Vibration Scattering Using GeoFoam Material as Vibration Wave Barriers

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ABSTRACT
Active and passive wave barriers are used to reduce the ground vibrations induced by machine foundations, high speed trains, blasting activities, etc. Most these vibrations propagate in the form of surface (Rayleigh) waves. An innovative approach to construct wave barriers using GeoFoam material is proposed in this study. Two-dimensional and three-dimensional numerical models were conducted by utilizing the finite element package, ABAQUS. To ensure complete energy dissipation at the model boundaries, infinite non-reflecting boundaries are implemented. The numerical models are verified and excellent agreement with previously published results was observed. A comprehensive parametric study is conducted to examine the effectiveness of different configurations of GeoFoam wave isolation barriers in screening ground borne vibrations with emphasize on excitations due to machine operation. The results of the parametric study are analyzed and interpreted to provide recommendations for implementation in design.

RÉSUMÉ
Active et passive des vagues obstacles sont utilisés pour réduire les vibrations induites par le sol par la machine des fondations, des trains à grande vitesse, les activités de dynamitage, etc La plupart de ces vibrations se propagent sous la forme de surface (Rayleigh) waves. Une approche novatrice pour la construction d'ondes en utilisant des barrières GeoFoam matériel est proposé dans cette étude. À deux dimensions et en trois dimensions des modèles numériques ont été réalisées en utilisant l'ensemble des éléments finis, ABAQUS. Pour assurer la dissipation d'énergie au modèle limites, infini limites non réfléchissantes sont mises en œuvre. Les modèles numériques sont vérifiés et excellent accord avec les résultats publiés précédemment a été observée. Une étude paramétrique est menée pour examiner l'efficacité de différentes configurations de GeoFoam vague isolement des obstacles au dépistage du terrain la charge de mettre l'accent sur les vibrations excitations en raison de fonctionnement de la machine. Les résultats de l'étude paramétrique sont analysés et interprétés afin de fournir des recommandations pour la mise en œuvre dans la conception.

1 INTRODUCTION

Active and passive wave barriers are used to reduce ground vibrations induced by different sources such as machine foundations and high speed trains in the form of surface (Rayleigh) waves. They are usually used to scatter the vibrations for environmental reasons or to protect structures housing sensitive equipment. Wave barriers can be established in the form of open trenches, in-filled concrete or bentonite trenches, sheet-pile walls and rows of solid or hollow concrete or steel piles.

Several analytical, numerical and few experimental researches to study vibration isolation using wave barriers (also known as vibration screening) have been carried out in the last few decades to better understand the vibration scattering phenomenon. Woods (1968) performed a series of scaled field experiments on vibration isolation by installing open trenches very close to the wave source (known as an active isolation) as well as in the far field (known as a passive isolation). Based on the experimental findings, some guidelines were proposed for the dimensions of an open trench to achieve a ground amplitude reduction equal to or more than 75%. Haupt (1981) carried out a series of model scale tests on the vibration isolation of various measures in a laboratory ground. The experimental program focused on solid barriers (concrete walls) and light weight barriers such as rows of bore holes and open trenches. He found that the screening effect of these barriers was a function of characteristic parameters expressed in terms of wavelength-normalized dimensions.

Numerical modeling is an efficient tool to investigate the wave propagation problems. The finite Element Method (FEM) and Boundary Element Method (BEM) have been widely used in wave barrier simulations. Haupt (1977) employed the FEM to investigate the effect of installing concrete walls with different geometrical configurations and material characteristics on the efficiency of vibration isolation, and compared the numerical results with those obtained from small-scale laboratory tests involving harmonic loading. Waas (1972) utilized the FEM to perform frequency domain simulation of screening horizontal shear waves (SH) by trenches. El Naggar and Chehab (2005) analyzed the effectiveness of various types of vibration barriers for the isolation of shock producing equipment using a two dimensional (2D), time domain finite element analysis. Andersen and Nielsen (2005) employed a coupled FEM – BEM model to investigate the reduction of ground vibrations by means of barriers or soil improvement along a railway track. Beskos (1986) developed a BEM algorithm to investigate the vibration isolation of surface waves in both homogeneous and layered soils. Al-Hussaini and Ahmad (1991) conducted an extensive numerical study on the screening effectiveness of a rectangular barrier by using higher-order boundary element algorithm (BEM). In addition, it was found that open trenches, in-filled (concrete or bentonite) barriers, sheet pile walls, or even rows of piles could be effective wave barriers. Al-Hussaini et al. (2000) compared the BEM results with experimental data available in the literature.

