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RESEARCH ARTICLE

Ground vibration isolation using mass scatters: A comparative study with trench barriers and wave-impeding blocks

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Abstract

Traffic-induced ground vibrations cause significant problems for residents and nearby structures. Reducing the effect of these vibrations on the neighboring environment is a key challenge, particularly in urban areas. This study presents both numerical and experimental investigations of the performance of mass scatters for screening ground vibrations. A three-dimensional numerical model is validated and extended to conduct a comparative study on the efficiency of three geotechnical methods of isolation. These methods include trench barriers, wave-impeding blocks (WIBs), and mass scatters. The results showed that mass scatters represent an efficient way of scattering ground vibrations, and their efficiency is mainly related to the weights of mass scatters and their natural frequency, which control the dynamic soil response in the frequency domain. Rigid trench barriers are less effective than soft ones, and their efficiency is more pronounced regarding the WIB. Soft barriers with a depth of an order of half of the wavelength can decrease the vibration levels by up to 50%, which is comparable to the performance of enormous mass scatters. The dimensions of WIBs must be chosen according to the wavelength of incident waves and the cutoff frequency of the topsoil layer. Considering the significant wavelength of traffic-induced vibration, the use of trench barriers or WIBs becomes impractical and expensive; therefore, mass scatters appear to be an efficient and practical solution.

KEYWORDS

ground-borne vibration, isolation, mass scatter, trench barrier, wave-impeding block

Highlights

- Ground-borne vibrations are a frequent source of environmental problems.
- A full-scale experiment is presented to study the isolation potency of mass scatters placed on the ground surface.
- A 3D numerical model is validated to verify the efficiency of three methods of isolation: trench barriers, wave-impeding blocks, and mass scatters.
- Soft barriers are more effective vibration countermeasures than stiff ones and their efficiency is more pronounced in comparison to the wave-impeding blocks.
- Mass scatters represent an innovative and efficient means for impeding the propagation of incident waves without the need for excavation of the soil or the roadwork.

1 | INTRODUCTION

Ground-borne vibrations generated by heavy trucks and buses are a common source of environmental problems as they can cause damage to nearby structures, annoyance to residents, and affect the performance of sensitive equipment. Although research has been widely carried out to analyze ground-borne vibrations from different sources, for example, rail and road traffic, there are still very few investigations aimed at developing an effective isolation system. Wave barriers are the most studied isolation system, consisting of an empty or infilled trench that reduces ground motion by diffraction, scattering, and interception of the surface waves.

Numerous experimental studies have been carried out to investigate the screening efficiency of trench barriers using full-scale tests (Ajel et al., 2022; Coulier et al., 2015; Toygar & Ulgen, 2021). In addition, different numerical models have been developed in the literature to compute the variation of ground response due to the installation of trench barriers, either in the time or frequency domain (Adam & Von Estorff, 2005; Ahmad et al., 1996; Bo et al., 2014; Gao et al., 2023; Leung et al., 1991; Saikia & Das, 2014; Tsai & Chang, 2009). However, because of soil instability and water table-level problems, it is necessary to search for a suitable in-filled material that can provide sufficient isolation potency. Naggar and Chehab (2005) demonstrated the efficiency of barriers filled with gas cushions using self-hardening cement bentonite. Different filling materials are also studied and analyzed, such as water and bentonite (Çelebi et al., 2009), concrete (Yarmohammadi et al., 2019), geofoam (Alzawi & Hesham El Naggar, 2011; Jazebi et al., 2023), rubber–sand mixture (Chew & Leong, 2019), shredded tire chips (Tandon et al., 2023), and the ceramiste-sand mix, according to Xi et al. (2022). The studies cited above revealed that the main parameters that control the isolation performance are the depth of the trench barrier, the frequency of incident vibration, and the relative rigidity of the filling material. For example, the trench should have a depth equal to at least half of the wavelength (λ) to achieve a good effect of isolation; when the trench depth is equivalent to the wavelength, the isolation efficiency is about 50%–70%. Soft barriers (filled by gas cushions, soil bentonite, or geofoam) are more powerful than stiff barriers; the width of the trench barrier has little influence on the efficiency of screening.

