Experimental Investigations on Vibration Isolation Using Open and GeoFoam Wave Barriers: Comparative Study

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ABSTRACT
Ground vibrations induced by machine foundations can cause unfavourable effects which can be minimized by installing a suitable wave barrier. A full scale field study has been conducted to investigate the protective performance of both open and in-filled GeoFoam wave barriers and to examine the influences of the geometry and location. Experimental results show that the proposed wave barriers can effectively scatter the generated surface steady state waves. The protective performance has been assessed numerically by developing a 2D FE model. The field investigations have been compared with those obtained numerically, interpreted and some guidelines regarding some key parameters are outlined.

RÉSUMÉ
vibrations du sol induites par des fondations machine peut provoquer des effets défavorables, qui peuvent être minimisés par l'installation d'une barrière d'onde appropriée. Une étude à grande échelle sur le terrain a été menée afin d'évaluer les performances de protection à la fois ouvert et rempli de barrières vague GeoFoam et d'examiner l'influence de la géométrie et l'emplacement. Les résultats expérimentaux montrent que les barrières d'onde proposée diffusant de façon efficace la surface des vagues générées état d'équilibre. La performance de protection a été évaluée numériquement par l'élaboration d'un modèle 2D FE. Les enquêtes sur le terrain ont été comparés avec ceux obtenus numériquement, interprété et des lignes directrices en ce qui concerne certains paramètres clés sont énoncés.

1 INTRODUCTION

Wave barriers are used to reduce ground vibrations induced by different vibration sources such as machine foundations, which can cause unfavourable effects. The vibration disturbance may affect people, sensitive machines or neighbouring residential areas. Most of the vibratory energy from machine foundations is carried by surface waves that propagate close to the ground surface. To control the transmitted vibrations and their disturbance, suitable wave barriers can be a successful technique to scatter the generated steady state surface waves. Wave barriers can also be used to scatter environmental vibrations. The geometry, location and composition of the barrier influence its vibration isolation performance. Wave barriers can be constructed 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 studies were focused on vibration isolation using wave barriers in order to improve the understanding of the vibration scattering phenomenon. Woods (1968) performed a series of scaled field experiments on vibration isolation involving open trenches close to the wave source (known as an active isolation) and in the far field (known as a passive isolation). Based on the experimental observations, he presented some guidelines for sizing open trenches to achieve a ground amplitude reduction equal to or more than 75%.

Haupt (1981) conducted a series of model tests on the vibration isolation of various measures in a laboratory setup. He investigated solid barriers (concrete walls) and light weight barriers such as rows of boreholes and open trenches. The experimental results showed that the screening performance of these barriers was a function of characteristic parameters in terms of wavelength-normalized dimensions. Baker (1994) has conducted a series of field tests to investigate the effectiveness of barriers made of bentonite (i.e. soft barrier) and concrete (i.e. stiff barrier) installed near and far from the source of disturbance, which are known as active and passive vibration screening, respectively. He compared his experimental findings with results obtained from a numerical model the boundary element method (Lee,1994) and the empirical design equations developed by Al-Hussaini (1992).

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) used an FEM model to investigate the performance of solid trenches (concrete walls) in terms of their geometrical and material characteristics. The numerical results were compared with small-scale laboratory tests for harmonic loading generated by a heavy machine. Waas (1972) used FEM to perform frequency domain simulation of screening horizontal shear waves (SH) by trenches. El Naggar and Chehab (2005) analyzed the efficiency 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 efficiency of a rectangular barrier by using higher-order BEM algorithm. They 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 due to Baker (1994) and reported a reasonable agreement between the predicted values for the average amplitude reduction ratio.

A few studies have been performed using the GeoFoam material as wave barriers. Davies (1994) carried out a series of 20-g centrifuge tests to investigate the screening performance of expanded polystyrene (EPS) barrier and concrete wall on the nearby buried structures. The centrifuge test results indicated that barriers containing low acoustic materials were highly effective in the attenuating the stress wave. Davies (1994) concluded that a well-designed wave barrier could reduce the magnitude of ground shock loading significantly on buried structures. On the other hand, Wang (2008) has conducted numerical investigations to evaluate the performance of the 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 considered in the numerical simulation. The numerical model was developed based on the prototype dimensions of the centrifuge test conducted by Davies (1994). Based on the numerical model results, Geofoam barriers performed well in reducing the blast-induced stress waves. Wang (2000) concluded that the Geofoam barrier is designable, which means it can be used practically as a permanent protection barrier. However, it should be noted that the vibration sources in the above-mentioned studies were blast-induced ground shocks.