A few studies have been performed to explore using the GeoFoam material as wave barriers. Experimentally, Davies (1994) carried out a series of 20-g centrifuge tests to investigate the screening effect of Geofoam barrier, concrete wall and their composites on adjacent buried structures. The centrifuge test results indicated that barriers containing low acoustic materials were highly effective in the attenuation of stress wave propagation. A well-designed wave barrier could largely reduce the magnitude of ground shock loading on buried structures. Wang (2008) has conducted numerical investigations on the performance of expanded polystyrene GeoFoam (also called a soft porous layer) to protect the buried structures against the effect of blast-induced ground shock. An open trench, an inundated water trench, three in-filled Geofoam walls with different densities, and a concrete wall have been included in the numerical simulation. The numerical model simulated the prototype dimensions of a centrifuge test carried out by Davies (1994). Based on the numerical model findings, the Geofoam barriers were found to significantly reduce the blast-induced stress waves. In addition, Wang (2008) noted that the Geofoam barrier is considered to provide flexibility in design that can be easily and efficiently implemented in the field. However, it should be noted that vibration sources in the above-mentioned two studies were blast-induced ground shock.

An innovative vibration isolation system using Geofoam material is introduced in this paper. The objective of this study is to examine, numerically, the behaviour and the efficiency of this promising material under periodic harmonic loadings in the vertical direction. Both 2D and 3D numerical models were developed in the time domain by utilizing a finite element package, ABAQUS. The soil was modeled as a homogeneous, isotropic, elastic, half-space. A comprehensive parametric study has been carried out to investigate the protection performance of the proposed GeoFoam barrier configurations.

2 METHODOLOGY OF STUDY

Well-calibrated 3D finite element models have been established in order to investigate both active and passive isolation problems. The calibration process of the models was conducted using three well-documented reference studies. For the active case, the analysis simulated a 3D wave-diffraction open-trench case analyzed by Kattis et al. (1999). For passive isolation case, the model was calibrated based on a 3D boundary element analysis developed by Ahmad and Al-Hussaini (1991) and Beskos *et al*. (1986). In order to limit the computational effort and time, two-dimensional (2D) plane-strain conditions were adopted for the passive isolation case. The accuracy of the 2D plane-strain model was verified by comparing the obtained results with those from the reference study. A staged mesh refinement has been carried out to obtain an optimized meshing configuration.

Different configurations of the GeoFoam trench were adopted based on the verified models. A comprehensive parametric study has been carried out to investigate the performance of the proposed GeoFoam trenches as active and passive wave barriers in the form of box-wall, single-continuous wall, double-continuous and double-staggered wall systems. It is worth noting that all four systems can be used as active or passive isolation systems, except the box wall system which is only applicable for the active isolation case. The simulated model results are analyzed and interpreted to provide recommendations for design purposes. All geometric parameters are normalized by the Rayleigh wavelength, λ_R.

3 FINITE ELEMENT MODELS

Both 2D and 3D finite element analyses were performed employing the finite element package, ABAQUS. The 3D model was mainly used for studying the active box-wall system and the active and passive double-staggered wall systems. In these models, the soil and wave barriers were modeled using 8-noded first-order hexahedron elements with relevant properties. The 2D model was adopted for single-continuous and double-continuous passive wall systems. The soil and wave barriers were modeled using 4-noded first-order plane-strain rectangular elements with relevant properties. To assure accurate model results, the maximum element size was kept less than one-eighth the shortest possible Rayleigh wavelength λ_R (Kramer 1996).

To ensure complete energy dissipation, infinite non-reflecting boundaries have been imposed to simulate the half-space soil conditions. First-order 8-noded solid continuum, one-way infinite elements were assigned to represent the non-reflecting boundaries in the 3D model while first-order plane-strain 4-noded solid continuum, one-way infinite elements were used to represent the non-reflecting boundaries in the case of the 2D model.

Based on the symmetrical nature of the considered 3D problems, a reduced quarter model was adopted in the case of the box-wall active system. Similarly, a reduced half model was utilized in the case of active and passive double-staggered wall systems. Thus, symmetry boundary conditions were applied by restraining the displacement in the perpendicular direction to the symmetry surfaces. However, for the 2D models the axis of symmetry was placed across the point of load application.

The surface waves have been generated by applying vertical harmonic dynamic loading represented by a sine function. The load was applied at varying distances from the barriers and pointed directly on the ground surface. For modelling purposes, the footing carrying the dynamic load was eliminated as it did not practically affect the vibration results (Kattis 1999).

