Modeling of vibration isolation using geofoam barriers in centrifuge

Modélisation en centrifugeuse de barrières anti-vibration en polystryrène

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ABSTRACT

Vibrations produced by traffic, industrial activity, blasting, piling, constructions operations, and natural phenomena like earthquakes can potentially damage the buildings, disturb the people and affect sensitive equipment and technical process. Of particular interest are the traffic vibrations produced by heavy vehicles or trains, these are high frequency transient vibrations that produces highly perceptible vibration of some structural elements located close to roads. The installation of a barrier in the soil is one of the suitable methods to reduce the ground vibrations since the barrier disturbs the natural spreading of the waves and screens the buildings in a certain region behind the barrier.

Parameters involving the geometry of the barrier, their position, and their material affect the effectiveness of the barrier isolation systems. Analytical solutions of the wave's propagation problem with barriers are extremely difficult to obtain since this requires the solution of the wave diffraction problem. Few researches about the efficiency of isolation barriers using reduced scale models have been carried out. These studies are accessible using centrifuge modeling techniques since for the wave's propagation problems the replication of the stress field is crucial. This paper presents the results of a study about the efficiency of geofoam barriers focusing on the effect of the depth of the barrier on the reduction of vibrations.

RÉSUMÉ

Les vibrations qui sont produites par le trafic, les activités industrielles, les explosions, les constructions, et les phénomènes naturels tels que les séismes, peuvent potentiellement endommager les constructions, perturber les personnes et affecter les équipements sensibles. Les vibrations produites par les véhicules lourds et les trains ont un intérêt particulier car ce sont des vibrations transitoires de haute fréquence qui engendrent des vibrations importantes dans les éléments structurels qui sont proches des routes. L'installation d'une barrière dans les sols est l'une des méthodes envisageables pour réduire les vibrations du sol car ces barrières modifient la propagation naturelle des ondes et protègent les bâtiments dans une certaine zone au-delà des barrières.

Les paramètres tels que la géométrie de la barrière, sa position, et son matériau contribuent à leur efficacité dans un système d'isolation. Les solutions analytiques de la propagation des ondes avec une barrière sont extrêmement complexes car il s'agit de la solution d'un problème de diffraction d'ondes. Ces études sont faisables en utilisant la technique de modélisation en centrifugeuse car dans la propagation des ondes la réplication des contraintes naturelles est cruciale. Cet article présente les résultats d'une étude sur l'efficacité des barrières en polystyrène expansé et en particulier l'effet de la profondeur de la barrière dans la réduction des vibrations.

Keywords : vibration isolation, Rayleigh waves, centrifuge modelling, geofoam barriers.

1 INTRODUCTION

Traffic vibrations due to heavy vehicles or trains are particularly representative of the nuisance caused to structural elements located close to roads or railways. The installation of an isolation barrier in the soil can reduce ground vibrations significantly by preventing the transmission of vibratory waves to the buildings in a determined zone behind the barrier (Luong 1994). The geometry, the position and the composition of the barrier affect the isolation performances. A survey of the literature on the results achieved with the two main types of barriers (open or in-filled barriers) shows that open trenches appear more effective than in-filled trenches (Beskos et al. 1985, Ahmad et al. 1991, Luong 1994, and Segol et al. 1978). However, the behaviour of in-filled barriers is dependent on filling material characteristics. The literature survey also reveals that few studies have been devoted to the efficiency of barriers made of expanded polystyrene (EPS). A major difficulty facing the physical modeling of wave propagation is the adequate replication of the in situ stress field. Centrifuge modeling in this case proves a useful tool. With this technique, Davies (1994) has studied the feasibility of isolating buried structures from underground explosions whereas Itoh et al. (2002, 2005) have examined barrier efficiency on the decrease of vibrations produced by trains. Both conclude that barriers made of low acoustic impedance materials, like EPS, are very effective in preventing the propagation of vibratory forces while reducing the vibratory amplitude of the shocks on the structures.

Although EPS barriers are effective in decreasing the transmission of traffic vibrations, their geometric characteristics providing the best reduction are not yet established. This paper presents the results of a parametric study conducted to examine the efficiency of EPS barriers in the reduction of traffic vibrations focusing on the effect of the barrier depth.

