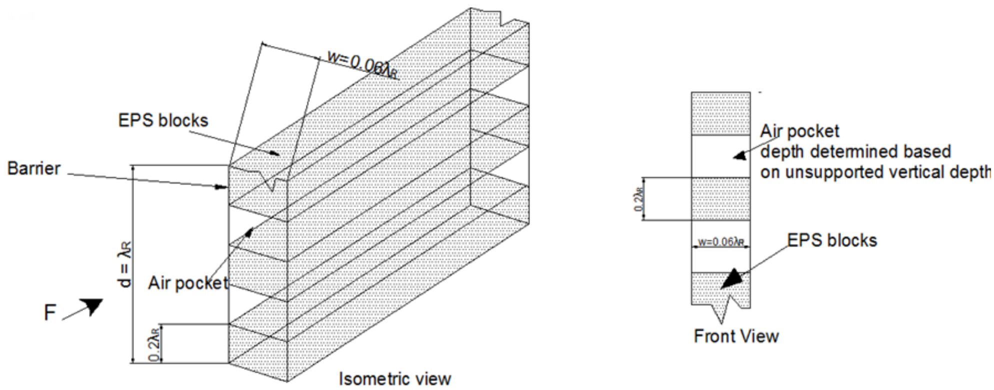


Fig. 3 Details of geometry of intermittent geofoam in-filled trench

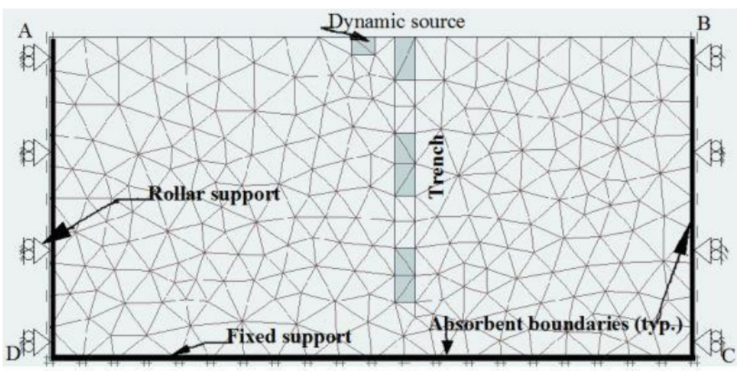


Fig. 4 Finite element discretization and boundary conditions

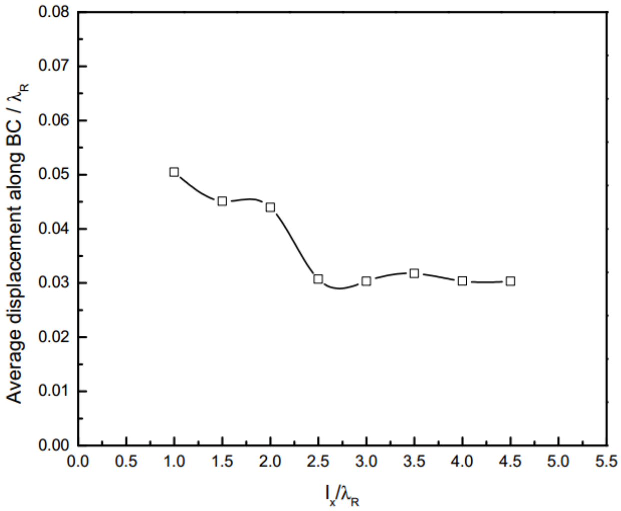


Fig. 5 Sensitivity analysis for domain size along horizontal direction

between the geofoam and the soil.

Sensitivity analysis is carried out to determine the optimum domain size based on the average displacement along the vertical boundary (BC) of the influence domain (ABCD) normalized with respect to λ_R of the soil deposit (Fig. 1). The magnitude of λ_R of the soil deposit corresponding to 5 Hz frequency is mentioned in Table 2. The average displacement along the vertical boundary is obtained by averaging the displacements recorded along BC at an interval of $0.1\lambda_R$. The results of sensitivity analysis are shown in Fig. 5. It can be observed that the effect of domain size beyond $2.5\lambda_R$ in the horizontal direction (l_x) on the normalized average displacement along the vertical boundary (BC) is minimal. Hence, the domain size is assumed as $2.5\lambda_R$ along the horizontal direction, whereas the domain along the vertical direction is considered up to the bed rock level (11.7 m).