3.1 Finite Element Models Verification

The developed models were verified by analyzing both the active and passive isolation problems using open trenches to simulate the conditions described in the referenced studies. The simulated results were presented in terms of the vertical response amplitude reduction factor, A_r. The amplitude reduction factor is defined as the normalized post-trench installation maximum vertical response amplitude, $(U_v)_{After}$, to the maximum vertical response amplitude before trench installation, $(U_v)_{Before}$, as given in Equation 1. The maximum vertical response amplitudes were obtained at specified monitoring nodes from the simulated time histories. Woods (1968) considered the averaged vertical response amplitude reduction ratio to be smaller or equal to 0.25 for an effective isolation system.

$$A_r = \frac{(U_v)_{After}}{(U_v)_{Before}} \qquad [1]$$

For active isolation, an open trench of depth d=0.5λ_R, and width w=0.06λ_R located at a distance x=0.4λ_R from the source of vibration in an elastic half-space soil. The material properties of the soil medium were in accordance to Kattis *et al*. (1999): shear wave velocity Vs=275 m/sec, Poisson's ratio ν=0.25, Rayleigh wave velocity V_R=253 m/sec, Rayleigh wave length λ_R =5.0 m, mass density ρ=17.5 KN/m^3 and Rayleigh damping ξ=5%. The source of vibration is modeled as a vertical harmonic load of magnitude of 1.0 kN and frequency of 50 Hz. Figure 1 illustrates that results from the present study in terms of A_r coincide favourably with those obtained by Kattis *at al*. (1999).

For the passive isolation, an open trench of depth d=1.0λ_R and width w=0.1λ_R located at a distance x = 5.0λ_R from the source of vibration, which was a periodic harmonic load of magnitude of 1.0 kN frequency of 31 Hz, in an elastic half-space soil. The material properties of the soil medium were in accordance to Yang and Hung (1997): shear wave velocity Vs=101 m/sec, Poisson's ratio ν=0.25, Rayleigh wave velocity V_R=93 m/sec, Rayleigh wave length λ_R =3.0 m, mass density ρ=18 KN/m^3 and Rayleigh damping ξ=5%. Figure 2 shows a good agreement between the simulated results and those reported by Ahmad and Al-Hussaini (1991) and Beskos et al. (1986).

4 COMPUTATIONAL CONFIGURATIONS

Four configurations of GeoFoam barriers were numerically investigated: box, single-continuous, double-continuous and double-staggered GeoFoam walls with a density of 80 kg/m^3. The dynamic properties of GeoFoam material were evaluated using Bender Element Tests: shear wave velocity of 330 m/sec. A summary of the adopted GeoFoam barriers configurations is demonstrated schematically in Figure 3. Top view of the proposed layouts is shown in Figure 4 while Figure 5 shows a typical vertical section.

Unless stated otherwise, soil properties, magnitude and frequency of the applied load were considered the same as those used in the active verification case. Numerical results are presented in the subsequent text.

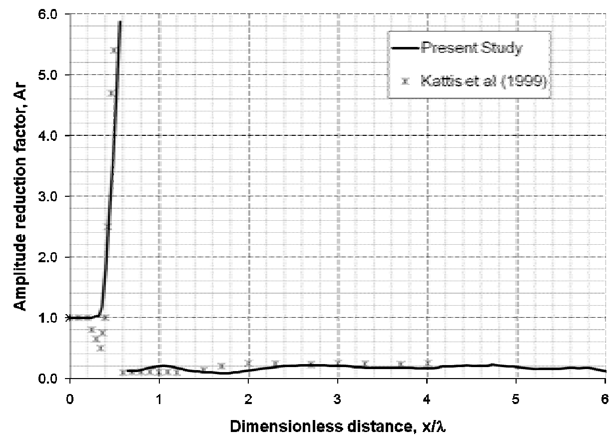

Figure 1. Finite element model verification, comparative study for active isolation by open trench (W=0.06, D=0.5, X=0.4)

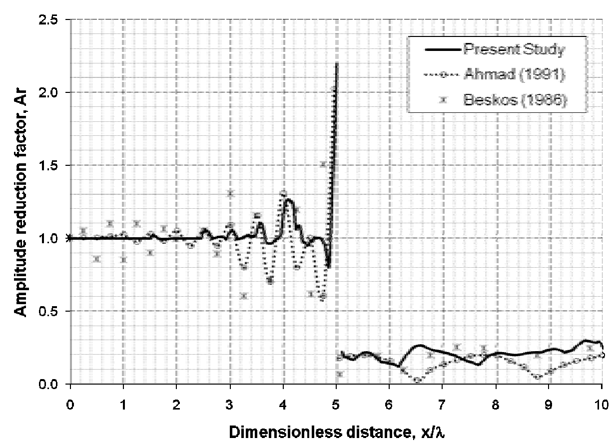

Figure 2. Two dimensional FE model verification, comparative study for passive isolation by open trench (W=0.1, D=1, X=5)

