Attenuation of Ground Vibrations: Numerical Simulation of In-filled Wave Barriers

S. D. Ekanayake
Institute for Infrastructure Engineering, University of Western Sydney, Australia.

D.S. Liyanapathirana and C.J. Leo
School of Computing, Engineering and Mathematics, University of Western Sydney, Australia.

ABSTRACT: Construction induced ground vibrations have become a major issue in modern day construction industry due to the adverse effects on structural health of adjacent substructures and superstructures. It is of utmost importance to eliminate, or to minimize, the propagation of ground vibrations towards nearby sensitive structures. Among numerous mitigation measures, wave barriers are widely used to attenuate ground vibration propagation. This paper investigates the effectiveness wave barriers in attenuating ground vibrations, using a three-dimensional finite element model. Finite element model was verified using data from a set of full-scale field experiments carried out using geofoam in-filled wave barriers. The model is then used to evaluate the effectiveness of EPS geofoam and water in-filled wave barriers in attenuating ground vibrations. Results conclude that EPS geofoam is the most efficient fill material that can be used in wave barriers.

1 INTRODUCTION

Due to the rapid population growth, suitable land for construction has become a scarce resource. As a result, construction activities are often carried out in the vicinity of existing structures. Vibrations generated from construction activities can cause severe damages to adjacent structures. Depending on the intensity of the ground vibrations, these damages can vary from minor architectural damages to severe structural failures, necessitating expensive rectification processes and causing delays in ongoing construction projects.

Peak particle velocity (PPV) is a parameter used to measure the intensity of ground vibrations because the strains induced due to vibrations in the ground are proportional to the particle velocity of the ground (Athanasopoulos and Pelekis, 2000). The most appropriate method of obtaining the PPV is by calculating true vector sum of velocities in three orthogonal directions. Numerous standards and design codes have published a range of PPVs to prevent building damage and to preserve human comfort (Ekanayake et al. 2013).

Different methods are available to minimise the intensity of construction induced ground vibrations: varying the excitation frequency, changing the location of the source, adjusting the soil characteristics to improve attenuation and using wave barriers to isolate the vibration source (Celebi et al., 2009). Isolation approaches used in practice can be categorised into two, based on the location of the wave barrier: active (near field) isolation and passive (far field) isolation.

Several full-scale field and centrifuge tests and numerical studies have been conducted to determine the efficiency of the open and in-filled wave barriers in attenuating ground vibrations. Celebi et al. (2009) carried out field experiments on efficiency of bentonite, concrete and water filled wave barriers. According to them, open trenches are the most effective wave barriers, however, practical applications are limited to shallow depths due to instability of trench walls. Also they concluded that the passive isolation is more effective than the active isolation.

Andersen and Nielsen (2005) used a coupled finite element-boundary element model to study the effectiveness of wave barriers against ground vibration propagation. They observed a reduction in wave amplitude beyond the barrier when there were deep wave barriers and high frequency excitations. They also studied the behaviour of concrete and rubber chips filled wave barriers and concluded that softer barriers are more efficient in attenuating ground vibrations.

Efficiency of water filled wave barriers in attenuating ground vibrations was investigated by Ju and Li (2011) by carrying out a set of three-dimensional finite element analyses. According to them, water in-filled barriers slightly outperformed open trenches in attenuating shear waves perpendicular to the direction of wave propagation, but less effective in attenuating dilation waves (Ju and Li, 2011).

However, the potential of different fill materials as wave barriers is yet to be fully understood. In this study, the effectiveness of EPS geofoam and water in-filled wave barriers in attenuating ground vibration propagation was investigated. A three-dimensional model was developed to simulate free field ground vibration propagation and attenuation of ground vibrations from open and geofoam filled wave barriers. First, the model is verified using data available from a full-scale field experiment. Then, the efficiency of EPS geofoam and water in-filled wave barriers in attenuating ground vibration was studied using the verified model. During the study, sensitivity of barrier performance to the frequency of the source is also investigated.

2 VERIFICATION OF NUMERICAL MODEL

A three-dimensional dynamic finite element model was developed using ABAQUS/Explicit (ABAQUS, 2011) to simulate the ground vibration propagation through open and in-filled wave barriers. The finite soil domain was modelled using eight-node linear brick continuum elements with reduced integration and hourglass control (C3D8R). The infinite domain beyond 30 m is modelled using eight-node linear continuum infinite elements (CIN3D8), to reduce the computational cost of the numerical simulations. A fixed boundary condition was applied to simulate the bedrock. The maximum element size was determined based on the minimum Rayleigh wavelength of soil, in order to prevent filtering of higher frequencies by large elements. Due to the symmetrical nature of the problem, only half of the domain was modelled to reduce the computational effort. The finite element mesh of the model with an open trench is illustrated in Fig. 1.