Murillo et al. (2009) performed centrifuge tests to simulate the traffic vibration and to investigate the effectiveness of EPS barriers in scattering this type of ground borne vibrations. The centrifuge tests involved a parametric study to examine the EPS barriers performance in terms of the barrier dimensionless geometry and its location from the source of disturbance. The results showed that the barrier performance depends mainly on its depth and location from the vibratory source. They also found that the barrier width has a minor influence in the case of deeper barriers and higher frequencies. On the other hand, a remarkable influence of barrier width can be observed in shallow barriers and lower frequencies.

An innovative vibration isolation system using Geofoam material is introduced in this paper. The objective of this study is to investigate the performance of GeoFoam walls and open trenches as wave barriers under periodic harmonic loadings in the vertical direction. Full scale experimental tests have been conducted. In these tests, the effects of barrier geometry and location from the source of disturbance have been explored. The influence of changing the ratio between the barrier depth and its location has also been investigated. The obtained experimental are used to calibrate a 2D time-domain numerical models utilizing a finite element package, ABAQUS for open and GeoFoam wave barriers considering the same experimental conditions. This numerical model can then be used to perform a parametric study to better understand the factors that influence the performance of GeoFoam barriers.

2 SITE INVESTIGATION AND MATERIALS PROPERTIES

The test site is a flatted area located 5 km west of Ponoka, Alberta. The seismic cone penetration test (SCPT) was used to establish the soil profile at the test site. The boreholes show that the site soils are silty clays, calyey silt and sandy silt underlain by stiff fine grained and cemented sand layer. The soil density varies between 1812.5 and 1955.25kg/m^3, material damping of about 5%, and Poisson's ratio of 0.4.

The Multichannel Analysis of Surface Waves (MASW) method is adopted to characterize the soil layering and to establish the shear wave velocity profile. In the MASW method, the seismic surface waves generated by a seismic source are measured at different locations. The measured wave propagation is analyzed in order to evaluate the propagation velocities and deduce shear wave velocity (Park et al. 1999). The shear wave profile established for the test site is shown in Figure 1.

Figure 1. Adopted shear wave velocity profile

The GeoFoam material used in this study was a two-component Polyurethane lightweight material supplied by URETEK Canada. It is also known as URETEK polymer. The GeoFoam material has a density of 61 kg/m^3. The dynamic properties of GeoFoam material were evaluated using Bender Element Tests: shear wave velocity of 330 m/sec, and Poisson's ratio is close to zero.

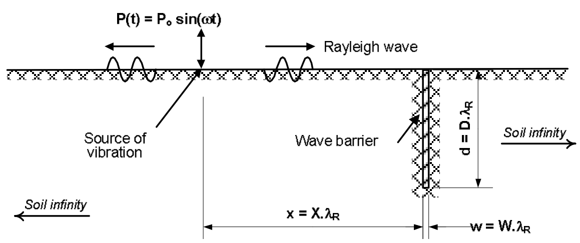


Figure 2. Typical schematic of the vibration isolation system and geometric parameters

3 EXPERIMENTAL PROGRAM

The experimental program was performed in three stages. The first stage consisted of exciting the ground and recording measurements of ground motion before digging the trench wall. A trench wall of 20m length, 0.25m width, and 3.0m depth was constructed using a hydro-dig technique. Because the water table was well below the target depth and due to the nature of soil, stiff sandy silt to silty clay, the excavated trench could stay stable without collapse. That means the ground can be excited and measurements can be taken while the trench is open in order to make a comparison between the open and the GeoFoam barriers protective effectiveness for the same soil profile and testing conditions. Stage two consisted of exciting the ground again and measurements of ground motion were recorded at the same excitation frequencies considered in stage one. The GeoFoam material was then installed in the open trench. After the curing process of the GeoFoam is completed, the ground was excited for the third time (stage three, with GeoFoam barrier) and ground motion measurements were recorded for the same excitation frequencies as was done in stages one and two.

The vibration source was a Lazan type (MO 2460) mechanical oscillator with a maximum operating speed of 3600rpm with no loads. To simulate a machine foundation case, and to keep the system acceleration during the excitation less than 1g, the oscillator was placed centrically on top of a steel mass (twenty steel plates) and they were bolted together using four threaded steel rods. To ensure good contact between the source of disturbance and the ground, the excitation system was embedded about 25cm below the ground surface.