5 PARAMETRIC STUDY AND RESULTS ANALYSIS

The results of the parametric study will be presented in the form of system efficiency. As mentioned earlier, in all published literature, the system effectiveness was evaluated according to how much soil particle response amplitude reduction will be achieved. However, in practice, the effect of transmitted vibration is judged according to how much the soil particle velocities are at zones of interest. This means presenting the results (system effectiveness) in terms of reducing the soil particle velocity. Thus, the velocity reduction factor, V_r, at a node on the assigned monitoring path (Figure 4) can be obtained by normalizing the post-trench installation maximum vertical velocity component amplitude, $(V_v)_{After}$, by the maximum vertical velocity component amplitude before trench installation, $(V_v)_{Before}$, measured on the ground surface (Equation 2). The maximum vertical velocity component amplitudes are obtained at monitoring nodes from their time history.

$$V_r = \frac{(V_v)_{After}}{(V_v)_{Before}} \qquad [2]$$

To evaluate the system effectiveness (screening effectiveness) of the wave barrier system on the ground surface behind the wave barrier, the averaged vertical velocity reduction factor, $\overline{V_r}$, was calculated by using the following equation:

$$\overline{V_r} = \frac{1}{x}\int V_r \, dx \qquad [3]$$

where, $\overline{V_r}$, is the averaged vertical velocity reduction factor over a distance $x=5\lambda_R$ behind the GeoFoam barrier. Thus, the system effectiveness is calculated using Equation 4 as follows:

$$Eff_V = \left(1-\overline{V_r}\right)\times 100 \qquad [4]$$

A parametric study was performed to examine the proposed isolation systems effectiveness by investigating the effects of the GeoFoam barrier dimensions (thickness and depth), location, barrier-system type and load frequency.

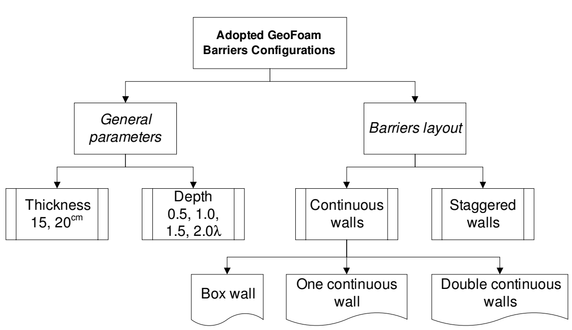

Figure 3. Proposed GeoFoam barriers configurations

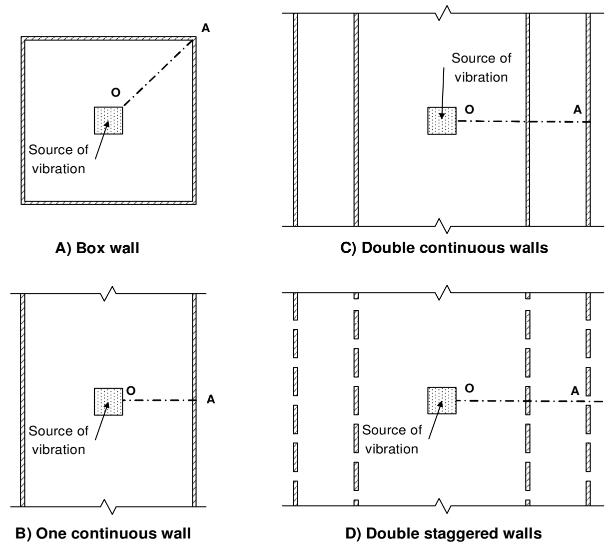

Figure 4. Plan views of GeoFoam isolation systems

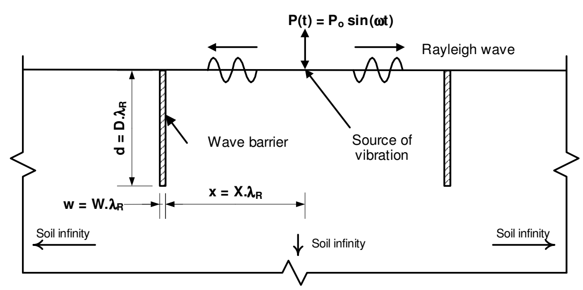

Figure 5. Typical schematic of the vibration isolation system (active or passive) and geometric parameters.

5.1 Box Wall Isolation System

The normalized distance between the box wall and the source of vibration X was varied from 0.4 to 2.0 and the normalized depth D was varied from 0.5 to 1.5 for the adopted two thicknesses, 15 and 20 cm, respectively. The particle vertical velocity was monitored along the path OA shown in Figure 4-A.