Another isolation technique is the use of wave-impeding blocks (WIBs), which are based on the behavior of vibration transmission in the soil stratum lying over the bedrock. This method consists of introducing a rigid horizontal base; thus, the above soil layer has special eigenmodes for the surface waves to transverse (Antes & Estorff, 1994; Schmid et al., 1991). According to Chen et al. (2022), no waves can propagate outward for vibrations with frequencies lower than the natural frequency of the soil stratum ($f = C_s/4H$) due to the existence of the rigid base, where H is the depth of the soil stratum and C_s is the speed of the shear wave in the soil. Therefore, by taking advantage of this vibration transmission feature, it is possible to impede the propagation of vibration by placing an artificial rigid plate at a specified depth below the propagation path of waves. Gao et al. (2015) found that with a reasonable embedded depth, a concrete WIB can greatly decrease ground vibration due to continuous vertical loading. Shi and Li (2019) analyzed the performance of a buried WIB in the frequency domain using the elastic boundary element method, and the results showed that increasing the thickness of the WIB and reducing the embedded depth of the WIB can lead to a better vibration isolation efficiency. Zhang and Ma (2023) concluded that using a WIB could lead to better vibration isolation performance in unsaturated soil foundations. The surface response decreases significantly with an increase in the load frequency, embedded depth, rigidity, and thickness of the WIB. Cao et al. (2024) conducted a series of laboratory tests to investigate the performance of a combined vibration isolation system consisting of an open trench and a WIB.

To develop a new and effective method of isolation, Jones and Petyt (1986) have proposed a promising method of screening by placing heavy masses on the ground surface near railways or roads (e.g., rock or concrete blocks, masonry walls, etc.). The simple behavior model of these masses predicts that mass scatters can reduce the amplitude of vibrations in certain frequency ranges; these ranges of frequencies can be matched to the vibration spectrum of the source and provide a theoretical foundation upon which such schemes can be developed. Krylov (2007) explained the principle of this method by the fact that when these masses are shaken in both horizontal and vertical directions by the impact of incident surface waves, they disperse the surface waves at different directions on the ground surface and deep into the ground, thus resulting in remarkable attenuation of transmitted surface waves. The natural frequencies of mass scatters must be chosen within the frequency range of the traffic-induced vibrations, generally between 5 and 50 Hz (Mhanna et al., 2011). Baziar and Shabazan (2024) found that placing heavy mass scatters on the ground surface is a simple and cost-effective measure that can provide a better alternative to the well-known screening methods. They affirmed that mass scatters are especially beneficial for low-frequency vibrations where use of deep barriers becomes impractical. The competitive advantages of mass scatters can be attributed to their lower maintenance and construction costs and easier implementation.

All the studies carried out to date seem to have focused on trench barriers and lack comparison with different mitigation measures. Mass scatter, considered a trenchless method, seems to be an efficient and practical countermeasure. The added masses, such as natural rocks or specifically designed blocks, may also be used to provide security or to enhance the visual appearance of the studied area. Therefore, this study aims to present both experimental and numerical studies on the effectiveness of mass scatters. Furthermore, the numerical model is extended to conduct a comparative study on the efficiency of the three proposed methods for screening traffic-induced ground vibrations. The performance of the three methods is evaluated, and suggestions are made to improve the effectiveness of each method using some key parameters.

2 | EXPERIMENTAL STUDY AND MODEL VALIDATION

2.1 | Test description

The experimentation was conducted in the city of Lille in the north of France. The properties of the local soil profile were evaluated based on the results of the soil investigation, including the pressuremeter and the surface wave test. The soil layers at the site are characterized as chalky silt and sandy silt, situated above a clayey silt layer. The adopted soil configuration is shown in Table 1.

The dynamic load is generated using the Dynaplaque machine, which is a pulse generator that applies dynamic loading on the ground surface. The Dynaplaque consists of a falling mass and a spring damper placed on a load plate. The resultant load is similar in intensity and duration to that caused by a vehicle with a 13 000 kg axle load traveling at a speed of 60 km/h; the duration of the impact is (15 ± 5) ms (Mhanna et al., 2014). The impact load and the soil response are recorded by sensors located in the load plate, which is connected to a computer to display the results of the measurements, as shown in Figure 1.