The harmonic excitation was applied with ten different frequencies of vibration were. For planning the experimental setup, and later when evaluating the results, all the geometrical properties of the trench wall (i.e. dimensions) are normalized by the Rayleigh wavelengths, λ_R. For the different excitation frequencies considered here, the Rayleigh wavelengths, barriers dimensionless geometry, and locations are listed in Table 1. A typical schematic of the vibration isolation system and geometric parameters are shown in Figure 2.

To study the influence of the proximity of the disturbance source to the isolation system on its protective effectiveness, three locations for the excitation system were adopted: 2.5, 5, and 10m from the barrier center. Table 2 present the experimental parameters.

Table 1. Dimensionless geometry of the experiment.

Rayleigh wave-length	Barrier dimensionless depth	Dimensionless distance from vibration source		
		First location	Second location	Third location
λ_R, m	$D=d/\lambda_R$	$X_1=x_1/\lambda_R$	$X_2=x_2/\lambda_R$	$X_3=x_3/\lambda_R$
14.09	0.21	0.17	0.35	0.52
10.57	0.28	0.22	0.46	0.70
8.46	0.35	0.28	0.58	0.87
7.05	0.43	0.34	0.69	1.05
6.04	0.50	0.39	0.81	1.22
5.28	0.57	0.45	0.92	1.40
4.70	0.64	0.51	1.04	1.57
4.23	0.71	0.56	1.15	1.74
3.84	0.78	0.62	1.27	1.92
3.59	0.84	0.66	1.36	2.05

Table 2. Experimental parametric test.

Barrier width (m)	w	0.25
Barrier depth (m)	d	3.0
Distance from the source of disturbance (m)	*l*	2.5, 5, 10
Exciting frequencies (Hz)	f	15, 20, 25, 30, 35, 40, 45, 50, 55, 58.84

An 8 sec record of soil particles velocities was acquired for each selected frequency using vertical component geophones with a 1 millisecond sampling interval, which resulted in 8000 data points. The geophones were deployed along a line perpendicular to the barrier center with 2.5m intervals. The experimental layout is illustrated in Figure 3. The geophones were connected to a 24-channel Geode/ES-3000 seismic station. A laptop computer equipped with PCMCIA card was used to control the seismic station through Seismodule Control Software.

4 FINITE ELEMENT MODEL

A 2D finite element (FE) model was developed by utilizing the software ABAQUS (2005). The soil and wave barriers were modeled using 4-noded first-order plane-strain rectangular elements. To ensure complete energy dissipation, infinite non-reflecting boundaries have been

imposed to simulate the far field conditions. 4-noded first-order plane-strain one-way infinite elements were used to represent the non-reflecting boundaries.
the subsequent section.

The vibration source was modeled as a vertical harmonic load represented by a sinusoidal function. The load was applied at distances 2.5m, 5.0m and 10.0m from the center of the barrier (i.e. first, second and third locations, respectively) and pointed directly on the ground surface. For modelling purposes, the footing supporting the dynamic load was eliminated as it did not practically affect the vibration results (Kattis 1999). The symmetry of the problem was exploited and symmetry boundary conditions were applied by restraining the displacement in the perpendicular direction to the symmetry surfaces. Hence, the axis of symmetry was placed across the point of load application. The soil profile was established based on MASW and SCPT results. The bedrock was assumed to be at 30.0m below the ground surface.

