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Surface wave attenuation by periodic hollow steel trenches with Bragg band gap and local resonance band gap

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Abstract

The use of phononic crystals and elastic metamaterials has been a significant concern as an efficient approach to attenuate the surface waves of ambient vibration and seismic vibration. In previous research, elastic metamaterials with periodic array of pillars or other forms of standing structures (such as H-fractal steel or built-up structural steel) erected on soil substrate can achieve a low frequency surface wave band gap (BG). However, such metamaterials with standing structures occupy land and affect the esthetics of cities, and buried metamaterials such as cross-like-cavity or hollow-cylinder structures with large size in soils necessitate continual maintenance for the stability of cavity soil structure. Thus, this study proposes two types of periodic hollow steel trenches exhibiting both a Bragg BG and a local resonance BG, the steel plates are used to support the soil on both sides of the trench to meet the stability requirements of cavity soil structure and avoid toppling or landslide of soils. The dispersion relations of periodic hollow steel trenches are calculated by using finite element method and the mechanism of generation for two kinds of BGs are interpreted by the eigenmodes. Furthermore, the effectiveness of periodic hollow steel trenches on isolating surface waves within the BGs is demonstrated in both frequency domain and time domain analysis. Several significant geometrical and material parameters on BGs that can affect the BG are studied as well. This study provides a new approach using the coupling effects of Bragg BG and local resonance BG to simultaneously attenuate the surface waves induced by the ambient and seismic vibration in a more practical way.

Keywords: surface waves; periodic structure; band gap; Bragg scattering; local

resonance.

1. Introduction

Excessive vibrations caused by traffic, construction activity, machine operation and earthquake cause damage to adjacent structures and residents, such as disturbing residents health, affecting the work of delicate instruments, even destroying buildings and threatening human lives [1]. Surface waves (Rayleigh waves) at middle and low frequencies have received more research attention due to the fact that they can travel further, decay slowly along the ground and be potentially more disruptive. Therefore, the methods of ground vibration attenuation by constructing wave barriers such as open trenches, infilled trenches, pile barriers, etc across the propagation paths of surface waves in soils has received more research attention and become a major concern in recent years [2-10]. These wave barriers in half-space soils may intercept, scatter or diffract incident surface waves sufficiently to reduces their amplitudes. The open trench is the most effective measure to isolate surface waves among any other wave barrier, because its stress-free boundaries act as perfect reflectors of waves [6-10]. However, its practical application is limited to relatively shallow depths due to the instability of soils and water table, and it may be turned to a water-filled trench caused by the fluctuation of water table, which can result in the efficiency reduction of vibration isolation and environmental problems such as mosquito breeding and germ spreading due to the contamination of water [10]. In addition, the open trench in public places may pose a serious threat to security of pedestrian. By contrast, the proposed hollow steel trench exhibits practical values in engineering. On the one hand, the form of hollow steel trench (like a cavity structure) is similar to that of open trench, which means it can provide a desirable vibration reduction effectiveness. On the other hand, the use of hollow steel trench can necessitate no continual maintenance of trench structure and no treat to health and security of residents, because the steel plates can support the soil on both sides of the trench to meet the requirements of soil stability and avoid toppling or landslide.

Recently, the research of phononic crystals [11-13] and elastic metamaterials [14-16] has promoted the study of periodic wave barriers for vibration mitigation based on the band gap (BG), frequency regions where waves are prohibited from propagation. It is well-known that most of energy of ambient or seismic vibration is carried by surface waves and they travel further, decay more slowly along the ground than body waves. BGs can be achieved to cover the frequencies domain of ambient or seismic vibration with a rational design of periodic trenches [17-20], periodic pile barriers [21-24] and seismic metamaterials [25-30]. Mechanisms for the BG generation are classified as Bragg scattering and local resonance. Bragg scattering originates from the spatial periodicity of the impedance mismatch and results from the destructive interference of incident and scattered waves, occurring at wavelengths being comparable to unit cell sizes [11-13]. Distinct from the Bragg scattering mechanism, the relevant wavelength with regard to the local resonance is much larger than unit cell sizes, which contributes to opening the BG at low frequencies. Local resonance mechanism stems from the hybridization effect between the bands of the resonant modes inside the units and the propagating modes of the substrate media [14].