Also, six accelerometers were installed along a measurement line perpendicular to the center of the load plate for recording the vertical soil particle acceleration (SPA). The distances (D) between the load and the accelerometers are set to vary between 1.5 and 15.0 m. High-speed data recording, for a period of 5 s with a simultaneous sampling rate of 1 ms, is registered, which results in 5000 data points. A digital filter with a high-pass filter is applied to eliminate the undesirable noise. Steel tanks filled with water are installed as mass scatters. The dimensions of each tank were 1.75 m × 0.75 m × 0.75 m, thus imposing heavy weight on the ground surface of about 1000 kg. The distance between the mass scatters and the Dynaplaque is set as 2 m. The steel tanks and the accelerometer used in this study are shown in Figure 2.

2.2 | Test results and discussion

The time history of SPA at different points of measurements is recorded and treated to obtain the typical attenuation curve. Figure 3 shows the time history of SPA measured on the ground surface at distances of 5 and 10 m from the load either in a free field or with mass scatter.

To evaluate the reduction in the vibration levels, the amplitude reduction ratio (A_r) is a term that is widely used; it consists of calculating A_r by normalizing the vertical response of grounds surface after placing the isolation device ($A_{z,\mathrm{after}}$) to the vertical response of the ground surface before the isolation device ($A_{z,\mathrm{before}}$), as shown in the below equation.

$$A_\mathrm{r} = \frac{A_{z,\mathrm{after}}}{A_{z,\mathrm{before}}}. \tag{1}$$

Figure 4 shows the amplitude reduction ratio obtained by normalizing the measured SPA after placing the mass scatters on the measured SPA in the free field. It is observed that the isolation of mass scatters can reach values up to 25%. It is also noted that the reduction curve shows two different parts: the first one spreads across a distance of the order of wavelength ($\lambda = C_\mathrm{s}/f = 200/45 = 4.5$ m). In this part, a significant decrease in the amplitude of vibration is noticed. The second part of the reduction curve (distance > λ) indicates a slow attenuation in the amplitude of vibration with distance from the source. Indeed, surface waves become dominant in the second part due to their lower attenuation ratio compared to that of the body waves.

TABLE 1 Soil layers and the characteristics of each layer.

Soil layer	Thickness (m)	Young modulus (MPa)	Shear wave speed (m/s)
1	0.6	200	220
2	1.2	150	180
3	4.2	25	65
4	9.0	50	105

3 | VALIDATION OF THE THREE-DIMENSIONAL NUMERICAL MODEL

Numerical modeling is performed using a finite difference method implanted in FLAC^{3D} program. Wave propagation could be properly simulated using an elastic model due to the low deformation level produced in the case of traffic-induced vibrations. The size of the model is 30 m × 21 m × 15 m (length/width/depth) and only half of the model is taken into account with respect to the symmetry in loading and geometry. Viscous dashpots are applied in the shear and normal directions at model boundaries to prevent wave reflection (Lysmer & Kuhlemeyer, 1969). A Rayleigh damping scheme has been introduced to provide a damping

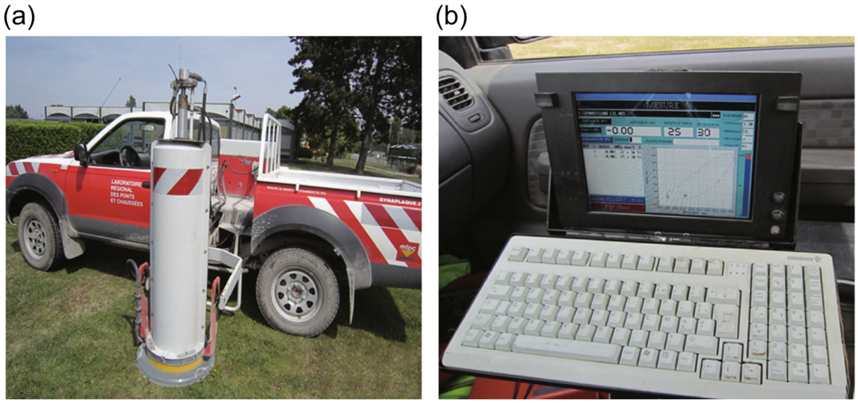

FIGURE 1 (a) Dynaplaque used as a source of excitation and (b) the recorded impact load.