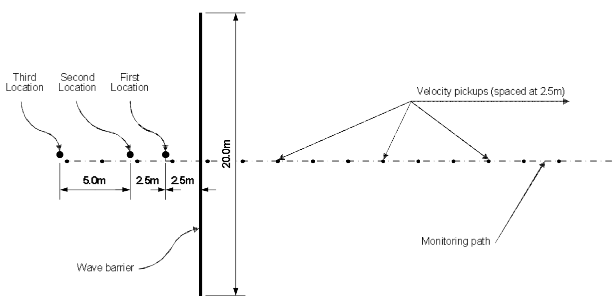


Figure 3. Experimental layout

4.1 Finite Element Model Verification

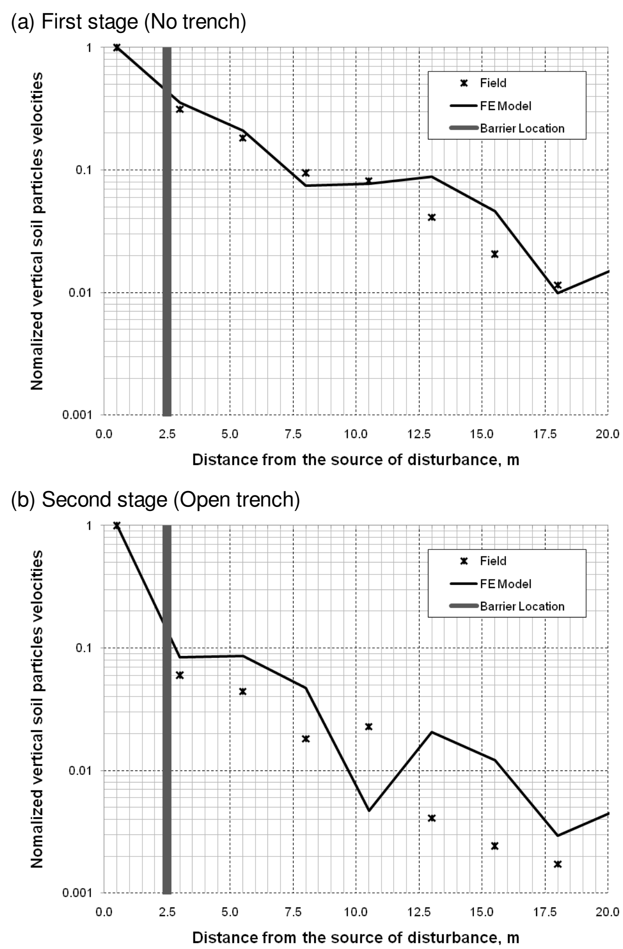
Figures 4 and 5 present the ground motion measured in the field and that obtained from the FE model for the exciting frequencies 40Hz and 50Hz, and the oscillator located at first and second location, respectively. The figures demonstrate a good agreement between the numerical and experimental results. However, the FE model gives slightly higher values at some points and lower values at others. This is attributed to the idealized soil profile with homogeneous soil layers with horizontal interfaces, which is not necessarily the case in the field. Another source of discrepancy between the field and the FE model results could be the presence of large stones that were observed while digging the trench (i.e local soil inhomogeneities). Therefore, it is concluded that the FE model is adequate model for simulating the performance of the wave barriers with reasonable accuracy.

Furthermore, the attenuation curves show steep decay, which indicates that the soil material damping is high. It is worth noting that as the excitation frequency increased, the geometric damping increased resulting in further attenuation of the generated surface waves.

Finally, it is noted from Figures 4 and 5 that the velocity amplitude at the measuring point located 20.0 m from the vibration source is less than 2% of that at the source. Therefore, the analysis of barrier effectiveness will be limited to a distance 18.0 m from the source, as the amplitudes at larger distances are negligible, even without any wave barrier. In other words, including the measured responses at distant points will not allow reliable and meaningful evaluation of the barrier effectiveness.

5 RESULTS AND DISCUSSION

Because of the large number of experiments conducted in this study, only a representative sample of the results is presented here. Only the influence of barrier normalized depth and the coupling effect of barrier location on the system screening effectiveness will be discussed. The analysis of barrier effectiveness is evaluated in terms of the amplitude reduction ratio A_r which will be explained in the subsequent section.



(c) Third stage (GeoFoam trench)

