Active screening for axi-symmetric machine loading using EPS geofoam

Mainak Majumder i) and Priyanka Ghosh ii)

i) Ph.D Student, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.
ii) Associate Professor, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.

ABSTRACT

In this paper, the application potential of expanded polystyrene (EPS) geofoam as a vibration screening material in an in-filled trench has been investigated under circular machine loading. Circular machine foundations are commonly used for the foundations of reciprocating engines, compressors, turbines, generators etc. The numerical analysis is performed using two-dimensional finite element method under dynamic condition. The present analysis considers the foundation bed as linearly elastic, isotropic and homogeneous soil deposit. The inclination of the trench is also considered as a special parametric study. The vertical displacement amplitudes of the ground vibrations are analysed at different pick-up points along the ground surface to determine the amplitude reduction factor (ARF).

Keywords: Amplitude reduction factor, geofoam, machine foundation, vertical displacement, vibration screening

1 INTRODUCTION

Rapid urbanization virtually removes the restriction of recommended spacing between the industrial and the residential structures and modern industrialization demands the installation of various heavy machines such as turbines, compressors, power plant equipments, gas and diesel generators etc. These heavy machines transmit dynamic stress waves to the sub-soil which may cause undesirable vibrations to the nearby structures thus causing unsafe situation for the structure or unpleasant condition to the inhabitants. Therefore, screening of such unwanted machine vibrations is necessary for any nearby structure from strength and serviceability as well as residents’ comfort point of view. Screening of vibration waves may be achieved following different techniques such as changing the position of the source, using some damping devices at the base of the foundation etc. However, these methods sometime are seen to be infeasible or cost ineffective. On the contrary, in several situations construction of some barriers across the path of the propagating waves is found to be most suitable alternative for the vibration screening technique. Woods (1968) has explored the screening effectiveness of open trench as the vibration barrier experimentally. Haupt (1981) has performed a series of model tests in the laboratory with open and in-filled trenches. Later, a number of investigations have been carried out using different in-filled materials such as concrete, soil-bentonite (Al-Hussaini and Ahmad 1996), pile (Kattis et al. 1999), gas-cushion (Massarsch 2005). However, the use of expanded polystyrene (EPS) geofoam as an in-filled trench material in vibration screening is scanty.

EPS geofoam is a geosynthetic product which has been mostly used in different geotechnical applications such as seismic buffers (Inglis et al. 1996), subgrade and fill material in pavement structures (Zou et al. 2000, Duskov 1997), compressible inclusions to reduce the active earth pressure in the retaining wall (Karpurapu and Bathurst 1992, Zarnani and Bathurst 2007), large strain applications (Hazarika 2006), inclusive material in the rigid retaining wall under seismic condition (Matsuo et al. 1998, Bathurst et al. 2007, Wang and Bathurst 2008). However, its application as the vibration screening material has not been explored by many researchers other than Wang et al. 2006, Murillo et al. 2009, Alzawi and El Naggar 2009. Therefore, a need is felt to develop a simplified vibration screening technique using EPS geofoam in-filled trench under the propagation of surface waves.

Different researchers (Dasgupta et al. 1986, Banerjee et al. 1988, Ahmad et al. 1996) have studied active vibration screening or near source screening of surface waves. In the present analysis, active vibration screening in presence of the vertical sinusoidal oscillating circular machine foundation is considered. The problem in hand satisfies the axi-symmetric condition under the dynamic condition and the soil is assumed to be isotropic, linearly elastic material under the wave propagation. A parametric study is performed considering trench geometry, layering effect of soil deposit, operating frequency of the vibrating source and inclination of the trench.
2 PROBLEM STATEMENT

A rigid embedded circular machine foundation subjected to vertical dynamic excitation is placed on dry, homogeneous and non-homogeneous soil deposits with embedment factor \( (D_f / B) \) of 1.0, where \( D_f \) and \( B \) are the depth and the diameter of the foundation, respectively. The geometry of the influence domain is shown in Fig. 1. In addition to the dynamic load, the circular foundation carries a static working load causing uniform static load intensity without violating the ultimate state.