The average element size ($0.121\lambda_R$) is chosen by satisfying the criteria of wave propagation as proposed by Kramer (1996). In case of static analysis, the boundaries can be considered completely free or fixed in one or two directions so that the extreme boundaries of the failure domain do not significantly influence the deformation behaviour of the structure to be modelled, whereas the model boundaries are generally taken far away in case of dynamic analysis than that considered in the static analysis to avoid the disturbances due to possible reflections of waves leading to distortion in the computed results. Total fixities are applied at the base of the model, whereas horizontal fixities are applied at the extreme vertical boundaries restraining the motion along the horizontal direction as shown in Fig. 4. In addition, the absorbent boundary condition is considered at the extreme boundaries to absorb the increment of stresses on the boundaries caused by the dynamic loading and to avoid the reflection of waves back to the soil body as described by Lysmer and Kuhlmeyer (1969). Total dynamic excitation time is considered as 10 seconds, where the time step considered in the present dynamic analysis satisfies the following relation (Valliappan and Murti 1984)

$$\Delta t \leq \frac{Average\ element\ size}{Velocity\ of\ slowest\ propagating\ wave} \tag{1}$$

The damping is an important factor influencing the dynamic analysis significantly (Prathap Kumar *et al*. 2010, Babaei *et al*. 2015, Chatterjee *et al*. 2015). The damping ratio (ξ) of 5% is quite common in the vibration isolation problem (Al-Hussaini and Ahmad 1996, Alzawi and Naggar 2009) and therefore, in this study the magnitude of ξ is assumed as 5%. Rayleigh damping is assumed for simulating the viscous damping, which is proportional to the mass and stiffness of the system and can be defined as

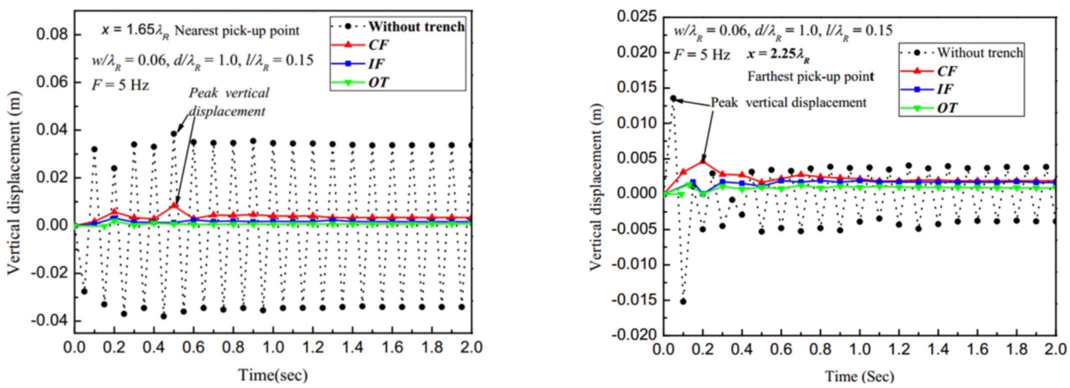
$$[C] = \alpha[M] + \beta[K] \tag{2}$$

where, α and β are the Rayleigh damping coefficients. In Eq. (2), α and β determine the influence of mass and stiffness in the damping of the system, respectively. The values of Rayleigh damping coefficients (α and β) can be evaluated by choosing 1st and 2nd natural frequency (f_1 and f_2) of the soil deposit. The magnitudes of α and β for the soil deposit are determined considering a constant damping ratio of 5% and are given in Table 2.

3. Results and discussion

Three types of vibration screening techniques namely, open trench, continuous geofoam in-filled trench and intermittent geofoam in-filled trench are considered in the present study. The efficiency of the vibration barrier against the ground vibration can be estimated by measuring the reduction in the vertical displacement at different pick-up points along the ground surface before and after installation of the barrier. More precisely, it can be quantified using amplitude reduction factor (*ARF*) which is defined as the ratio of peak vertical displacement measured at a particular pick-up point after and before installation of the vibration barrier (Woods 1968). Hence, lesser the magnitude of *ARF* better is the screening performance. The location of pick-up points along the ground surface is varied from $1.65\lambda_R$ to $2.25\lambda_R$. Figs. 6(a)-(b) present the vertical displacement response of the soil deposit recorded at the nearest pick-up point (x/λ_R = 1.65) and at the farthest pick-up point (x/λ_R = 2.25), respectively.