Figure 6 summarizes the obtained results. It is clear that increasing the wall thickness improved the system effectiveness. For example, the system effectiveness increased by about 11% as the wall thickness increased from 150 to 200 mm for the normalized wall depth D of 0.5 located at a normalized distance X of 0.4. Moreover, the system efficiency increased by about 22% as the wall thickness increased from 150 to 200 mm for D = 0.5 and X = 1.5. Furthermore, increasing the normalized wall depth D from 0.5 to 1.5 showed a slight improvement. For instance, increasing the wall depth D from 0.5 to 1.0 resulted in an improvement of about 7.5% with no significant improvement for walls deeper than $1.0\lambda_R$.

However, the system effectiveness decreased as the normalized distance between the box wall and the source of vibration X increased. For example, the system efficiency decreased by about 35% as X increased from 0.4 to 2.0 for the wall thickness of 150 mm and D = 0.5. It is obvious that the system efficiency values are the same for the same normalized distance and the same thickness regardless of the wall depth. In conclusion, the gained improvement from increasing the wall thickness was mainly affected by the wall thickness and system location rather than the wall depth.

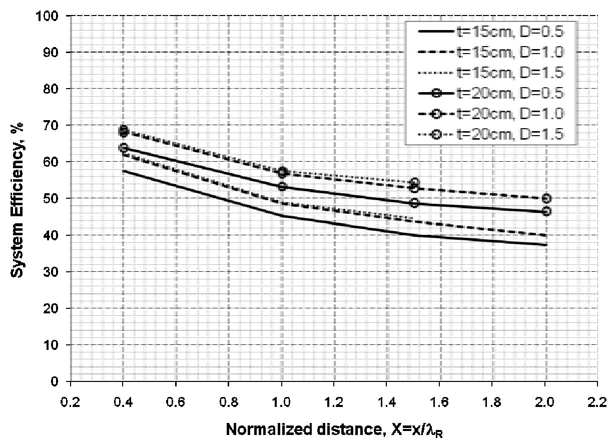

Figure 6. Effect of wall dimensions and location on the box-wall system effectiveness (f=50Hz).

5.2 Single Continuous Wall Isolation System

Since this system can be used as an active or passive isolation system, the normalized distance X was varied from 0.4 to 5.0. The load frequency ranged from 20 to 50Hz and the normalized depth D varied from 0.5 to 2.0 for two barrier thickness values, 150 and 200 mm. The particle vertical velocity was monitored along the path OA shown in Figure 4-B.

Figure 7 summarizes all the computed results for the load frequency 50Hz. By changing the normalized distance X of the wall for the same normalized depth D, it is observed that the effectiveness declined for increased distances from the vibration source. For example, the system effectiveness decreased by about 22% as the normalized distance increased from 0.4 to 5.0 for the wall thickness of 15cm and D = 0.5. Also, as the normalized wall depth D became greater than 1.0, no significant improvement was observed. Thus, the effectiveness values are the same for D = 1.5 and 2.0. In contrast, the system efficiency increased by about 13.5% as the wall thickness increased from 15cm to 20cm for D = 0.5 and X = 5.0.

Another important parameter, load frequency, which could affect the system performance, was investigated to understand the performance of GeoFoam material used as wave barriers. Thus, a parametric study was carried out by changing the load frequency from 20 to 50Hz. The effect of load frequency is plotted against the normalized distance in Figure 8 for wall thickness of 150 mm and D = 0.5. It is observed that system effectiveness decreased as the load frequency decreased. For example, at X = 5.0, the system effectiveness decreased by 46% and 49% as the load frequency decreased from 50 to 20Hz, respectively, for D = 0.5 and 1.0.

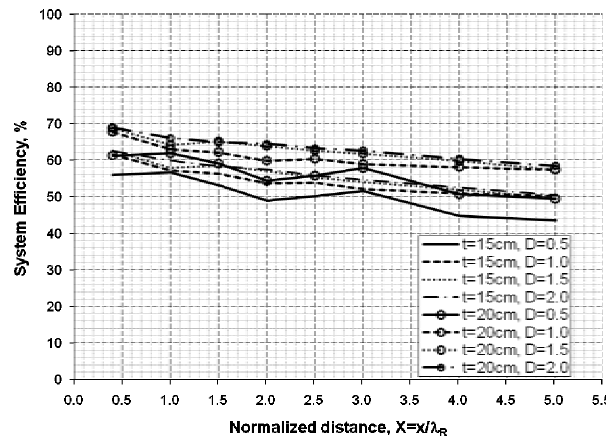

Figure 7. Effect of wall dimensions and location on the single-wall system effectiveness (f=50Hz).