An annular trench with width, \( w \) and depth, \( d \) is palced at an annular radius of \( l \) from the dynamic source as shown in Fig. 1. The primary objective is to determine the active vibration screening efficiency of geofoam in-filled trench due to the application of sinusoidal dynamic excitation on the footing in terms of the amplitude reduction factor (ARF) by obtaining the reduction in the displacement amplitudes at different pick up points as shown in Fig. 1. The ARF can be expressed as (Woods, 1968)

\[
\text{ARF} = \frac{(U_y)_{\text{After}}}{(U_y)_{\text{Before}}}
\]

Where \( (U_y)_{\text{Before}} \) and \( (U_y)_{\text{After}} \) are the vertical displacement at different pick up points before and after the installation of the trench, respectively.

3 ANALYSIS

3.1 Materials

Four different homogeneous soil deposits resting on the strong bed rock at 11.7 m below the ground surface is considered in the present study, which is similar to that reported by Ghosh et al. (2011) and Ghosh (2012). Table 1 presents the mechanical and strength properties of each soil deposit. The Poisson’s ratio \( (\nu) \) for each deposit is assumed to be 0.3. The effect of the soil non-homogeneity under the wave propagation is explored by assuming soil deposit-5. Deposit-5 consists of four layers of soil followed by a strong bed rock at 11.7 m. The soil layer starting from the ground surface to 3 m from the ground surface has the properties of soil deposit-1; from 3 m - 6 m, properties correspond to soil deposit-2; 6 m – 9 m, properties correspond to soil deposit-3; 9 m – 11.7 m properties correspond to soil deposit-4. The water table is found 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 × 10^9 kN/m² and 1.04 × 10^7 kN/m², respectively. The change in the stiffness of the soil deposit under dynamic loading is determined by following the theory reported by Alpan (1970). The dynamic stiffness (\( E_d \)) corresponding to the static stiffness (\( E_s \)) is determined from the empirical curves proposed by Alpan (1970). The dynamic properties of soil deposits are listed in Table 2.

Table 1. Properties of different soil deposits (Ghosh et al. 2011, Ghosh 2012)

| Properties          | Deposit-1 | Deposit-2 | Deposit-3 | Deposit-4 |
|---------------------|-----------|-----------|-----------|-----------|
| Static modulus of elasticity, \( E_s \) (kN/m²) | 2.06 × 10^3 | 8.02 × 10^3 | 1.12 × 10^4 | 4.52 × 10^4 |
| Undrained cohesion, \( c_u \) (kN/m²) | 19.4 | 75.7 | 106 | 427 |
| k unit weight, \( \gamma \) (kN/m³) | 17 | 18 | 19 | 20 |
| Main friction angle, \( \phi \) (°) | 24.7 | 29.5 | 30.9 | 36.2 |
| Rayleigh damping coefficient | 0.146 | 0.186 | 0.278 | 0.192 |
| Rayleigh damping coefficient | 2.215 × 10^-3 | 1.742 × 10^-3 | 1.632 × 10^-3 | 1.160 × 10^-3 |

Table 2. Dynamic properties of soil deposit

| Properties          | Deposit-1 | Deposit-2 | Deposit-3 | Deposit-4 |
|---------------------|-----------|-----------|-----------|-----------|
| Dynamic elastic modulus, \( E_d \) (kN/m²) | 4.20 × 10^4 | 7.21 × 10^4 | 8.68 × 10^4 | 1.80 × 10^5 |
| Shear modulus, \( G \) (kN/m²) | 1.61 × 10^4 | 2.77 × 10^4 | 3.33 × 10^4 | 6.95 × 10^4 |
| Shear wave velocity, \( V_s \) (m/s) | 96.57 | 123 | 131.29 | 184.71 |
| Rayleigh wave velocity, \( V_R \) (m/s) | 89.52 | 114.02 | 121.71 | 171.23 |
| \( \alpha \) (Rayleigh damping coefficient) | 0.146 | 0.186 | 0.278 | 0.192 |
| \( \beta \) (Rayleigh damping coefficient) | 2.215 × 10^-3 | 1.742 × 10^-3 | 1.632 × 10^-3 | 1.160 × 10^-3 |
In the present study, the EPS geofoam with the lowest available density (11.2 kg/m³) is considered as per ASTM D6817. It has elastic modulus and Poisson’s ratio of 3.3 MPa and 0.1, respectively.

3.2 Dynamic and static loading on foundation
A constant amplitude of sinusoidal dynamic load intensity with 10 seconds duration is applied on the foundation (Eq. 2)

\[ p(t) = p_0 \sin(\omega t) \]  

Where \( p(t) \) = dynamic load intensity with constant amplitude; \( \omega \) = operating circular frequency; \( t \) = time; \( p_0 \) = amplitude of vertical load intensity = 1 kN/m².