The vertical displacement amplitudes for all the cases at x/λ_R = 1.65 (Fig. 6(a)) are found to be significantly higher than those observed at x/λ_R = 2.25 (Fig. 6(b)), which confirms the dimini-



(a) (b)

Fig. 6 Vertical displacement response at pick-up points: (a) $x = 1.65\lambda_R$; (b) $x = 2.25\lambda_R$

shing trend of displacement amplitude with increase in the distance from the vibration source. However, in both the extreme pick-up points, considerable reduction in the peak displacement amplitude can be noticed with the inclusion of vibration barriers when compared to a situation without any vibration barrier.

3.1 Validation

A number of investigations on the vibration screening technique using open trench are available in literature; however, the same using continuous geofoam are scanty and it is almost nil using intermittent geofoam. Hence, an attempt has been made to compare the open trench results obtained from the present study to those of reported studies. Fig. 7 shows the comparison of *ARF* values obtained from the present analysis considering open trench vibration barrier with the values reported by Kattis *et al*. (1999), and Alzawi and El Naggar (2009) with l/λ_R = 0.4, w/λ_R = 0.06, d/λ_R = 0.5 and F = 50 Hz. It can be noticed that the *ARF* values obtained from the present study compare reasonably well with the values reported in literature. The present model is also validated with the reported experimental (Ahmad *et al*. 1995) as well as theoretical (Ahamd and Al-Hussaini 1991, and Ahmad *et al*. 1994) investigations considering concrete (PCC) in-filled barrier. The excitation frequency used for the machine foundation has been reported as 300 Hz (Ahmad *et al*. 1995). Ahamd and Al-Hussaini (1991), and Ahmad *et al*. (1994) have considered boundary element method to obtain the screening efficiency of concrete in-filled barrier. Fig. 8 shows the variation of average amplitude reduction ratio (A_{rr}) with normalized concrete wall depth, where A_{rr} can be defined as the average vertical displacement amplitude along the ground surface with and without the wave barrier. The present results are found to vary within 7-15% from the values reported by Ahamd and Al-Hussaini (1991), and Ahmad *et al*. (1994, 1995), which fairly justify the authentication of the current numerical model.

3.2 Efficiency of intermitted geofoam

In this section, the screening efficiency of *IF* over *OT* and *CF* is examined. Parameters