Surface wave BGs around middle frequencies were obtained based on Bragg scattering in the research of the periodic trench barriers, which can be available for the application in the ambient vibration isolation [17-20]. Periodic geofoam-filled trenches [17,18], periodic composite infilled trenches [19] and layered periodic structures [20] were verified as effective wave barriers to attenuate surface waves induced by trains, and these surface wave BGs were obtained from 40 Hz to 70 Hz. Different from the Bragg BG, the local resonance BG appearing in the periodic pile barriers and elastic metamaterials was around low frequencies (below 20 Hz), which can be used to safeguard large infrastructures from seismic threats [21-31]. Additionally, a pillared metamaterial in phononics which was composed of periodic arrangement of pillars erected on a plate provides a new tool to manipulate the propagation of surface waves. It is interesting that Bragg BG and local resonance BG can be simultaneously observed in pillared metamaterials [32-35], the Bragg BG is induced by the system's periodicity and local resonance BG is originated from the occurrence of branching pillars acting as the local resonators. It is possible for using such metamaterials to simultaneously attenuate the surface waves in ambient vibration at middle frequencies and shield the seismic waves at low frequencies. Some researchers further proposed the hollow pillar metamaterials, localized modes relative to low-frequency BG were synthesized by introducing hollow parts in the pillars. As the existence of whispering-gallery modes (WGMs), the local resonance BG was shifted toward extremely low frequencies and the Bragg BG became much wider [36,37].

However, elastic metamaterials consisted of a periodic arrangement of hollow pillars or other forms of standing structures such as H-fractal steel [25] or built-up structural steel [26] standing on the ground, which can occupy land and affect the esthetics of cities. Lots of elastic metamaterials were buried in a semi-infinite soil for the control and manipulation of surface waves propagation [28,29,31,38], but it was not easy to maintain the stability of the cavity soil structure such as cross-like-cavity or hollow-cylinder structures with large size in soils [31]. In this study, two types of periodic hollow steel trenches featuring both Bragg BG and local resonance BG are proposed. Steel plates are exploited to maintain the stability of soils on both sides of the trench and avoid the toppling or landslide, which can be conductive to practical engineering applications. We also explore the generation mechanism of Bragg BG and local resonance BG appearing in periodic hollow steel trenches. Furthermore, the desired performance of vibration mitigation for periodic hollow steel trenches within Bragg BG and local resonance BG are validated in frequency domain and time domain analysis. Finally, parametric analyses are carried out to analyze the effect of geometrical and material parameters on BGs. The aim of this study is to achieve Bragg BG and local resonance BG in both middle frequencies and low frequencies respectively with periodic hollow steel trenches, which open up new perspectives for the isolation of ambient or seismic vibration in the field of civil engineering.

2. Methodology and modeling

Fig. 1(a) shows the surface wave attenuation by embedding periodic trenches in a semi-infinite substrate (brown). In this paper, two types of trenches are considered namely periodic hollow sealed steel trenches and periodic hollow unsealed steel trenches respectively, and the Fig. 1 (b) and (c) present the typical unit cells with periodic boundary conditions (PBCs) in respect of two types of periodic trenches. The hollow sealed steel trench in Fig. 1(b) is achieved by filling open trench with a hollow sealed steel frame (dark grey), and the hollow unsealed steel trench in Fig. 1(c) is obtained by filling open trench with a hollow unsealed steel frame (dark grey). A hollow steel trench which is a cavity structure similar to the open trench can provide a desirable vibration isolation effectiveness, and rely on steel plates to support the soil on both sides of the open trench to meet the requirements of soil stability. Moreover, hollow steel trenches are embedding periodic trenches in a semi-infinite substrate, which can block the surface waves falling into the BGs effectively. In addition, there are new local resonance band gaps by using periodic hollow steel trenches compared with using periodic in-filled trenches, which will be discussed in the following analysis. As can be seen from the Fig. 1(b) and (c), a is the lattice constant of two types of trenches, b is the width of trenches, d is the depth of trenches, c is the thickness of steel plate and h is the depth of the soil. Corresponding material properties and geometrical parameters of periodic hollow steel trenches are summarized in Tables 1 and 2, respectively.