2 WAVE'S INDUCED BY TRAFFIC AND ISOLATION BARRIERS

Cars, heavy vehicles and trains produce ground vibrations, which may transmit to the structural elements close to heavy traffic routes under the form of highly perceptible vibrations. The vibration level depends on road/railway performances (roughness, structural condition) and on traffic characteristics (speed and vehicle weight). The energy arising from the traffic is transmitted to the ground through body and surface waves

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(Woods 1968). In a homogeneous half space medium, body waves propagate according to a spherical wave front in all directions, whereas surface waves propagate exclusively along the surface separating the two media without spreading through the inside of the earth. Consequently, the geometrical attenuation is greater for body waves than for surface waves.

According to Woods (1968), the main problem for foundation isolation is Rayleigh waves. Their amplitude decreases exponentially with depth and most of the energy, which propagates within a narrow zone near the surface, is roughly equal to one wavelength.

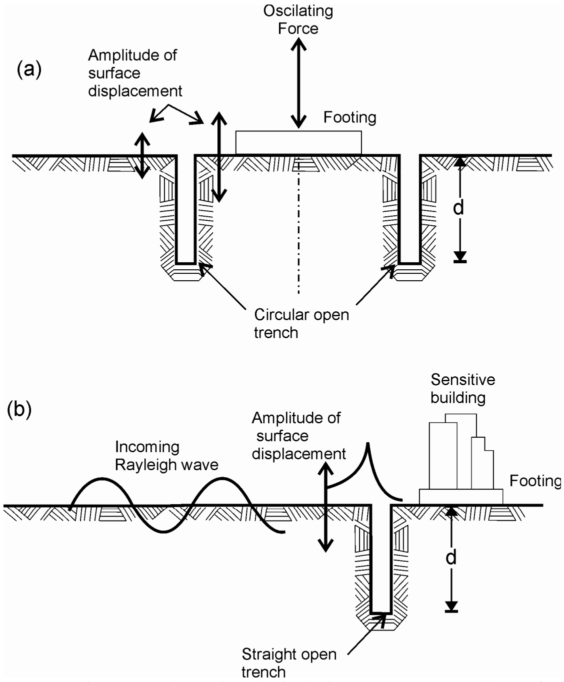

Figure 1. Active (a) and passive (b) isolation systems, Woods (1968).

Wave barriers can be divided into two groups, namely, active and passive isolation systems (Figure 1). Barriers placed around the vibratory source are active isolation systems, whereas barriers located farther from the source and close to a site where the vibratory amplitude must be reduced are defined as passive isolation systems.

Dimensions and materials properties are the most important parameters in the efficiency of isolation barriers. Experimental and numerical methods have been used to determine the influence of the geometric parameters for both active and passive isolation systems with open and in-filled barriers. Length ℓ, width w, and depth d of the barrier as well as the distance r from the source are the main geometrical criteria to be considered for the design of isolation systems. As Rayleigh waves make up the most important part of the traveling energy, the influence of the geometrical parameters is assessed in relation to their wavelength λ_R: length $L=\ell/\lambda_R$, width $W=w/\lambda_R$, depth $D=d/\lambda_R$, and distance $R=r/\lambda_R$.

Depth is the most important parameter for trench design. In the case of open trenches, the depth must be equal to the surface wavelength. Consequently, the use of open trenches as wave barriers is restricted to small to medium depths in order to minimize soil instability and water table level problems appearing with bigger depths. When the transmitted waves have long wavelengths, open trenches cannot be used as effective wave barriers because of their limited depth (Richart et al. 1970).

In-filled trenches are more convenient for construction than open trenches. Concrete, bentonite, soil bentonite– mixtures are the most common filling materials (Al-Hussani & Ahmad 1996). However, other materials such as rubber modified asphalt and EPS have also been used to fill the trench, Zeng et al. (2001), Zhong et al. (2002), Itoh (2003), and Itoh et al. (2005).