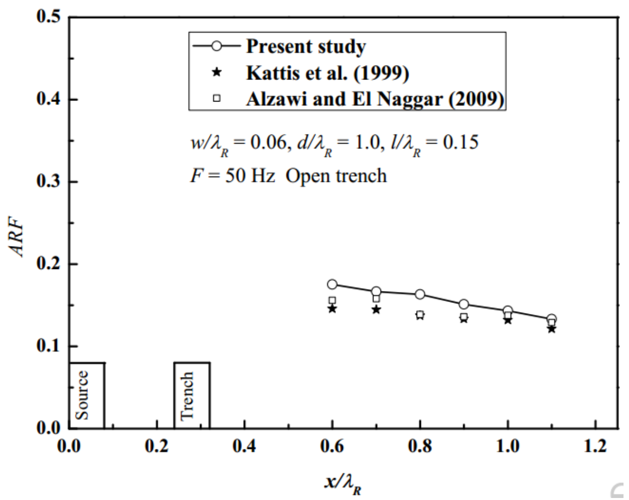


Fig. 7 Results from the validation study on open trench vibration barrier

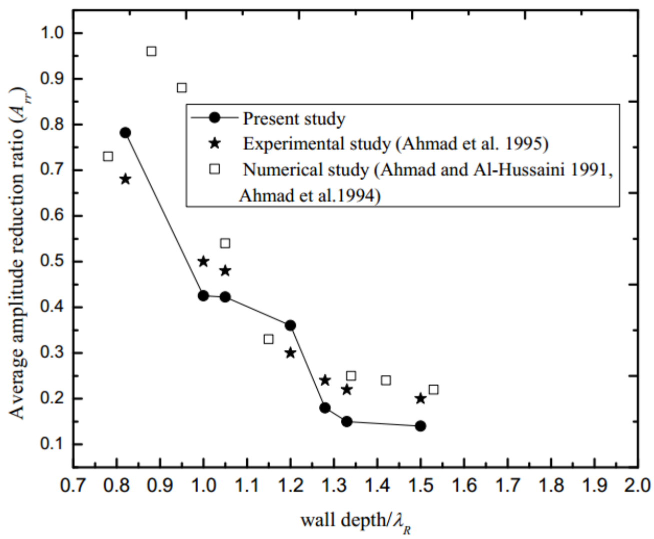


Fig. 8 Results from the validation study on concrete in-filled vibration barrier

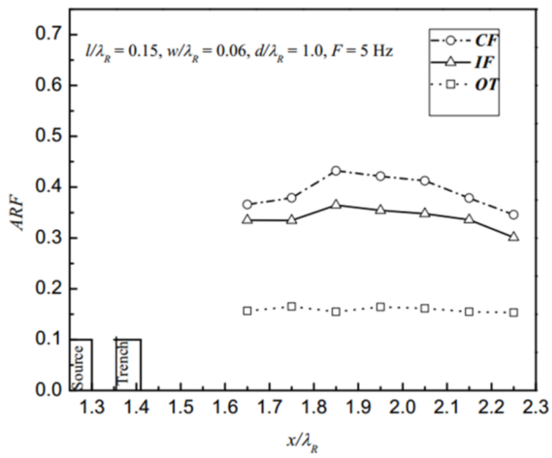


Fig. 9 Comparison of *ARF* among *OT*, *CF* and *IF* at different pick-up points

considered for the analysis are l/λ_R = 0.15, w/λ_R= 0.06, d/λ_R = 1.0 and F = 5 Hz. Fig. 9 shows the variation of *ARF* at different pick-up points obtained from various screening techniques. It can be noted that the *ARF* value does not reach maximum at the nearest pick-up point (x/λ_R = 1.65), rather happens at the pick-up point at x/λ_R = 1.85, which is in line with the observation made by Woods (1968). Hence, all the results are reported here based on the *ARF* values obtained at the pick-up point at x/λ_R = 1.85. It is worth noting that the *ARF* values obtained using open trench is found to be the lowest indicating the lower bound of the screening efficiency, hence for all subsequent figures the *ARF* variation of open trench has been included. It is also interesting to note that the screening efficiency of *IF* is found to be significantly lower than that of *CF*, which clearly demonstrates the applicability of the intermittent geofoam as an effective vibration barrier in comparison with the continuous geofoam. With an increase in d/λ_R from 1.0 to 1.2, keeping other

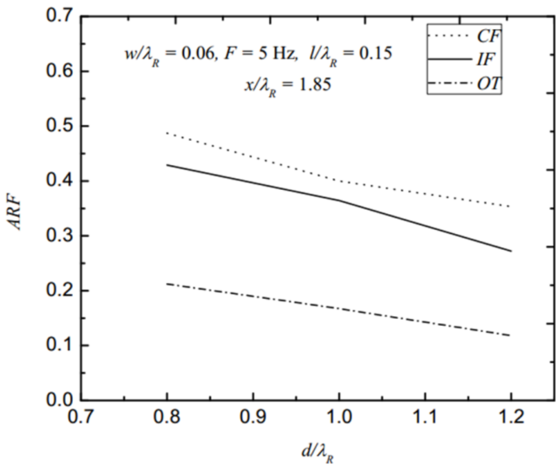


Fig. 10 Variation of *ARF* with depth of trench

parameters constant, the *ARF* value of *IF* is found to be reasonably lower than that of *CF* (Fig. 10). Therefore, by reducing the volume of geofoam or increasing the height of air pockets in the intermittent geofoam in-filled trench, it is possible to achieve better screening efficiency with *IF*. Having demonstrated the higher screening efficiency of *IF* over *CF*, the influence of geofoam density, location and inclination of the trench, and the excitation frequency on the performance of *IF* is addressed in the following sections.

3.3 Influence of geofoam density

The influence of density of geofoam on the screening efficiency of *IF* is studied by varying the density of geofoam as 28.8 kg/m^3 (EPS29), 18.4 kg/m^3 (EPS19), 14.4 kg/m^3 (EPS15), 11.2 kg/m^3 (EPS12), as per relevant ASTM standard (Table 1). Parameters considered for the analysis are $l/\lambda_R = 0.15$, $w/\lambda_R = 0.06$, $d/\lambda_R = 1.0$ and $F = 5$ Hz. Fig. 11 shows the variation of *ARF* with different