Considering a moderately high-speed machine (operating frequency less than 17 Hz) and the criteria to avoid resonance the maximum amplitude of the dynamic load intensity of 1 kN/m² with an operating frequency of 10Hz is considered in the present analysis. In addition, a static working load intensity of 10 kN/m² is considered on the circular foundation as the self-weight of the machine and other accessories.

3.3 Finite element modeling
The soil 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. The problem in hand satisfies the axi-symmetric condition and hence, half of the domain is considered for the analysis. 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 Rayleigh wavelength, \( \lambda_R \) for all deposits (Fig. 1). The average displacements along the vertical boundary are obtained by averaging the displacements taken along BC at an interval of 0.1 \( \lambda_R \). It can be seen that the effect of the domain size beyond 2.5 \( \lambda_R \) is negligible. Therefore, the domain size is assumed to be 2.5 \( \lambda_R \) along the horizontal direction, whereas the domain size along the vertical direction is considered up to the bed rock level (11.7 m).

In case of static analysis, the boundaries are considered completely free or fixed in one or two directions so that the extreme boundaries of the domain do not significantly influence the deformation behavior of the domain to be modeled, 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. 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 domain as described by Lysmer and Kuhlmeyer (1969). The time step considered in the present analysis satisfies the criteria by Valliappan and Murti (1984). The damping ratio (\( \xi \)) of 5% is considered as used in several vibration screening problems (Al-Hussaini and Ahmad 1996, Alzawi and Naggar 2009). The values of Rayleigh damping coefficients (\( \alpha \) and \( \beta \)) are evaluated by choosing 1st and 2nd natural frequencies (\( f_1 \) and \( f_2 \)) of the deposits and are shown in Table 2. The deposit-5 (non-homogeneous) has \( \alpha \) of 0.192 and \( \beta \) of 1.687×10⁻³, which has not been mentioned in Table 2.

4 RESULTS AND DISCUSSIONS

In the present analysis, the ARF values are calculated up to a distance of \( \lambda_R \) from the ground surface at an interval of 0.1 \( \lambda_R \). The location of pick-up points is varied from 0.4 \( \lambda_R \) to 1.0 \( \lambda_R \) as shown in Fig. 1. The pick-up points are chosen along the ground surface since the maximum response is expected to be observed along the ground surface. A nomenclature, \((L_iW_jD_kF_mI_n)_{CF/OT}\) is defined to identify the problem and associated details are:
- \( L_i \): represents the location factor of the trench i.e. the annular radius of the trench normalized with respect to \( \lambda_R \), where \( i \) stands for different magnitude of \( L = \{0.10, 0.15, 0.20, 0.25, 0.30\} \)
- \( W_j \): represents the thickness factor of the trench i.e. normalized width with respect to \( \lambda_R \), where \( j \) stands for different magnitude of \( W = \{0.02, 0.04, 0.06, 0.08\} \)
- \( D_k \): represents the depth factor of the trench i.e. normalized depth with respect to \( \lambda_R \), where \( k \) stands for different magnitude of \( D = \{0.6, 0.8, 1.0, 1.2\} \)
- \( F_m \): represents the frequency of the vibrating source normalized with respect to \( \lambda_R \), where \( m \) stands for different magnitude of \( F = \{10, 20, 30, 40, 50\} \) Hz
- \( I_n \): represents the inclination of the trench (in degrees), where \( n \) stands for different magnitude of \( I = \{45, 60, 90\} \)
- CF and OT represent continuous geofoam in-filled trench and open trench, respectively.

In Fig. 2, the variation of ARF at different pick up points in deposit-1 is shown for continuous geofoam in-filled trench keeping other parameters constant such as \( W = 0.06, D = 1.0, F = 10Hz, I = 90^° \). It can be seen that the magnitude of ARF decreases from 0.397 to 0.246 with decrease in \( L \) from 0.30 to 0.10, which indicates enhancement in the screening effectiveness with decrease in the annular radius of the trench. From the analysis, it can be observed that beyond \( L = 0.15 \) there is no significant decrease in ARF. Hence, \( L = 0.15 \) is considered as the optimum location factor for
determining the effect of other input parameters on the screening efficiency.