The amplitude reduction ratio, A_{RR} for a selection of points is the starting point for the determination of isolation system efficiency, Woods (1968). A_{RR} is the ratio of the amplitude with a barrier A_I to the amplitude A_0 without isolation system, ($A_{RR}=A_I/A_0$), expressed in terms of ground vertical motion or spectral densities (Woods 1968, May & Bolt 1982). Trench barrier efficiency is satisfactory when A_{RR} is lower or equal to 0.25 (Woods 1968, Richart et al. 1970).

3 MATERIALS AND METHODS

The present paper addresses the problem of isolation barriers using centrifuged small scale models for a parametric experimental study. The tests were performed reducing the geometry of the problem to a 2D problem, therefore the barrier length is not considered.

1.1 *Centrifuge physical modeling*

Centrifuge modeling is a powerful tool for the study of geotechnical structures using reduced scale physical models. It is particularly relevant when stress gradient or free surface are important, like in surface waves propagation.

In centrifuge modeling, the similarity of the conditions between the model (reduced scale) and the prototype (full scale) is guaranteed by the scaling factors. These scaling laws are presented in Philips (1869), Mandel (1962), Corté (1989), Garnier (1995), and Garnier et al. (2007). Regarding time, two scaling laws are possible, namely, a factor of 1/N in the case of wave propagation and a factor of $1/N^2$ for diffusion problems. For coupled processes where diffusion is due to the wave propagation (i.e., soil liquefaction), a time scale conflict appears, which is solved by using fluids with controlled viscosity. In the case of surface wave propagation due to the low permeability of the soils, no significant water migration occurs during loading. It is a classical dynamic problem where the time scaling factor is 1/N.

1.2 *Materials properties*

The soil used for this study is a NE34 Fontainebleau well-graded silica sand. The main properties are given in Table 1. The dry volumetric weight is $16.3 kN/m^3$ and the shear wave velocity, measured with the centrifuge using the SASW technique, is close to 230 m/s (Murillo 2007).

Table 1. Properties of the Fontainebleau sand.

Density of solid particles	ρ_s	2.640
Maximum void ratio	e_{max}	0.833
Minimum void ratio	e_{min}	0.553
Coeficient of uniformity	C_u	1.778
Mean particle diameter	D_{50}	0.3

The studied barriers are made of EPS. This is a synthetic closed cell foam material made of fine to medium spherical particles of solid Polystyrene with a naturally occurring petroleum hydrocarbon mixed in as a blowing agent (Horvath 2001), the generic term is geofoam. The density of geofoam is only 1% to 2% that of the soil. Nevertheless, it has a remarkably high strength-to-density ratio and can withstand long-term compressive stresses up to 100 kPa (Horvath 2003). Two geofoam densities are used 14 kg/m^3 and 16 kg/m^3 for the 2-cm and 4-cm wide barriers, respectively. These densities correspond to an acoustic impedance of 0.007.

1.3 *Model Preparation*

The geofoam barriers are placed in a rectangular box (inside dimensions: 120 cm x 80 cm x 36 cm) at the desired position. Then the sand is introduced into the box using a technique known as "sand raining or pluviation ". The experiments carried out with this method reveal that the spatial variation of the density inside the model is lower than 0.25 kN/m^3 (Garnier et al. 1993).

1.4 *Piezoelectric actuator and instrumentation*

The vibratory source is a piezoelectric actuator (PEA). The PEA is a PPA40M actuator from Cedrat Technologies. This actuator uses an external deformable frame to pre-stress ceramics. The PEA is not placed directly on the soil surface but supported by a 30-mm diameter and 5-mm thick aluminium circular plate. The top of the PEA is fixed to a beam to maintain steady contact with soil and the transmission of vertical vibratory motions towards the model. To control the PEA behaviour, an accelerometer is placed on the circular plate and a load cell is fixed on the vertical axis of the PEA.