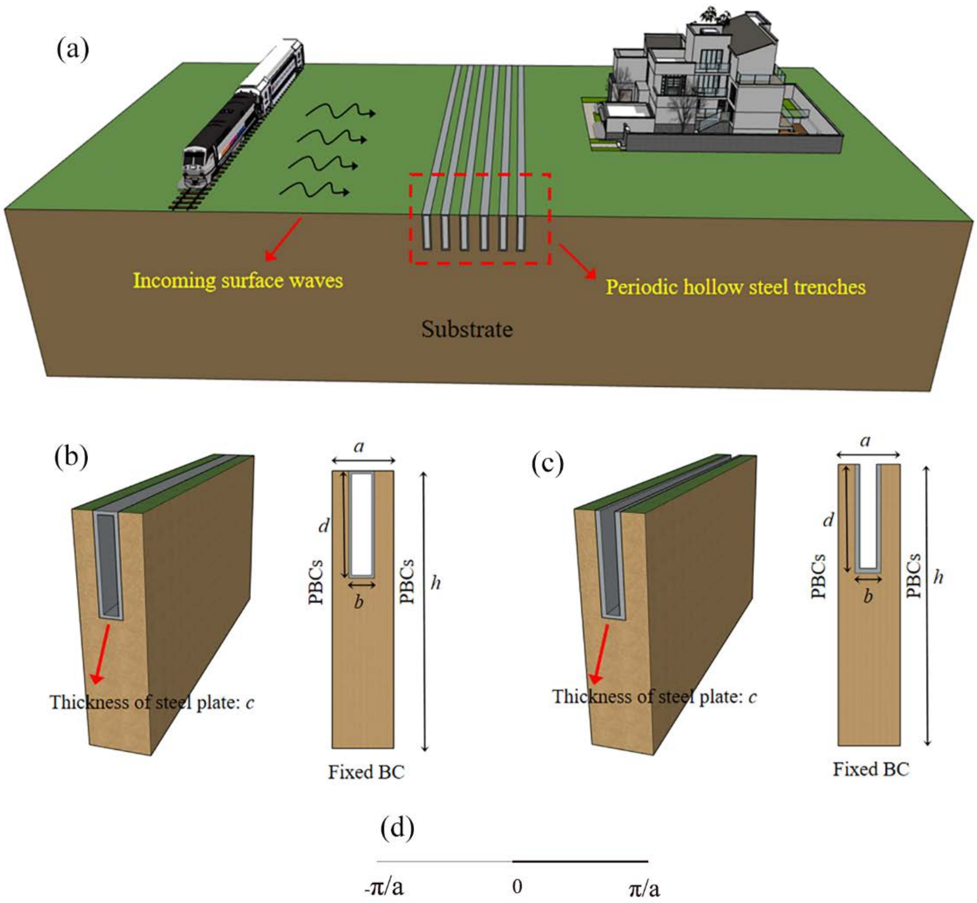


Fig. 1 (a) A schematic diagram of the periodic trenches; (b) unit cell of periodic hollow sealed steel trench; (c) unit cell of hollow unsealed steel trench; (d) the corresponding first irreducible Brillouin zone.

Table 1. Material parameters

Material	Young's modulus E (MPa)	Poisson ration v	Density ρ (kg/m^3)
Soil [5,17]	46	0.25	1800
steel	210,000	0.22	7856

Table 2. Geometrical parameters

a (m)	b (m)	d (m)	c (m)	h (m)
0.75	0.2	2	0.02	15

Assuming a homogeneous linear elastic medium with no damping, the governing equation can be written as:

$$\nabla\cdot(\mathbf{C}(\mathbf{r}):\nabla\mathbf{u}(\mathbf{r}))=\rho(\mathbf{r})\frac{\partial^2\mathbf{u}(\mathbf{r})}{\partial t^2}, \tag{1}$$

where ∇ represents the differential operator, $\mathbf{r} = (x, y, z)$ represents the position vector, $\mathbf{C}(\mathbf{r})$, $\mathbf{u}(\mathbf{r})$ and $\rho(\mathbf{r})$ represent the position-dependent elastic tensor, displacement vector and mass density, respectively. t is the time parameter. As per the Bloch-Floquet theorem of solid-state physics, the displacement vector can be expressed as:

$$\mathbf{u}(\mathbf{r}, t)=e^{\mathrm{i}(\mathbf{k}\cdot\mathbf{r}-\omega t)}\mathbf{u}_{\mathbf{k}}(\mathbf{r}), \tag{2}$$

where ω is the circular frequency, $\mathbf{k}$ is the Bloch-Floquet wave vector limited in the first Brillouin zone, and $\mathbf{u}_{\mathbf{k}}(\mathbf{r})$ is a modulation function of the displacement vector. For the periodic trenches, $\mathbf{u}_{\mathbf{k}}(\mathbf{r})$ is a periodic function defined in a unit cell, which can be written as:

$$\mathbf{u}_{\mathbf{k}}(\mathbf{r}+\mathbf{a})=\mathbf{u}_{\mathbf{k}}(\mathbf{r}), \tag{3}$$

where $\mathbf{a}$ is the periodic constant vector for periodic structure. Substituting Eq. (3) into Eq. (2), the PBC of a unit cell is acquired as:

$$\mathbf{u}_{\mathbf{k}}(\mathbf{r}+\mathbf{a}, t)=e^{\mathrm{i}\mathbf{k}\cdot\mathbf{a}}\mathbf{u}_{\mathbf{k}}(\mathbf{r}, t). \tag{4}$$