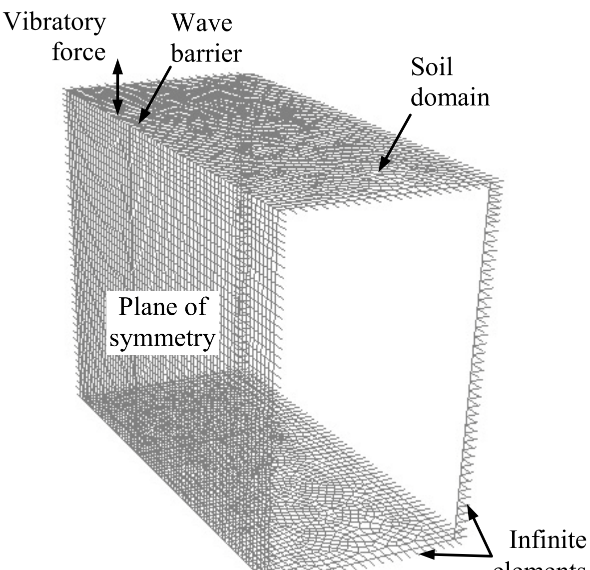

Fig. 1 Finite element mesh of the 3-D model simulating ground vibration propagation.

Data from the field tests conducted by Alzawi and El Naggar (2011) located in Ponoka, Alberta, Canada were used to verify the finite element model. The bedrock was found 30 m below the ground surface. The density of the soil increased from 1812.5 - 1955.3 kg/m^3 along the depth and the shear wave velocity increased from 225 - 456 m/s. This variation is considered to be linear along the depth during the numerical simulations. Since varying material properties cannot be assigned to infinite elements, material properties were applied to infinite domain in layers of soil with 3 m thickness averaged over each layer. Poisson's ratio of soil was 0.4. The trenches were filled with a light-weight polyurethane material known as URETEK, which has a shear wave velocity of 330 m/s and a density of 61 kg/m^3. Poisson's ratio of URETEK was zero. Rayleigh wave velocity near the surface was 214.8 m/s.

Maximum element dimension in a finite element model, $\boldsymbol{L_{max}}$, is given by,

$$L_{\max} \leq \frac{1}{4}\lambda_{R_{\min}} \tag{1}$$

where $\boldsymbol{\lambda_{R\min}}$ is the minimum Rayleigh wave length of the medium (Zerwer et al., 2002). $\boldsymbol{\lambda_{R\min}}$ is calculated by,

$$\lambda_{R\min} = \frac{V_R}{f_{\max}} \tag{2}$$

where $\boldsymbol{V_R}$ is the Rayleigh wave velocity and $\boldsymbol{f_{max}}$ is the highest frequency. An approximate solution for $\boldsymbol{V_R}$ can be obtained from below equation,

$$V_R = \left[\frac{0.72 - \left(\frac{V_R}{V_D}\right)^2}{0.75 - \left(\frac{V_R}{V_D}\right)^2} \right] \times V_S \tag{3}$$

where $\boldsymbol{V_S}$ and $\boldsymbol{V_D}$ are shear and dilation wave velocities in the medium, respectively. The only frequency used in this study is 50 Hz. Hence the maximum element size should not be greater than 1.06 m. However, for increased accuracy, maximum element size assigned was 0.5 m. Material damping applied for the soil domain was 5% of the critical damping, based on the first realistic eigen frequency of the model.

Three cases were considered to verify the finite element model. In the first case, free field ground vibration propagation is considered. In the second case, a 20 m long and 3 m deep open trench with 0.25 m width was installed in the ground. In the third case, URETEK geofoam is used to fill the open trench. Geophones were placed at 2.5 m intervals in a line perpendicular to the wave barrier.

Analysis was continued for 0.5 s and vertical particle velocities are extracted at intervals of 0.5 ms, totaling 1000 extraction points for each geophone. A vertical sinusoidal point load of 11.75 kN with a frequency of 40 Hz was applied on the ground surface, 2.5 m away from the center of the wave barrier. Fig. 2 compares the finite element predictions with field data from Alzawi and El Naggar (2011) by plotting normalized vertical PPV against normalized distance (d/$\boldsymbol{\lambda_R}$). Vertical PPVs are normalised by the highest velocity extracted 0.5 m away from the source. $\boldsymbol{\lambda_R}$ is the Rayleigh wavelength of the medium. Location of the wave barrier is shown by the dotted line in Fig. 2.