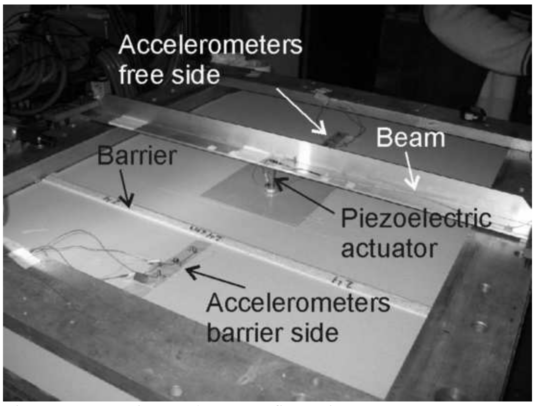

Figure 2. Experimental test configuration.

To measure the vibration, six mini-piezoelectric accelerometers, ICP ® 325ª10 model, are used. These sensors are used to measure the acceleration level in three different points (4, 8 and 12 cm away from the barrier) (Figures 2 and 3). The accelerometers are coupled to an integrated data acquisition system which is placed in the centrifuge swinging basket. The prescribed sampling rate is 50 kHz. A sheet of plastic is laid between the source and the soil to have a homogenous contact.

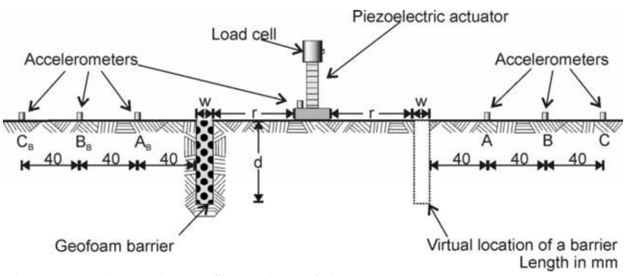

Figure 3. Schematic configuration of the tests.

1.5 *Experimental program*

The tests are carried out at a centrifuge acceleration of 50 G (N=50). According to the frequency ranges of vibrations due to traffic and to scaling factors for the frequency, the vibration frequencies on the models are within the range 150-2000 Hz.

In order to assess the influence of the depth in an active isolation system, six different geofoam barriers are tested. Each barrier is tested at four different distances from the vibratory source and twenty vibration frequencies are assessed.

4 EXPERIMENTAL RESULTS

1.6 *Attenuation*

The typical results of time history and fast Fourier transform for accelerometers A, B and C located on both the barrier and the free sides at the same distance from the source show that the attenuation becomes significant as the length increases in both time and frequency domains. The comparison of the acceleration signal amplitudes at different distances from the source on both barrier and free sides indicates a significant reduction in the amplitude, mainly near the barrier (Figure 4). These results correspond to a 1800-Hz input signal and a distance of 20cm between the barrier and the source.

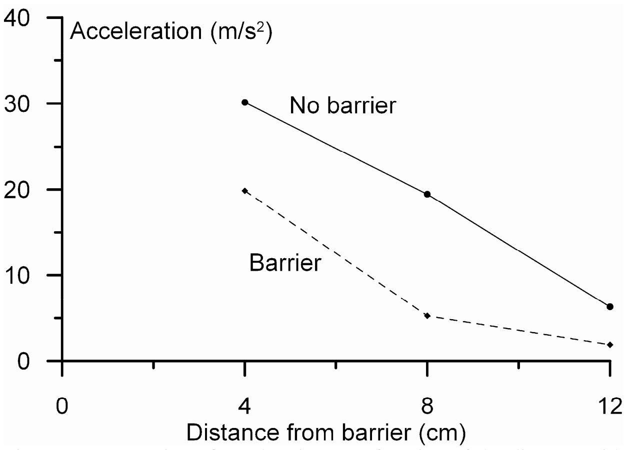

Figure 4. Attenuation of acceleration as a function of the distance with and without a barrier (r=20 cm, input signal frequency: 1800 Hz).

1.7 *Influence of the barrier on vibration decrease*

Figure 5 illustrates an example of the influence of the barrier in the reduction of the acceleration amplitude. The efficiency of the barrier increases when the excitation frequency is higher than 600 Hz. The barrier efficiency cannot be measured for lower frequencies (100-500 Hz), indeed the energy then transmitted to the soil by the source is not sufficient to disturb the medium.