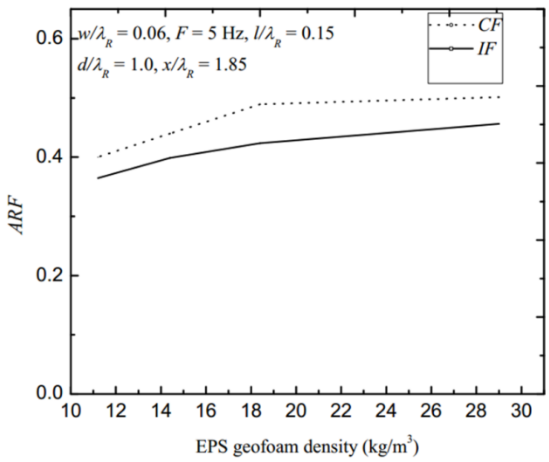


Fig. 11 Variation of *ARF* with geofoam density

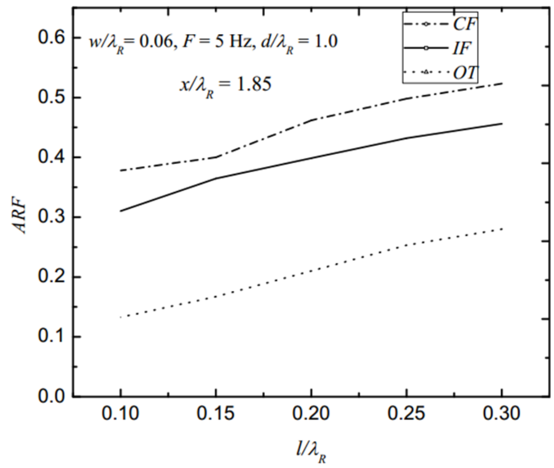


Fig. 12 Variation of *ARF* with location of trench

geofoam density. It can be noted that lower the density of geofoam, lower is the acoustic impedance and thus, better is the screening efficiency of *IF*. The maximum percentage increase in the efficiency of *IF* over *CF* in terms of *ARF* is found to be 13%.

3.4 Influence of location of vibration barrier

Various trench locations are considered to identify a suitable location of placing *IF* from the vibration source. Fig. 12 shows the variation of *ARF* with different trench locations keeping other parameters constant (w/λ_R = 0.06, d/λ_R = 1.0, F = 5 Hz). It can be noticed that the magnitude of *ARF* decreases from 0.456 to 0.310 with decrease in l/λ_R from 0.30 to 0.10, which indicates the enhancement in the screening effectiveness with decrease in the distance between the source and the trench. It is worth noting that the range of l/λ_R needs to be selected based on the wavelength of the Rayleigh wave. The location of trench is found to be an important parameter as the distance between the vibration source and the barrier increases; the screening efficiency reduces due to the arrival of more propagating waves. The maximum percentage increase in the efficiency of *IF* over *CF* in terms of *ARF* is found to be within 18%.

3.5 Influence of excitation frequency

Machines generally generate wide range of excitation frequencies. Hence, in order to understand the applicability of *IF* on different frequency domain, several frequencies ranging from 5 Hz to 50 Hz are considered in the analysis. Fig. 13 shows the variation of *ARF* with different excitation frequencies. It can be observed that the magnitude of *ARF* decreases with increase in the excitation frequency of the vibration source irrespective of vibration screening techniques. In other words, higher the frequency smaller is the wavelength and hence, there is an improvement in the screening efficiency. For example, at the pick-up point x/λ_R = 1.85, the *ARF* value decreases from 0.365 to 0.198 for *IF* and from 0.40 to 0.212 for *CF* with increase in the frequency from 5 Hz to 50 Hz. The maximum percentage increase in the efficiency of *IF* over *CF* in terms of *ARF* is found to be 15%.