Fig. 2. Variation of ARF at different pick-up points for continuous geofoam with different annular radius of trench in deposit-1.

Fig. 3 shows the variation of ARF with thickness of the trench for continuous geofoam in deposit-1 keeping other parameters constant such as $L = 0.15$, $D = 1.0$, $F = 10$Hz, $I = 90^\circ$. It can be seen that the screening efficiency increases (ARF decreases) with increase in geofoam thickness. In terms of magnitude, ARF is found to decrease from 0.397 to 0.265 with the increase in $W$ from 0.02 to 0.08. The improvement in ARF is expected to continue with increase in the thickness of the geofoam due to greater contrast in the stiffness of soil and in-filled material. However, an optimum geofoam thickness ($W = 0.06$) is considered for further analysis.

Fig. 3. Variation of ARF at different pick-up points for continuous geofoam with different geofoam thickness in deposit-1.

The influence of trench depth on the variation of ARF is presented in Fig. 4. It can be seen that the ARF value decreases from 0.478 to 0.266 with increase in the magnitude of depth factor $D$ from 0.8 to 1.2 with $L = 0.15$, $W = 0.06$, $F = 10$Hz, $I = 90^\circ$. The reduction in the displacement amplitude with increasing $D$ may be attributed to the delay in the arrival of wave at the pick-up points.

Fig. 4. Variation of ARF at different pick-up points for continuous geofoam with trench depth in deposit-1.

No significant variation in ARF can be observed beyond $D = 1.0$ and the optimum depth factor is therefore chosen as 1.0 for subsequent analysis.

The variation of ARF at different pick-up points for continuous geofoam for different excitation frequencies is shown in Fig. 5. It can be observed that the magnitude of ARF decreases with the increase in the excitation frequency of the vibrating source. The ARF value decreases from 0.285 to 0.182 with increase in frequency, $F$ from 10Hz to 50Hz corresponding to the pick-up point at $r/\lambda = 0.7$.

In Fig. 6, the variation of ARF is shown for different soil deposits to explore the effect of soil stiffness of different deposits on the screening efficiency with $L = 0.15$, $W = 0.06$, $D = 0.7$, $F = 10$Hz, $I = 90^\circ$. It can be seen that the magnitude of ARF decreases from 0.299 to 0.235 with the increase in the soil stiffness from deposit-1 (Homogeneous) to deposit-4 (Homogeneous) corresponding to the pick-up point $r/\lambda = 0.7$. The variation of ARF observed in deposit-5 is also presented in Fig. 6.
The influence of inclination of the trench, $I$, is also studied in the present investigation. In Fig. 7, the effect of inclination of the annular trench on the screening efficiency is shown. It can be noted that with decrease in the inclination from $90^\circ$ to $45^\circ$, ARF decreases from 0.285 to 0.20. The screening efficiency increases with the increase in the inclination as greater is the inclination of the trench, higher is the wave scattering.

5 COMPARISON

The present ARF values obtained for continuous geofoam in-filled trench are compared with that obtained with same annular open trench. It is worth mentioning here that the open trench is expected to serve better due to the presence of air voids within the trench. Fig. 8 shows the comparison of ARF values obtained for continuous geofoam in-filled trench and open trench for different depth factors. It can be seen that the difference in ARF values between CF and OT decreases with increase in the magnitude of $D$ from 0.8 to 1.2.

6 CONCLUSIONS

The present numerical investigation explores the effectiveness of continuous geofoam as vibration screener under the vibration of circular machine foundation. The effect of different parameters such as thickness ($w$), depth ($d$), inclination ($I$) and annular radius ($l$) of the trench as well as the excitation frequency and the soil stiffness on the amplitude reduction factor has been explored critically. Based on the current study the following conclusions can be made:

- The amount of reduction in ARF i.e.
screening effectiveness using continuous geofoam (CF) is significant. 

- The depth and annular radius of the trench are two important parameters associated with the effectiveness of CF.
- The present investigation reveals that the most optimum geometric parameters for CF are L = 0.15, W = 0.06 and D = 1.0.
- CF is found to be quite effective to reduce the vibration effect of turbines, high speed generators, and compressors as the screening efficiency increases with increase in the operating frequency of the machines.
- CF is found to be more effective in the stiffer deposit.
- The inclined trench is found to be more effective than the vertical one.

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