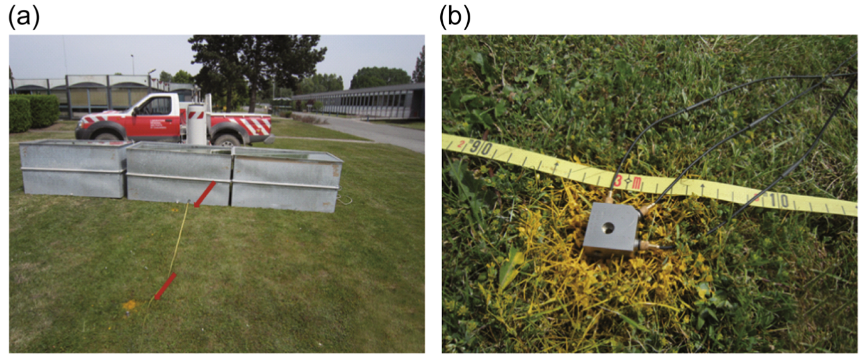

FIGURE 2 (a) Water tanks used as mass scatters and (b) three axes accelerometers used in the measurement.

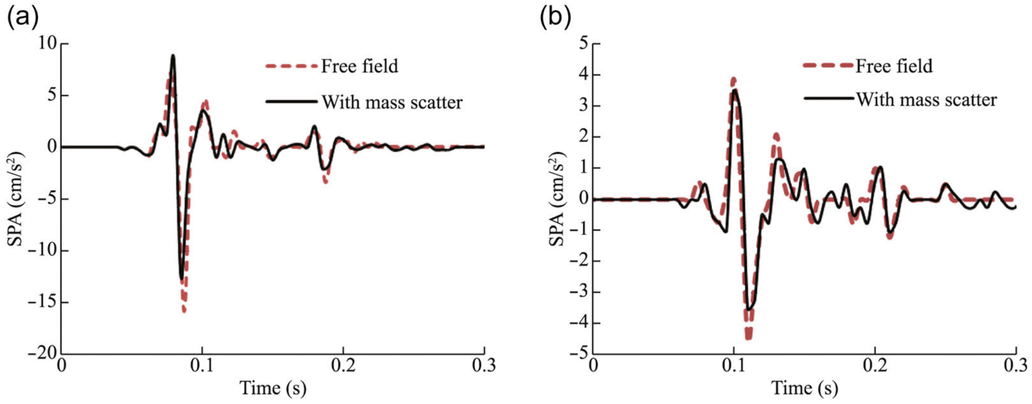

FIGURE 3 Measured soil particle acceleration (SPA) before and after placing the mass scatters at distances of (a) $D = 5$ m and (b) $D = 10$ m.

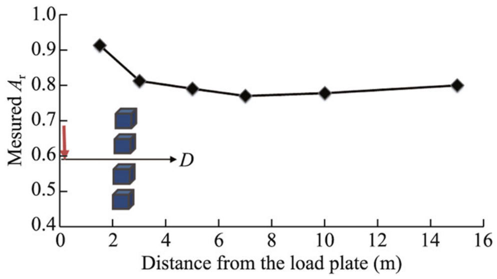

FIGURE 4 Amplitude reduction ratio due to placement of mass scatters on the ground surface.