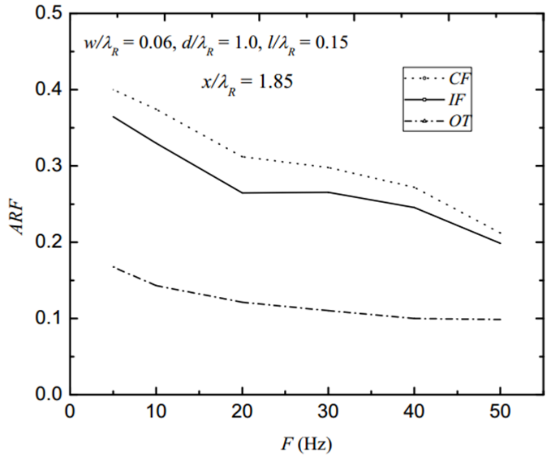


Fig. 13 Variation of *ARF* with excitation frequency

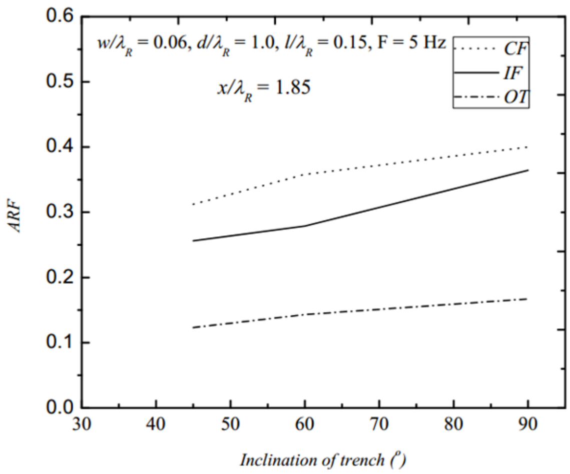


Fig. 14 Variation of *ARF* with inclination of trench

3.6 Influence of inclination of trench

The inclination of trench has been considered in the present analysis keeping the concept of inclined reflector in mind. The inclination of *IF* is varied from 45° (inclined towards source) to 90° (vertical). It can be seen in Fig. 14 that the magnitude of *ARF* decreases from 0.365 to 0.256 with decrease in the inclination of trench from 90° to 45° keeping other parameters constant (w/λ_R = 0.06, d/λ_R = 1.0, l/λ_R = 0.15, F = 5 Hz), which indicates that the inclined trench may be more effective than the vertical one. The percentage increase in the efficiency of *IF* over *CF* in terms of *ARF* is found to be 8.87% to 17.96%.

4. Conclusions

The present finite element analysis explores the possibility of vibration screening technique using intermittent geofoam in-filled trench. The effect of different parameters such as depth and inclination of trench, geofoam density, and excitation frequency on *ARF* has been explored critically. Based on the scope of the present investigation, the following conclusions can be made:

(1) A significant reduction in *ARF* can be achieved by using *IF* as compared to *CF*. As expected, the screening efficiency of *OT* is found to be more than that of *CF* and *IF* indicating the lower bound of screening efficiency. The results from the parametric study indicate that the maximum percentage increase in the efficiency of *IF* over *CF* in terms of *ARF* is found to be 13-18%.
(2) *IF* with w/λ_R = 0.06, d/λ_R = 1.0 and l/λ_R = 0.15 is seen to be most effective from both screening efficiency and economic point of view.
(3) The location of trench plays an important role in the evaluation of screening efficiency. The magnitude of *ARF* decreases from 0.456 to 0.310 with decrease in l/λ_R from 0.3 to 0.1 for w/λ_R = 0.06, d/λ_R = 1.0 and F = 5 Hz.
(4) It is noticed that the efficiency of *IF* increases with increase in the frequency of the vibration source and therefore, *IF* is expected to perform better for high frequency dynamic source such as high speed machines etc. With increase in the frequency from 5 Hz to 50 Hz, the *ARF* value is found to decrease from 0.365 to 0.198 for *IF* and from 0.40 to 0.212 for *CF* with l/λ_R = 0.15, w/λ_R = 0.06, d/λ_R = 1.0.
(5) The screening efficiency of *IF* increases significantly with decrease in the density of geofoam.

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Notation

ARF	Amplitude reduction factor
A_{rr}	Average amplitude reduction ratio
B	Width of the footing
c_u	Undrained cohesion of soil
CF	Continuous geofoam in-filled trench
$[c]$	Damping matrix
d	Depth of the trench
D_f	Depth of the strip footing
D_f/B	Embedment factor
EPS	Expanded polystyrene
E_d	Dynamic elastic modulus of soil
E_G	Elastic modulus of geofoam
E_s	Static elastic modulus of soil
H	Height of soil profile
F	Excitation frequency
IF	Intermittent geofoam in-filled trench
G	Shear modulus of soil
$[K]$	Stiffness matrix
l	Center to center spacing between source and trench
l_x	Domain size in x direction
$[M]$	Mass matrix
$P(t)$	Dynamic loading intensity with constant amplitude
P_0	Dynamic load amplitude
OT	Open trench
R_{inter}	Interface strength reduction factor
t	Time
V_P	Longitudinal wave velocity
V_R	Rayleigh wave velocity in soil
V_s	Shear wave velocity in soil
w	Width of the trench
Z_G	Acoustic impedance of geofoam
Z_S	Acoustic impedance of soil
λ_R	Rayleigh wavelength
ω	Circular frequency of vibration
α and β	Rayleigh damping coefficients
ϕ	Angle of internal friction of soil
ξ	Damping ratio of soil
v	Poisson's ratio
ρ	Density of material