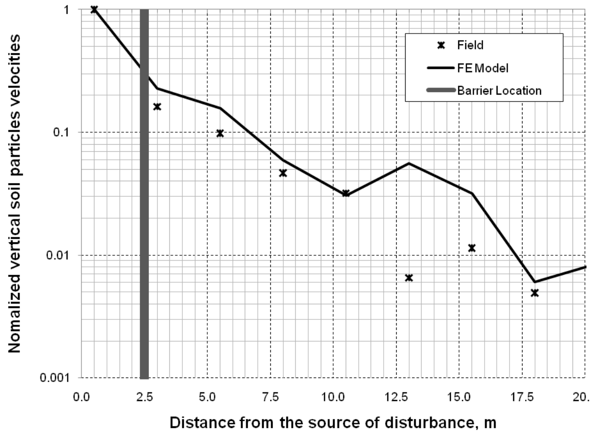
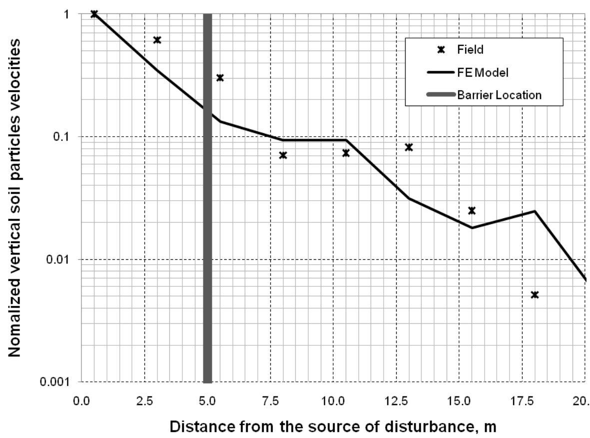
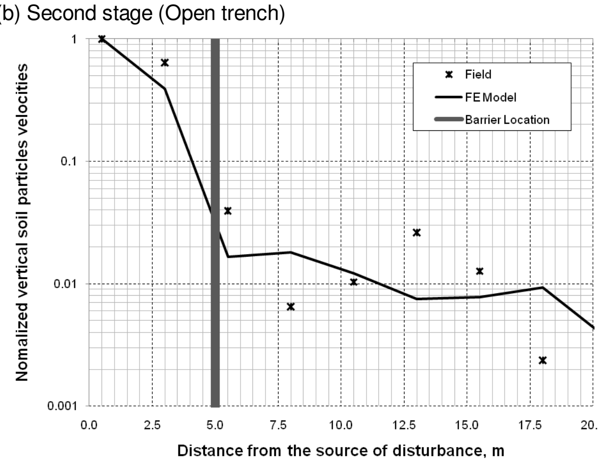


Figure 4. Comparison of field and FE model attenuation curves (40Hz & first location)

(a) First stage (No trench)



(b) Second stage (Open trench)



(c) Third stage (GeoFoam trench)

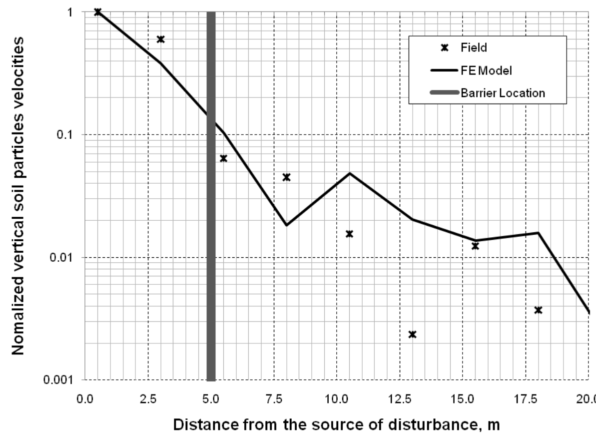


Figure 5. Comparison of field and FE model attenuation curves (50Hz & second location)

5.1 Amplitude Reduction Ratio (Ar)

The vibration source simulates the case of machine foundation vibration, which results in steady state response. Thus, the system effectiveness can be evaluated based on either the displacement, velocity or acceleration. In the literature, the system effectiveness is usually evaluated in terms of reduction in soil particle response amplitude. In practice, the effect of transmitted vibration is usually evaluated in terms of soil particle velocities at zones of interest. Since velocity pickups were used to measure the ground motion, the system effectiveness is presented here in terms of reduction in soil particle velocity.

The amplitude reduction ratio, A_r, is calculated from the experimental results by normalizing the post-trench maximum spectral amplitude, $(A_r)_{After}$, by the maximum spectral amplitude before trench installation, $(A_r)_{Before}$, (see Equation 1). The maximum spectral amplitude can be obtained from spectral curves by applying FFT to the time history records at the points of interest. For the FE model results, the amplitude reduction ratio, A_r, is evaluated at the nodes where geophones were deployed. The post-trench installation maximum vertical response amplitude, $(A_r)_{After}$, is normalized by the maximum vertical response amplitude before trench installation, $(A_r)_{Before}$, using Equation 1. The maximum vertical response amplitudes are obtained from the nodes response time histories.