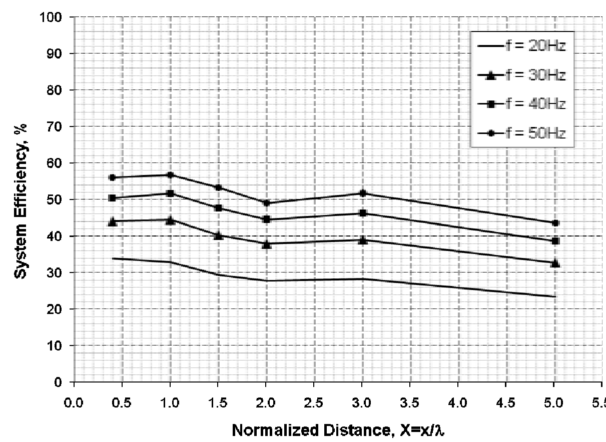

Figure 8. Effect of load frequency on the single-wall system effectiveness, (D=0.5, t=150 mm).

5.3 Double Continuous Walls Isolation System

Since this system can be used as either an active or passive isolation system, the normalized distance X was varied from 1.0 to 5.0. The load frequency was assigned as 50Hz and the normalized depth D ranged from 0.5 to 1.5 for wall thickness of 150 and 200 mm. The particle vertical velocity was monitored along the path OA shown in Figure 4-C.

A parametric study was carried out to find the optimum spacing between walls in order to reach the best isolation performance. According to the computed results, the optimum spacing of $0.5\lambda_R$ provided the best system efficiency.

The parametric study proceeded using the identified optimum spacing to investigate the effects of changing the walls location, thickness and depth on the system efficiency (Figure 9). It is noted that as the thickness and depth increased, the efficiency increased regardless of the system location, X. In terms of walls depth, a small improvement could be gained from increasing D from 0.5 to 1.0 while no remarkable improvement was observed as a result of increasing D from 1.0 to 1.5. Moreover, the increase of the thickness from 150 to 200 mm resulted in an improvement of only 10%. In contrast, no improvement in efficiency was monitored when varying the X value from 1 to 5.0. In other words, the system efficiency was not affected by its location from the source of vibration.

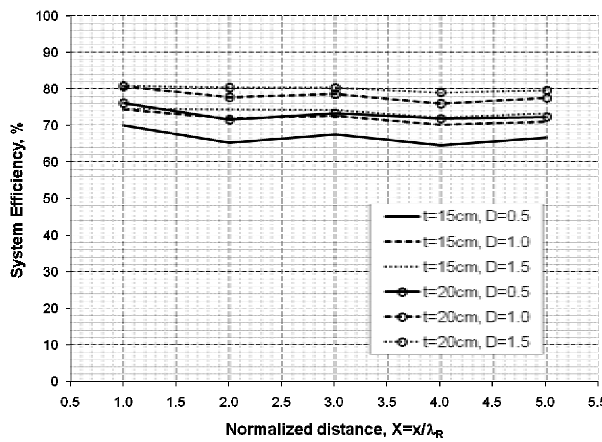

Figure 9. Effect of changing walls dimensions and location on the double-continuous walls system efficiency.

5.4 Double Staggered Walls Isolation System

To model this system, a 3D model was utilized. A parametric study was carried out to find the configurations of the staggered walls that offered the best isolation effectiveness. Table 1 lists the adopted segments lengths and gaps that could be practically established between every two wall segments. The obtained results showed that case 2 gave the best performance over the other two cases. Therefore, case 2 was adopted while performing the parametric study on this system. The spacing between walls was set to the obtained optimum spacing in the previous section which was $0.5\lambda_R$. The normalized distance X varied from 1.0 to 5.0. The load frequency was adopted as 50Hz and the normalized depth D ranged from 0.5 to 1.0 for two wall thicknesses, 150 and 200 mm. The particle vertical velocity was monitored along the path OA shown in Figure 4-D.

A parametric study of the same isolation system was carried out by changing the wall thicknesses, depth and location. Figure 10 summarizes the computed results. It is observed that increasing the wall thickness improved the system effectiveness. It increased by about 21.5% as the wall thickness increased from 15 to 20cm for the normalized wall depth D of 0.5 located at a normalized distance X of 4.0. However, no significant improvement (only 5.8%) was observed when increasing the walls thicknesses for the system located at X = 1.0. For systems located close to the source of vibration, increasing the walls thicknesses resulted in a negligible improvement. Furthermore, increasing the normalized wall depth D from 0.5 to 1.0 showed some gained improvement. For instance, increasing the wall depth D from 0.5 to 1.0 resulted in an improvement of about 9.5% when the system was located at X = 1.0 with thickness of 150 mm. On the other hand, the system efficiency decreased as the normalized distance X was increased. For example, the system effectiveness decreased by about 19% as X increased from 1.0 to 5.0 for the wall thickness of 200 mm and D = 1.0. It can be concluded that the system effectiveness is mainly affected by the system location rather than the walls dimensions.