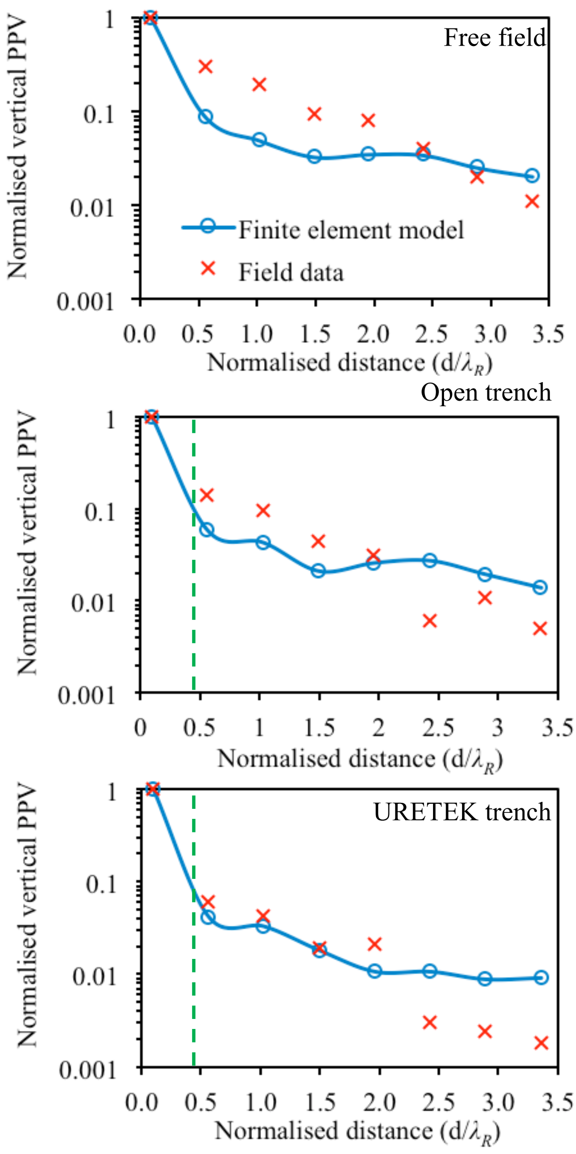

Fig. 2 Normalized vertical peak particle velocities for vibration attenuation.

Apart from the small discrepancies between finite element predictions and field data, overall, results prove that the finite element model developed in this study is capable of simulating ground vibration propagation with and without wave barriers.

3 IN-FILLED WAVE BARRIERS

In this section the effectiveness of EPS geofoam and water in-filled wave barriers are investigated using the verified finite element model. EPS geofoam is modelled using a constitutive model developed by Wong and Leo (2006) extending the Drucker-Prager yield criterion, assuming a non-associated flow rule. A finite element formulation of the constitutive model is developed using the explicit integration scheme and it is implemented in ABAQUS/Explicit using the user defined material subroutine VUMAT (Ekanayake et al., 2012). Material properties and rheological parameters used in this study, which were extracted by Wong and Leo (2006) from triaxial test data, are presented in Table 1.

Table 1. Material properties for EPS geofoam constitutive model

Young's modulus, E (kPa)		3950
Poisson's ratio, ν		0
Rheological parameters	R_o (kPa)	98
	K_p	-0.17
	β (kPa)	225
	K	-0.25

Water is modelled with the Mie-Grüneisen equation of state (Mie, G., 1903; Grüneisen, E., 1912; Mahamadi et al., 2004). A density of 1000 kg/m^3 and a viscosity of 1x10^{-3} Ns/m^2 was assigned to water with a compression wave velocity of 1490 m/s. The gradient of the linear relationship between shock velocity and the particle velocity was considered to be 1.79 and the Grüneisen ratio was considered to be 1.65 (Otsuka et al., 2004).

Geometry of the wave barrier was maintained to have a depth of 3 m, a length from 20 m and a width from 0.25 m. The soil properties are same as those described in the previous section. For each case, a sinusoidal force of 11.75 kN operating at 40 Hz is applied 2.5 m away from the center of the wave barrier. The simulations were then repeated for the same sinusoidal force operating at 50 Hz, to study the sensitivity of the efficiency of wave barriers to frequency of the source.

Fig. 3 shows the effectiveness of EPS geofoam wave barrier and water filled wave barrier against an open trench when the frequencies of the source are 40 and 50 Hz. It can be concluded that each type of in-filled wave barrier attenuates ground vibrations by a considerable amount for both frequencies considered in this analysis. However, EPS geofoam wave barrier outperforms water filled wave barrier at each case. Further, the efficiency of the EPS geofoam wave barrier is increased when the frequency of the source is increased.