By combining the displacement vector of Eq. (1) and the periodic boundary condition of Eq. (4), the dispersion analysis of the periodic trenches can be transferred into the solution of eigenfrequency equation:

$$(\widetilde{\mathbf{K}}-\omega^2\widetilde{\mathbf{M}})\cdot\mathbf{u}=0, \tag{5}$$

where $\widetilde{\mathbf{K}}$ and $\widetilde{\mathbf{M}}$ are the stiffness and mass matrices of a unit cell, respectively. The stiffness matrix $\widetilde{\mathbf{K}}$ represents a function of the Bloch-Floquet wave vector $\mathbf{k}$. The eigenfrequency ω and the dispersion relationship of the periodic trenches are achieved by scanning the wave vector $\mathbf{k}$ in the first irreducible Brillouin zone as shown in Fig.

1(d). In this study, the finite element method simulation using software (COMSOL Multiphysics 5.6) is performed to solve the eigenvalue equation and dispersion relations.

3. Results and discussions

3.1 Dispersion curves for different periodic trenches and Vibration modes

The unit cell models in respect of two types of hollow steel trenches are show in Fig. 1 (a) and (b), geometrical parameters and material properties can be seen from Table 1 and 2. A free triangular mesh is used to discretize the models. The maximum element size is 0.225 m, which is smaller than 1/5 of the minimum Rayleigh wavelength at 80 Hz and can contribute to the accurate simulation of waves with frequencies below the 80 Hz. The dispersion relations of periodic two types of trenches are illustrated in Fig. 2, where the thick black solid line is sound line and the shaded areas represent the band gaps. The sound cone method is adopted to obtain surface modes in dispersion relations [39]. The sound line is governed by the formula $w = \mathbf{k} \cdot v_s$, where $v_s = \sqrt{E/\rho}$ is the shear wave velocity of the soil substrate, E and ρ are the shear modulus and density of the soil substrate respectively. The surface modes are located inside the sound cone, while the bulk modes are outside it [40]. The existence of a BG is indicated by the absence of eigenvalues in some frequency ranges.

With respect to periodic hollow sealed steel trenches, BG1 is 49.7-67.6 Hz as presented in Fig. 2 (a). The vibration eigenmode at the point B_1 is a kind of guided surface wave modes as shown in Table 3, and such guided surface states correspond to typical Rayleigh-wave modes because of sin-like or cos-like displacement fields, which capture the localization of wave motion near the free surface [18]. Therefore, the band with point B_1 below the sound cone in the Fig. 2 (a) is called surface wave band, the lower boundary of BG1 is dependent on the surface wave modes B_1, and it can be deduced that BG1 is caused by the system's periodicity, so BG1 is called Bragg BG. It is also interesting that there are two new resonant bands, one appears below the surface wave band and another appears in the Bragg BG around in 55 Hz. Table 3 illustrates the vibration eigenmode at the point A_1, B_1, C_1. Note that the vibration modes at point A_1 and C_1 are locally resonant modes, and the main energy mainly occurs on the both sides of trench.

As regards periodic hollow unsealed steel trenches, a new surface wave band appears below the sound cone and a wider Bragg BG (BG1) is 44.2-64.4 Hz as shown in Fig. 2 (b). Compared with periodic hollow sealed steel trenches, two resonance bands are shifted to low frequency and a new narrow band gap appears in a low frequency range from 6.3 to 14.1 Hz, where this new BG (BG2) is called locally resonant BG. The type of band gap in the dispersion curve can be determined by the vibration modes of the upper and lower boundaries of the BG. It can be observed from Table 4 that the vibration eigenmode at the point B_2, D_2 are the surface wave mode where elastic energy confined near the free surface, besides the vibration modes at point A_2 and C_2 are locally resonant mode where vibration energy is concentrated in the steel plates and soil on both sides of the trench. The upper and lower boundaries of BG1 are dependent on the surface wave modes B_2 and D_2, and it can be concluded that BG1 is caused by the artificial periodic condition, so BG1 is a Bragg BG. On the other hand, the locally resonant mode A_2 determine the lower boundary of BG2, so BG2 is referred to as locally resonant BG. When resonance is reached, the wave energy is confined inside the steel plates and soil on both sides of the trench and the energy transmission through the trench array is strongly reduced. Compared with periodic hollow sealed steel trenches, the Bragg BG of periodic hollow unsealed steel trenches moves towards low frequency and a new locally resonant BG appears in low frequency caused by a downward shift of the fourth band. It is because that there is no top steel plate to limit the axial displacement of lateral soils and steel plates in the hollow unsealed steel trenches, such structures with large flexibility can provide larger displacement space for local resonance.