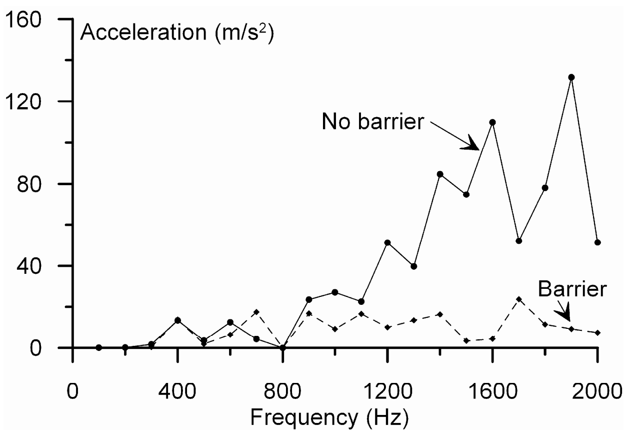

Figure 5. Influence of the barrier for different input frequencies (w = 4 cm, d = 12 cm, r =5 cm).

1.8 *Influence of the depth*

Figure 6 presents the average A_{RR}, as a function of the dimensionless barrier depth ($D = d/\lambda_R$). The results show the incremental efficiency of the isolation system for deeper barriers, the amplitude reduction ratio, A_{RR} is approximately 0.2 for D> 2.0 and for r = 5 cm.

For shallow barriers (D < 1.0), A_{RR} varies between 0.8 and 1.4. When the barrier is placed far from the source (r > 15 cm), the amplitude recorded behind the barrier increases significantly. Amplification becomes especially noticeable with the lowest input frequencies and, particularly, when the depth-to-wavelength ratio is low. Many waves, then, appear to break through the barrier.

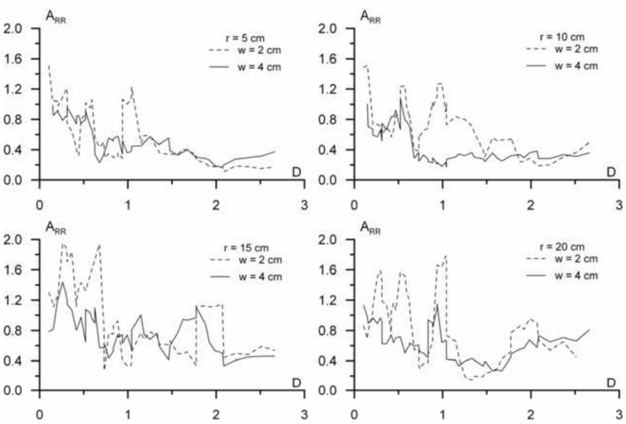

Figure 6. Influence of depth. A_{RR} vs. D with variable r.

5 CONCLUSION

Centrifuge modeling is used to simulate the vibrations generated by traffic to surrounding structures and to determine the efficiency of the isolation system using geofoam barriers.

In order to address this problem, a piezoelectric device is used to generate ground vibrations in centrifuge models at frequencies corresponding to actual traffic vibrations.

The barrier depth is assessed in order to determine their influence on the efficiency of the geofoam barrier isolation system.

The amplitude of the vibrations with and without a barrier is compared. The vibration reduction is quantified using the A_{RR} ratio. The results obtained show amplitude reductions ratio A_{RR} ranging from 0.2 to 1.8.

The results show that the efficiency of the isolation system is dependent on the barrier depth. When barrier depth increases, A_{RR} decreases. This relation is intensified when the barrier depth-to-wavelength ratio is higher than 1. For barrier depths from 0.5 to 1 times greater than the wavelength value, the acceleration can be amplified.

The results show that the barrier is an ineffective isolation system when the distance between the source and the barrier is smaller than $0.5\lambda_R$, because of reflected waves. Moreover, barriers placed far from the source can become ineffective depending on the wave attenuation level.

The efficiency of an active isolation using a geofoam barrier is satisfactory for D>1.5, and for a vibratory source-barrier distance within the range 0.5-1.2 times greater than the Rayleigh wavelength (0.5<R<1.2). This advice is valid for the soil mentioned in this study, for other parameters it is recommended practicing others tests.

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