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

To evaluate the effectiveness of the wave barrier, the averaged amplitude reduction ratio over a distance of interest x measured behind the wave barrier, $\overline{A_r}$, can be calculated by using the following equation:

$$\overline{A_r} = \frac{1}{x}\int A_r \, dx$$
[2]

The system effectiveness is then calculated as:

$$Eff_A = \left(1 - \overline{A_r}\right) \times 100$$
[3]

5.2 Influence of Barriers Dimensions and Locations on Screening Effectiveness Based on Field Results

The Rayleigh wavelength decreases as the excitation frequency increases, and consequently, for the same barrier geometrical dimensions, its normalized dimensions and the normalized distance, X, increase. Unlike all published experimental results in previous studies, the distance x is not constant in this study, as the vibration source was moved from one location to another. This allowed the evaluation of the coupled influence of barrier location and depth. The influence of barrier normalized width is ignored in this study since the proposed width to construct this type of GeoFoam barrier is 0.25 m for practical reason, which was found to provide excellent performance in scattering the induced ground vibration (Alzawi and El Naggar, 2009).

Figure 6 demonstrates the influence of barrier normalized depth, D, for both the open trench and GeoFoam barrier. It is noted that as the normalized depth, D, increased, the averaged amplitude reduction ratio, $\overline{A_r}$,decreased, i.e., the barrier protective effectiveness improved. The results show that a significant improvement can be achieved when D ≥ 0.57 for both open and GeoFoam barriers. Hence, D = 0.57 can be considered as an optimum depth for GeoFoam barriers. For example, an overall average amplitude reduction ratio of about 0.16 and 0.31 are achieved for the open and GeoFoam barriers systems, respectively. That means the vibration amplitudes are decreased by 84% and 69% (barrier effectiveness) for the open and GeoFoam barriers, respectively.

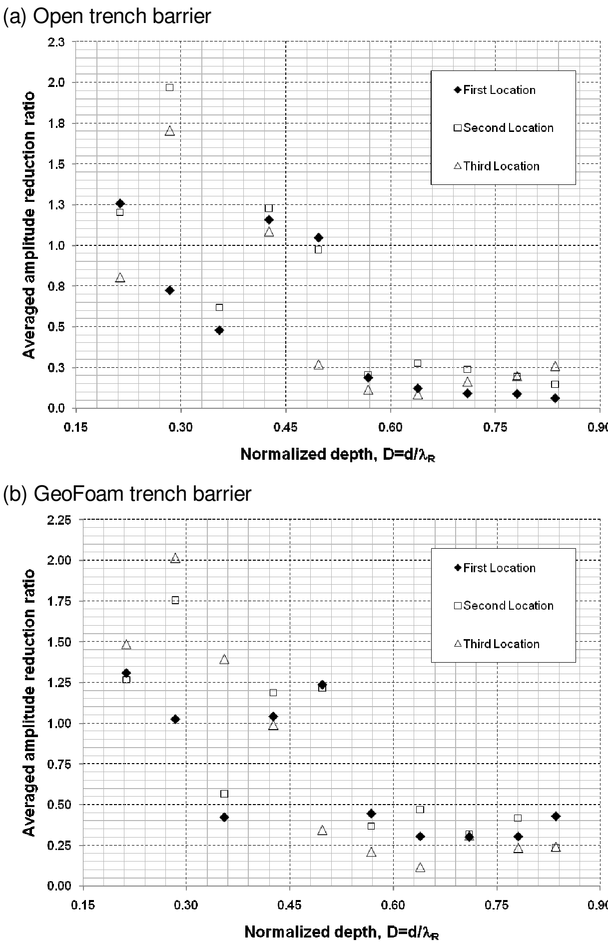
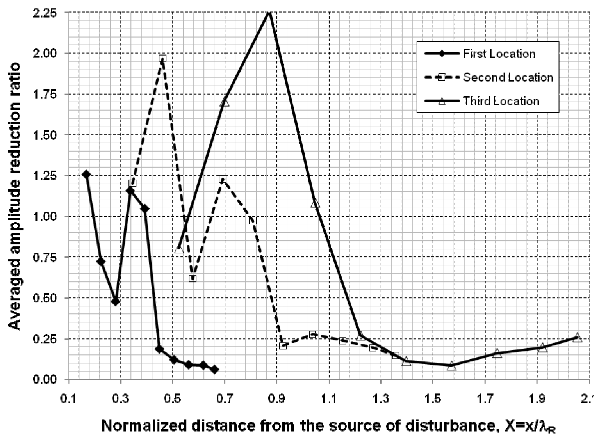