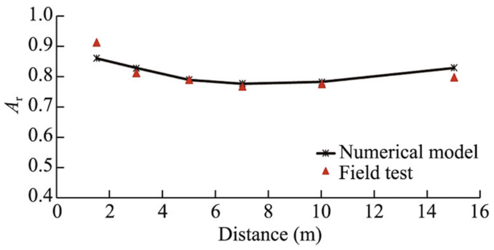

FIGURE 5 Numerical versus measured amplitude reduction ratio.

ratio $\zeta = 3\%$. The mesh sizes are refined near the source of vibrations (0.30 m × 0.30 m × 0.15 m) and increase progressively with the distance from the applied forces along axes X and Z. The dynamic applied load is considered as a Ricker pulse, which is analytically shown by the below equation:

$$F(t) = (a^2 - 1/2)\exp(-a^2),\\ a = \pi(t - t_s)/t_p, \tag{2}$$

where t_p is the period of the force and t_s is the time of maximum amplitude. The dominant frequencies of this dynamic load are mainly centered around the typical frequency $f = 1/t_p$. The amplitude of the dynamic load is taken as $F = 65$ kN according to the recorded impact during the tests, with the typical frequency of the Ricker pulse equal to 45 Hz. The steel tanks are modeled using massive elements of eight nodes, with density $\rho_w = 1$ g/cm^3 with a very low shear modulus. The contact between the soil and the steel tanks is simulated using shell elements with the following characteristics: thickness is 5 cm, density $\rho = 700$ kg/m^3, Young's modulus $E = 200$ GPa, and Poisson's ratio $v = 0.2$. The characteristics of the soil layers are shown in Table 1.

The proposed numerical model is validated by comparing the numerical results with those obtained in the field. The amplitude reduction ratio shown in Figure 5 indicates that the proposed model correctly simulates the dynamic soil response. A good agreement is observed between the calculated and measured response before and after installing the mass scatters. The small differences between the measured and calculated A_r at a distance of 15 m can be explained by the fact that the vibrations far from the source are very small and the distant accelerometer records a negligible value, which may interfere with the noise, resulting in a numerical error.

4 | COMPARATIVE STUDY OF VIBRATION REDUCTION MEASURES

Selection of an efficient isolation method in urban areas is important to avoid annoyance to residents and prevent structural damage. Therefore, the proposed numerical model is extended to analyze the efficiency of three different methods for screening ground vibration. These methods are mass scatters, trench barriers, and WIBs, as illustrated in Figure 6. The soil is assumed to be homogeneous, with the following characteristics: Young's modulus $E_1 = 50$ MPa; density $\rho_1 = 1600$ kg/m^3; and Poisson's ratio $v_1 = 0.3$. The dynamic load is generated by a Ricker pulse with a dominant frequency ($f_1 = 12$ Hz), which matches the dominant frequency of road traffic-induced vibration (Mhanna et al., 2014).

4.1 | Efficiency of masses scatters in ground vibration reduction

The performance of mass scatters is also investigated numerically. A series of separated heavy masses are placed near the source of vibration; the distance between two successive masses is 0.6 m. The horizontal dimension of each mass is 1.5 m × 1.5 m, while the heights vary between 0.5, 1.0, 1.5, and 2.0 m. The characteristics of these mass scatters are chosen such that they coincide with the characteristics of concrete or rigid rocks. Young's modulus of mass is taken as 20 GPa, and the mass density (ρ) is 2300 kg/m^3. Keeping in mind that these masses function as masses resting on Winkler foundations, the mass resonance frequency can be calculated as shown in Equation (5):

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M}}, \tag{3}$$

where k represents the stiffness of the Winkler spring and M is the mass. k can be calculated using Equation (6) for a square foundation (Mylonakis et al., 2006):

$$k = \frac{4.54\,G \times B}{1 - v}, \tag{4}$$

where G is the soil shear modulus, B is the width of the mass, and v is Poisson's ratio. The frequencies of motion of these masses calculated according to Equation (5) vary between 10 and 20 Hz and coincide well with the frequency of waves that pass along the ground surface. Figure 7 shows the effect of the weight of heavy masses on vibration reduction using mass scatters.

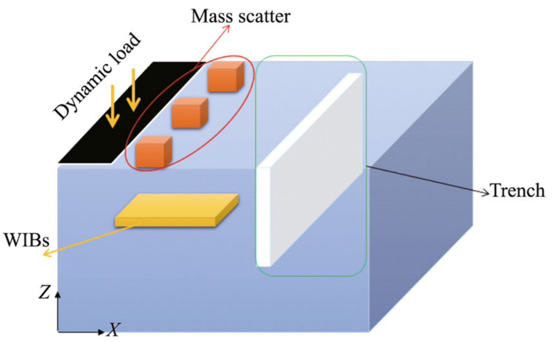

FIGURE 6 Schematic of different methods of isolation used in this study.