Table 1. Proposed staggered wall configurations.

Case #	Segment length, m	Gap length, m	Spacing, λ_R
Case 1	1.2	0.4	0.5
Case 2	1.4	0.4	0.5
Case 3	1.5	0.5	0.5

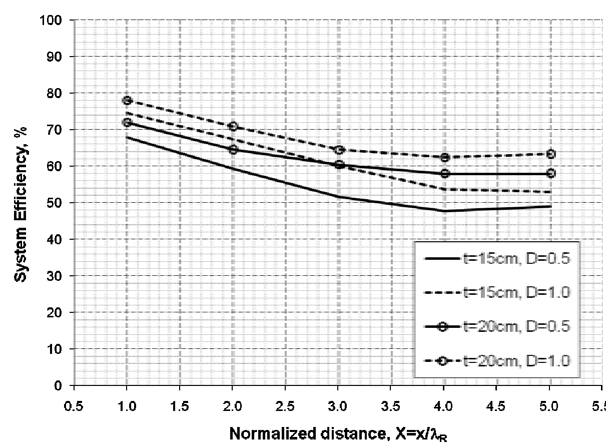

Figure 10. Effect of wall dimensions and location on the double-staggered wall system effectiveness.

5.5 Comparison between Isolation Systems

A comparison between the screening efficiency of all proposed isolation systems is carried out in this section. For all proposed isolation systems and for the sake of generalization, as the thickness and depth of the wall increased, the system screening effectiveness increased. Moreover, the results revealed that for all systems except the double-continuous walls system, where the normalized distance X had a minor effect on the system performance, as the system was placed far from the source of disturbance, the efficiency decreased.

Figures 11 and 12 compare the effectiveness of all systems considered in this study. It is clear that the double-continuous walls system, DCW, is most effective barrier in reducing the induced waves regardless their location from the source of vibration. On the other hand, box-wall system, BW, has the lowest system effectiveness. However, for systems located at X = 1.0, the double-staggered walls system, DSW, effectiveness is almost the same as DCW system effectiveness, except for X value of 4.0, the DSW system effectiveness becomes close to that of the single-continuous wall system, SCW. In other words, for active isolation case, the DSW system screening effectiveness is similar to that of the DCW system. For passive isolation case, however, its screening effectiveness is similar to the SCW system.

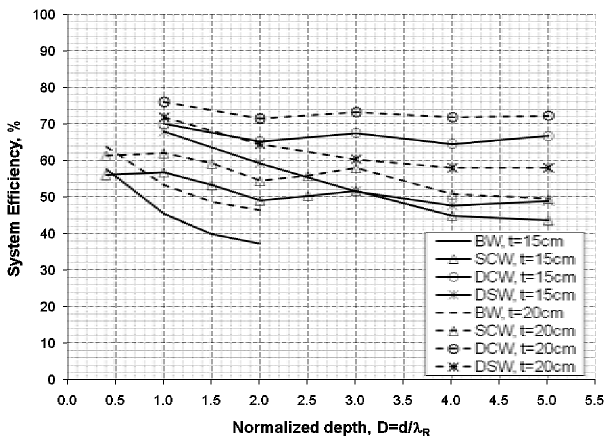

Figure 11. Comparison between four isolation systems effectiveness, (D=0.5, t=150 mm).

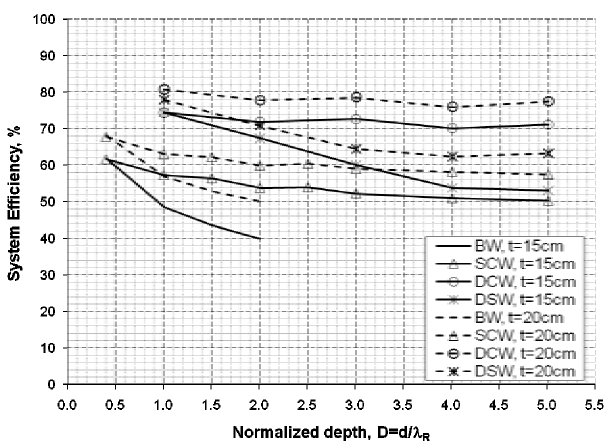

Figure 12. Comparison between four isolation systems effectiveness, (D=1.0, t=150 mm).