Figure 6. Influence of normalized depth (Field results)

The influence of barrier location on its effectiveness is demonstrated in Figure 7. The adopted ratios of x/d are 0.79, 1.63, and 3.29 for the first, second, and third locations, respectively. Figure 7 shows that as the distance between the barrier and the vibration source increased, a deeper trench is required in order to achieve the same barrier effectiveness. For example, in the case of an open trench with x/d = 0.79 (first location), 89% effectiveness can be achieved by placing the barrier at X ≥ 0.45 with D ≥ 0.57. Meanwhile, for x/d = 1.63 (second location), similar effectiveness can be achieved by placing the barrier at X ≥ 0.92 with D ≥ 0.57. Although similar trend is observed in the case of GeoFoam barrier, x/d has a smaller effect on the barrier performance. For example, an average system effectiveness of 65% can be achieved by placing the GeoFoam barrier at X = 0.45-0.66, with x/d = 0.79 and D = 0.57-0.84. Meanwhile, an average system effectiveness of 64% can be achieved by placing the barriers at X = 0.92-1.36, with x/d = 1.63 and D = 0.57-0.84. It can be concluded that for smaller x/d, a shallower barrier can be used to achieve the same system effectiveness.

(a) Open trench barrier



(b) GeoFoam trench barrier

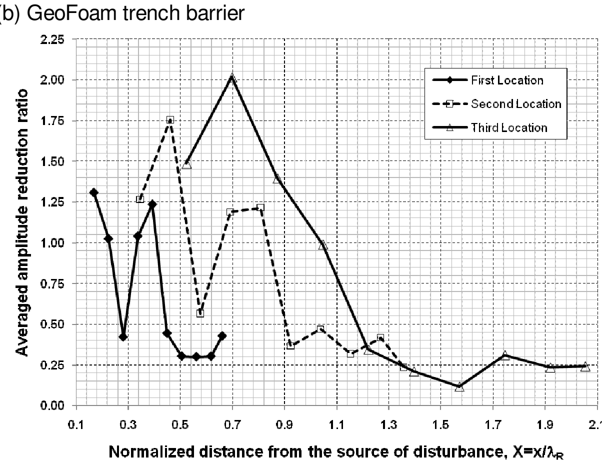
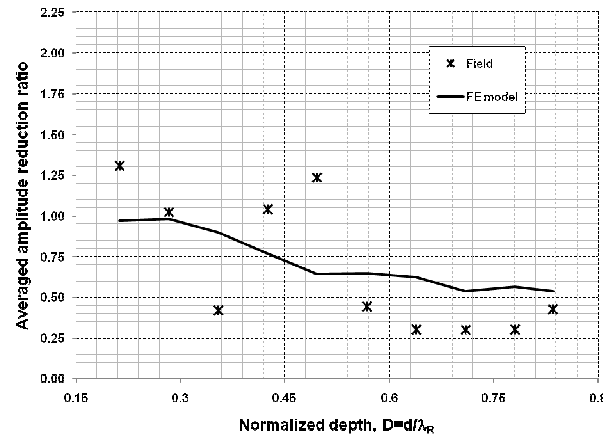


Figure 7. Influence of normalized distance

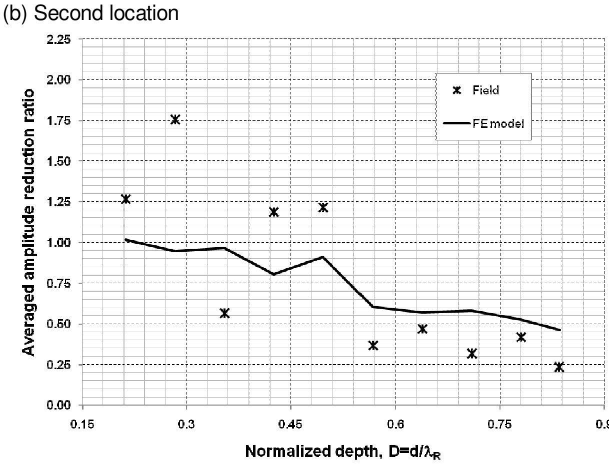
5.3 Comparison of Field and FE Model Results

Figure 8 presents the averaged amplitude reduction ratios for the GeoFoam barrier vs. its normalized depth. It is clear that FE model results are slightly higher than the measured values. The numerical results are slightly higher than the experimental ones. In other words, the averaged amplitude reduction ratios obtained by the FE model are considered to be conservative, i.e., underestimating the protective efficiencies compared with the field results. As noted by Al-Hussaini (2000), this is expected because of the 3D nature of the field study in which the waves were generated by a circular source. He concluded that a 3D analysis is more appropriate.