The efficiency of isolation increases proportionally with the weight of mass scatters. The augmentation in the weight of masses from 2500 to 10 000 kg results in considerable augmentation in the reduction ratio. In fact, the reduction ratio is up to 50% at certain locations beyond the blocks when using enormous concrete or rock masses ($M = 10\,000$ kg). Figure 8 shows the frequency of vibration at a depth of 1 m below the mass scatter. It is obvious that the frequency of the soil response in the free field is principally dominated by the typical frequency of the applied load ($f = 12$ Hz). The amplitude of the spectrum is significantly lower after using heavy masses. The augmentation of the weight of mass scatters shifts the dominant frequency to lower values, and thus the resonant frequency of mass scatters controls the soil response. By considering the nature of the motion of Rayleigh waves in which the soil particles move in elliptical paths with the major axis of the ellipse perpendicular to the surface of the soil, the efficiency of these masses will be determined by their heavy weight, which prevents upward movement and stops it from moving vertically under the mass scatters.

4.2 | Effect of trench barriers on ground vibration reduction

The proposed numerical model is extended to evaluate the effectiveness of trench barriers in screening traffic-induced vibrations. A trench barrier is installed at a distance of 3 m from the source to decrease ground vibrations. The trench has a depth $d = \lambda/2$, where $\lambda \approx 9$ m

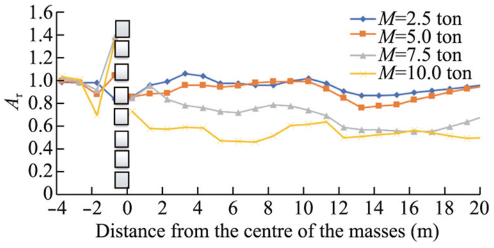

FIGURE 7 Effect of masses scatters in reducing ground vibration.

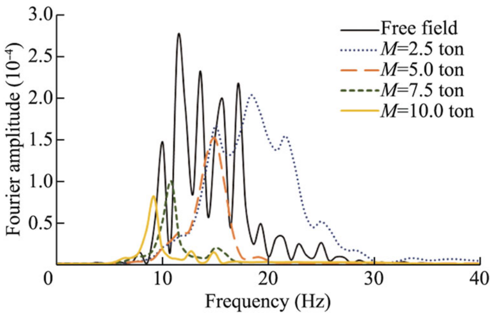

FIGURE 8 Frequency of soil response at a depth of 1 m below the mass scatter.

is the wavelength, while the width of the trench is chosen as $b = 0.3\,\text{m}$. A geometrical configuration of the trench barrier is depicted in Figure 9.

Different filling materials are used to evaluate the effect of material stiffness on vibration levels. The stiffness of the filling material (E_2) is chosen to be considerably different from that of the surrounding soil. In geotechnical engineering, the impedance ratio is a parameter that is widely used to classify whether the trench is rigid or soft considering the surrounding soil, which is given in Equation (3):

$$IR = \frac{\rho_2 C_{s2}}{\rho_1 C_{s1}}, \tag{5}$$

where ρ_1 and ρ_2 are the mass densities of the soil and the trench barrier, respectively, and C_{s1} and C_{s2} are the speeds of the shear waves of the soil and the barrier, respectively. The trench is considered a rigid barrier if $IR > 1$; otherwise, it is considered a soft barrier. The reduction ratio using a rigid trench barrier and a soft trench barrier is shown in Figure 10, respectively. It can be noted that:

1. The isolation performance of an open trench is about 50%, with a depth equivalent to ($\lambda/2$). A portion of the wave energy is reflected before the soft trench, which may increase the vibration levels. No vibration amplification takes place in front of the rigid trench because the stiff material is capable of transmitting a significant portion of the incident waves.
2. Considering filling materials, soft trenches are more effective than stiff ones. Trenches filled with a material with very small rigidity, such as a soil-bentonite trench ($IR = 0.2$), are similar in performance to open trenches. It is also noted that the isolation performance is limited to the vicinity of the rigid trench (within $0.5d$ behind the trench); its performance deteriorates significantly with distance.