6 CONCLUSIONS

Active and passive vibration scattering problems analysis was carried out to investigate the protective effectiveness of different configurations of GeoFoam barriers systems. The proposed systems were evaluated and compared based on the gained reduction in the soil particle velocities through an intensive parametric study. From the previous discussions and analyses of the results, the following understandings and conclusions can be made:

1) All the proposed GeoFoam barrier systems perform well in reducing the surface waves and the screening effectiveness varies between 38% and 80%. Furthermore, the GeoFoam barriers are of variable protection performances in low frequencies.

2) The most effective isolation system is the double-continuous walls system. However, this system protection effectiveness is not affected by its location from the source of disturbance.

3) The double-staggered walls system has capability to screen the vibration as the double-continuous walls system when used as an active isolation system. Thus, the double-staggered walls system is an economic solution as an active isolation system since less GeoFoam material will be used.

4) The single-continuous wall system and the double-staggered walls system perform almost the same as passive isolation systems. Thus, the single-continuous wall system is an economic solution as a passive isolation system since less GeoFoam material will be used.

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REFERENCES

Ahmad, S. and Al-Hussaini, T.M. 1991. Simplified Design for Vibration Screening by Open and In-Filled Trenches. *Journal of Geotechnical Engineering*, 117: 67-88.

Ahmad, S., Al-Hussaini, T.M. and Fishman, K.L. 1996. Investigation on Active Isolation of Machine Foundations by Open Trenches. *Journal of Geotechnical Engineering*, 122: 454-461.

Al-Hussaini, T.M. and Ahmad, S. 1991. Design of Wave Barriers for Reduction of Horizontal Ground Vibration. *Journal of Geotechnical Engineering*, 117: 616-636.

Al-Hussaini, T.M. and Ahmad, S. 1996. Active Isolation of Machine Foundations by In-Filled Trench Barriers. *Journal of Geotechnical Engineering*, 122: 288-294.

Al-Hussaini, T.M., Ahmad, S., and Baker, J.M. 2000, Numerical and Experimental Studies on Vibration Screening by Open and In-Filled Trench Barriers, in : S. Chouw(Ed.), *Wave 2000*, Balkema, Rotterdam, 241-250.

Beskos, D.E., Dasgupta, G. and Vardoulakis, I.G. 1986. Vibration Isolation Using Open or Filled Trenches, Part1: 2-D Homogeneous Soil, *Computational Mechanics* 1: 43-63.

Davies, M.C.R. 1994. Dynamic Soil Structure Interaction Resulting from Blast Loading. Leung, Lee and Tan(Eds.), *Centrifuge 94*, Balkema, Rotterdam, 319-324.

El Naggar, M.H. and Chehab, A.G. 2005. Vibration Barriers for Shock-Producing Equipment, *Canadian Geotechnical Journal*, 42: 297–306.

Haupt, W.A. 1977. Isolation of Vibrations by Concrete Core Walls, In Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering, vol. 2. Tokyo, Japan, 251-256.

Haupt, W.A. 1981, Model Tests on Screening of Surface Waves, Proceedings of the 10th Conference on Soil Mechanics and Foundation Engineering, Vol.3, Stockholm, 215-222.

Kattis, S.E., Polyzos, D. and Beskos, D.E. 1999. Vibration Isolation by a Row of Piles Using a 3-D Frequency Domain BEM. *International Journal of Numerical Methods in Engineering*, 46: 713-728.

Kattis, S.E., Polyzos, D. and Besko, D.E. 1999. Modeling of Pile Wave Barriers by Effective Trenches and Their Screening Effectiveness, *Soil Dynamics and Earthquake Engineering*, 18: 1–10.

Suhol, B. 1997. Infinite Boundary Elements for the Dynamic Analysis of Machine Foundations, *International Journal for Numerical Methods in Engineering*, 40: 3901-3917.

Woods, R.D. 1968. Screening of Surface Waves in Soils, *Journal of Soil Mechanics and Foundation Engineering Div,* ASCE, 94(4): 951–79.

Yang, Y.B., Kuo, S.R. and Hung, H.H. 1996. Frequency-Independent Infinite Elements Analysing Semi-Infinite Problems, *International Journal for Numerical Methods in Engineering*, 39: 3553-3569.

Yang, Y.B. and Hung, H.H. 1997. A Parametric Study of Wave Barriers for Reduction of Train Induced Vibrations, *International Journal for Numerical Methods in Engineering*, 40: 3729-3747.