(a) First location



(b) Second location



(c) Third location

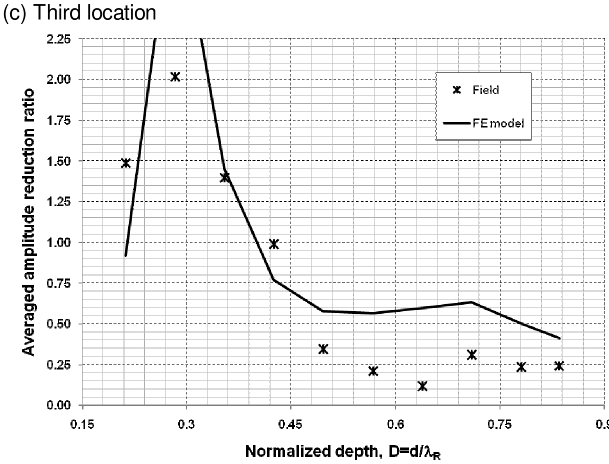


Figure 8. Comparison of field and FE model results for GeoFoam trench barrier

Tables 3 and 4 summarize the average protective efficiencies, Eff_A, by considering only the efficiencies obtained by exciting frequencies greater than or equal to 40Hz which are equivalent to D ≥ 0.57 for open trench and GeoFoam barriers. The average differences between FE model results and Field results are 10.65% and

35.19% for open and GeoFoam trench barriers respectively. The reason of having a discrepancy of about 35.19% between FE model and field results can be attributed to the fact that the FE model assumed full bonding between the GeoFoam wall and soil, which may not be the case in the real experiment. However, it can be concluded that the predicted protective efficiencies by the FE model are in a good agreement with those obtained from field measurements.

Table 3. Open trench barrier protective efficiency.

Trench location	1st location	2nd location	3rd location
Field (%)	89.08	78.82	83.68
FE Model (%)	76.35	78.08	69.69
Difference (%)	**14.29**	**0.94**	**16.72**

Table 4. GeoFoam trench barrier protective efficiency.

Trench location	1st location	2nd location	3rd location
Field (%)	64.53	63.92	77.73
FE Model (%)	41.79	45.11	45.93
Difference (%)	**35.24**	**29.44**	**40.91**

6 CONCLUSIONS

This paper summarizes the outcomes of a full scale experimental study with the objective of investigating the performance of open and GeoFoam trenches as wave barriers. The wave barriers protective effectiveness was evaluated based on the achieved reduction in soil particle velocity through a parametric study by changing the exciting frequency and the location of the wave barriers. The field results were compared with those obtained from the developed FE model. Based on the analysis of the results obtained, the following conclusions can be made:

1) The field results show that an open trench barrier is more effective than the GeoFoam trench barrier, however, GeoFoam barrier can be considered as a practical alternative, especially in cases where soil stability is a problem. Furthermore, the average GeoFoam barrier protective effectiveness can be up to 68%.

2) The system protective efficiency is a function of the barrier normalized depth and its proximity to the vibration source. The barriers have been found to be generally more effective when $D \geq 0.60$ for both open and GeoFoam barriers. For x/d of about 0.79, 1.63 and 3.29, the normalized distance X of 0.45, 0.92 and 1.22 are the optimum barrier locations corresponding to the optimum normalized depth D of about 0.57.

3) The results show that as x/d increases, the open trench barrier efficiency decreases. In contrast, changing x/d has a negligible influence on the GeoFoam trench barrier.

4) The results obtained from the FE model are comparable with those obtained experimentally. The differences between the Field and FE model results are 10.65% and 35.19% for open and GeoFoam barriers, respectively. Therefore, the FE model can be used to extrapolate the results and conduct a parametric study on the GeoFoam barrier performance with different configurations and in different soil profiles.

5) The observations made above are directly applicable to sites with soil conditions similar to those encountered at the test site. For different sites with different soil conditions, it is recommended to use the developed FE model to design the wave barrier.

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