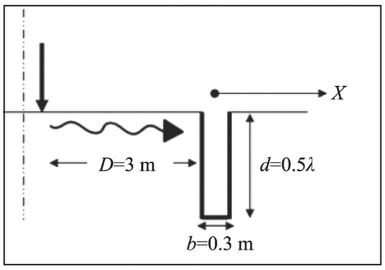

FIGURE 9 Geometrical configuration of the trench barrier system.

It is possible to explain the different efficiencies of the filling material in screening the vibration by the energy transmission coefficient (T_c), which is defined as the amplitude ratio of the transmitted wave across a barrier of a thickness (h) against the incident wave with frequency (ω), as depicted in Equation (4) (Semblat & Pecker, 2009):

$$T_c = \left[\varphi^2 + \frac{1-\varphi^2}{4}\left(\frac{1}{IR} + IR\right)^2\right]^{-\frac{1}{2}}, \qquad \varphi = \cos\left(\frac{\omega}{C_{s2}}h\right). \tag{6}$$

Figure 11 shows the variation of T_c with the corresponding IR. It is obvious that the transmission coefficient can be less than 1 only when the impedance ratio is different from 1. The incident waves are transmitted less at the interface between the soil and the soft barrier; therefore, the efficiency of isolation is high when the relative impedance of the trench is lower than 1. As a result, the soft barrier is more efficient than the rigid barrier in screening the incident waves.

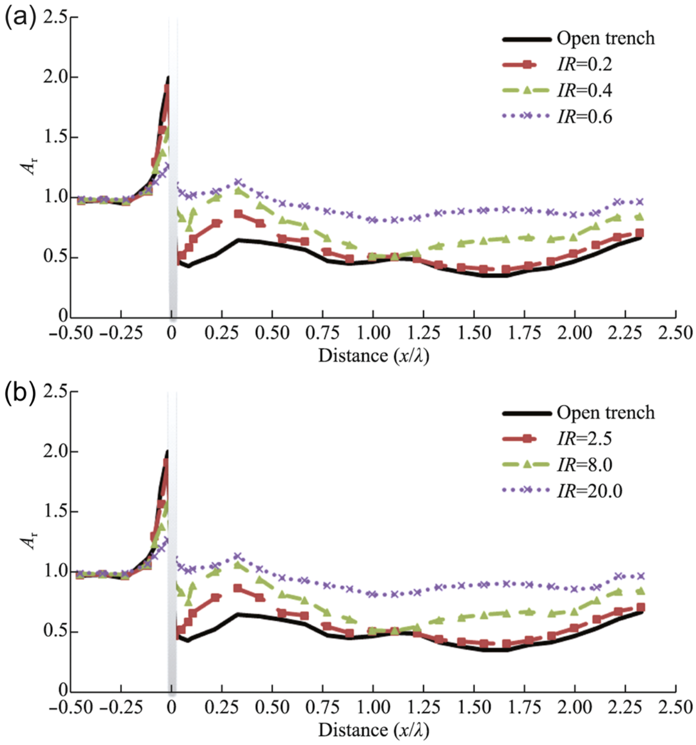

FIGURE 10 Amplitude reduction ratio versus normalized distance using (a) a soft barrier ($d = \lambda/2$) and (b) a stiff barrier ($d = \lambda/2$).

Despite their efficiency, unfortunately, the above-mentioned protective trenches are very expensive to build and maintain, regardless of the discomfort and disturbance to residents during their installation.