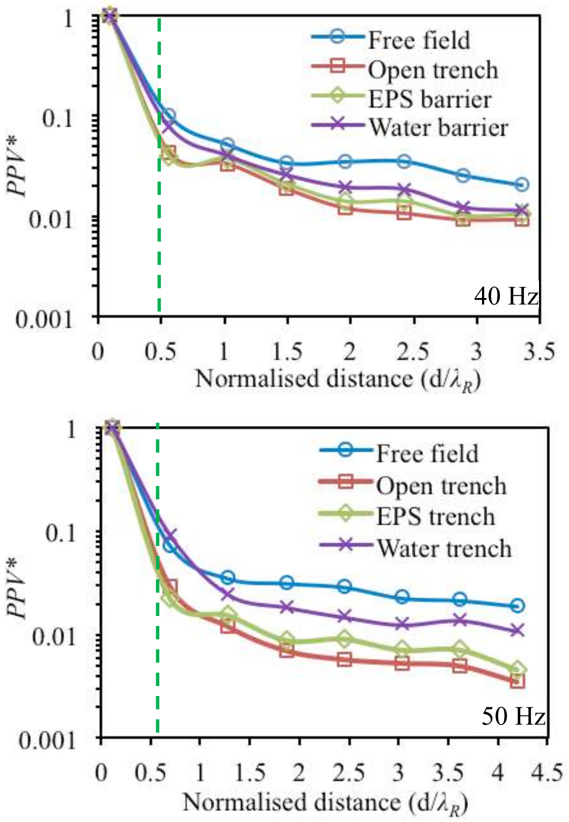

Fig 4. Vibration attenuation from open and in-filled wave barriers.

4 CONCLUSIONS

The effect of EPS geofoam and water in-filled wave barriers in attenuating ground vibrations is investigated in this study. A three-dimensional finite element model is developed using the finite element program ABAQUS/Explicit and it is verified with field data available for attenuation of ground vibrations. The model is then used to study the efficiency of EPS geofoam and water-filled wave barriers.

It can be concluded that EPS geofoam is the most effective fill material that can be used in wave barriers in attenuating ground vibrations. Efficiency of EPS geofoam wave barriers is closer to efficiency of open trenches. Performance of EPS geofoam wave barriers can be improved by increasing the frequency of the source.

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REFERENCES

ABAQUS Inc., ABAQUS version 6.11 user's manual, Providence, Rhode Island, USA; 2011.

Alzawi, A. and El-Naggar, M.H. (2011). ‘Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers’, Soil Dynamics and Earthquake Engineering, vol. 31(3), pp. 306–317.

Andersen, L. and Nielsen, S.R.K. (2005). ‘Reduction of ground vibration by means of barriers or soil improvement along a railway track’, Soil Dynamics and Earthquake Engineering, vol. 25, pp. 701–716.

Athanasopoulos, G.A. and Pelekis, P.C. (2000). ‘Ground vibrations from sheetpile driving in urban environment: measurements, analysis and effects on building and occupants’, Soil Dynamics and Earthquake Engineering, vol. 19, pp. 371–387.

Celebi, E., Fırat, S., Beyhan, G., Cankaya, I., Vural, I. and Kırtel, O. (2009). ‘Field experiments on wave propagation and vibration isolation by using wave barriers’, Soil Dynamics and Earthquake Engineering, vol. 29, pp. 824–833.

Ekanayake, S.D., Liyanapathirana, D.S. and Leo, C.J. (2012). ‘Finite element simulation of EPS geofoam behaviour: explicit integration method’, 11th Australia New Zealand Conference on Geomechanics, Melbourne, Australia, pp. 1135–1140.

Ekanayake, S.D., Liyanapathirana, D.S. and Leo, C.J. (2013). ‘Influence zone around a closed-ended pile during vibratory driving’, Soil Dynamics and Earthquake Engineering, vol. 53, pp. 26–36.

Grüneisen, E. (1912). ‘Theorie des festen Zustandes einatomiger Elemente’. Annalen der Physik, 344(12), pp. 257–306.

Ju, S.H. and Li, H.C. (2011). ‘3D Analyses of open trench barriers filled with water’, Journal of Geotechnical and Geoenvironmental Engineering, vol. 137(11), pp. 1114–1120.

Mahmadi, K., Itoh, S., Hamada, T., Aquelet, N. and Souli, M. (2004). ‘Numerical studies of wave generation using spiral detonation cord’, Materials Science Forum, vol. 465–466, pp. 439–444.

Mie, G. (1903). ‘Zur kinetischen Theorie der einatomigen Körper.’ Annalen der Physik, vol. 316(8), pp. 657–697.

Otsuka, M., Matsui, Y., Murata, K., Kato, Y. and Itoh, S. (2004). ‘A study on shock wave propagation process in the smooth blasting technique’, 8th International LS-DYNA Users Conference, Dearborn, MI, pp. 7:5–7:12.

Wong, H. and Leo, C. J. (2006). ‘A simple elastoplastic hardening constitutive model for EPS geofoam.’ Geotextiles and Geomembranes, vol. 24, no. 5, pp. 299–310.

Zerwer, A., Cascante, G. and Hutchinson, J. (2002). ‘Parameter estimation in finite element simulations of Rayleigh waves’, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 250, pp. 250–261.