4.3 | Effect of WIBs on ground vibration reduction

The basic principle of WIBs is to insert a layer of stiffened material; thereby, the stiffness properties and layer depth over a finite part of the ground will be modified, leading to an increase in the frequency at which the vibration will be propagated. To demonstrate the effectiveness of WIBs in reducing the amplitude of ground vibration, a plate of 2.0 m width and 0.7 m thickness is simulated under the soil surface at a depth of 2 m so that the cutoff frequency of the soil layer situated above the WIB equals 13 Hz. The properties of the plate are assumed to have the values of the jet grouting treatment. Peplow et al. (1999). proposed jet grouting as a substitute material for the construction of a WIB to avoid the cost of removal and replacement of the soil. Therefore, the density and Poisson's ratio are set as 1900 kg/m^3 and 0.2, respectively. On the other hand, Young's modulus (E_{WIB}) is assumed to vary between 1, 5, and 10 GPa to verify the influence of the base rigidity on the vibration levels. Figure 12 shows the reduction ratio using the WIB for different values of rigidity. It can be observed that a WIB with sufficient rigidity can reduce the amplitude of vibration up to 40% above the center of the WIB, while the reduction ratio is limited to 25% beyond the WIB. Indeed, the WIB does not represent a real bedrock, and its limited width compared to the wavelength is not enough to impede the wave.

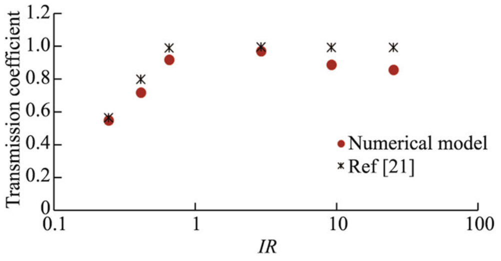

FIGURE 11 Influence of the impedance ratio on the transmission coefficient of filling materials.

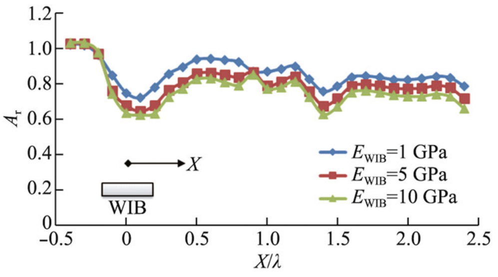

FIGURE 12 Effect of wave-impeding blocks (WIB) rigidity on the reduction ratio.

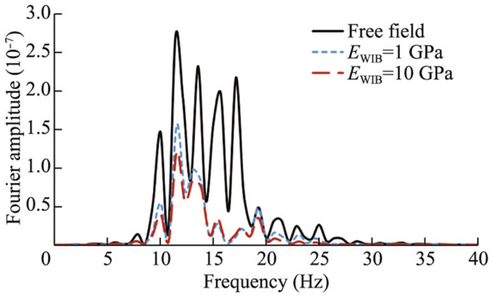

FIGURE 13 Effect of a wave-impeding blocks (WIB) on the frequency of vibration at a distance of 5 m.

Since the isolation competence of a WIB depends principally on the frequency content of the incident wave, a frequency analysis of the free field vibration is conducted to evaluate the effect of a WIB in the frequency domain. Figure 13 illustrates the frequency content of vibrations at a distance of 5 m from the center of a WIB. It is shown that the presence of a WIB leads to a drastic decrease in the frequency of vibration, and the resonant frequencies shift to lower values, especially frequencies less than the cutoff frequency of the above layer.

5 | CONCLUSION

This study evaluated the effectiveness of mass scatters in reducing traffic-induced ground vibrations using both experimental and numerical methods. Experimental results show the screening effectiveness of mass scatters without the need for excavation of the soil or the roadwork. Numerical results show that a reduction factor of up to 50% could be achieved using enormous mass scatter, which is similar to results obtained using a soft trench barrier with a depth equal to $\lambda/2$. The weight and the natural frequency of mass scatters play crucial roles in screening ground vibrations. The performance of trench barriers is mainly related to their depth and filling material properties. Soft trench barriers were shown to be more effective vibration countermeasures than stiff ones, and their efficiency is more pronounced in comparison with the WIB. The dimensions of the WIB must be chosen according to the wavelength of incident waves and the cutoff frequency of the topsoil layer to achieve a reasonable reduction ratio of up to 40%. According to the previous results, the choice of trench barrier, or the WIB, becomes impractical and expensive due to the significant wavelength of traffic-induced vibrations. Therefore, the solution involving use of a heavy mass is favorable because of its ease of construction and low cost. The numerical model can also be used in the case of soil stratification and superstructure. Unfortunately, a single study cannot cover the scope of such a comprehensive parametric investigation.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request due to privacy/ethical restrictions.

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