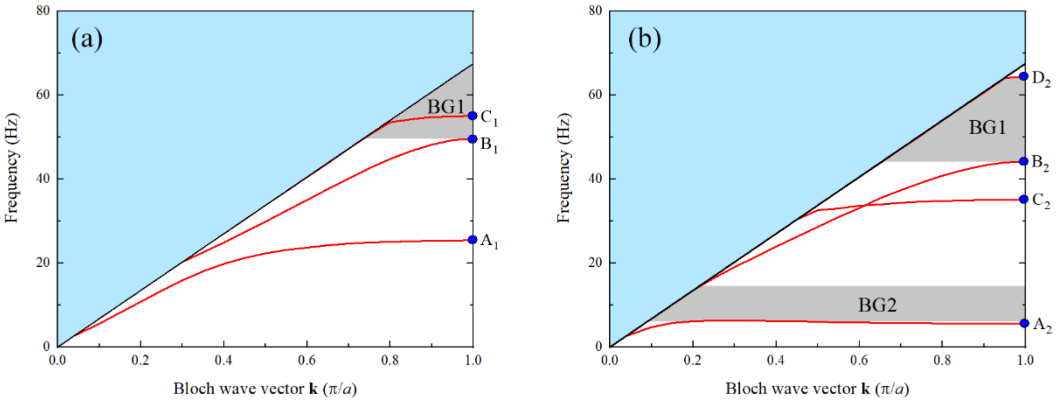


Fig. 2 Dispersion curves of (a) periodic hollow sealed steel trenches, (b) periodic hollow unsealed steel trenches.

Table 3. Vibration modes of periodic hollow sealed steel trenches

Order of vibration	A_1	B_1	C_1
Frequency (Hz)	25.4	49.7	55.1

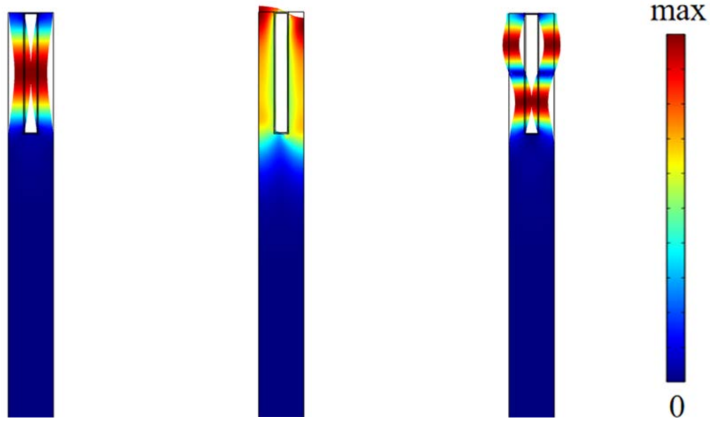
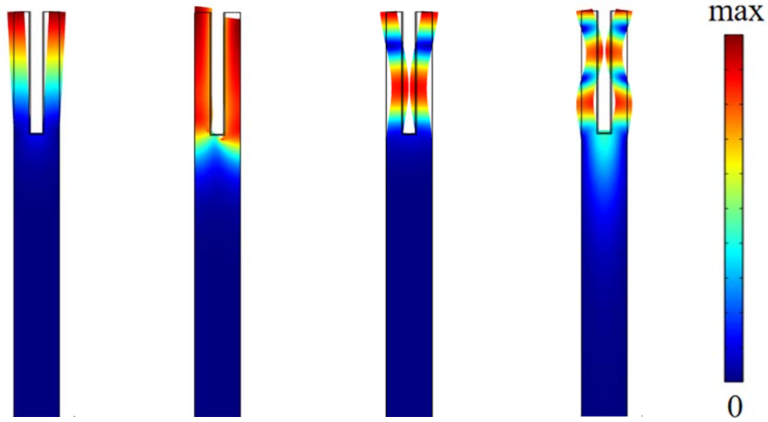
Vibration modes	

Table 4. Vibration modes of periodic hollow unsealed steel trenches

Order of vibration	A_2	B_2	C_2	D_2
Frequency (Hz)	5.6	44.2	35.2	64.4
Vibration modes				

3.2 Frequency domain analysis

The BGs of two types of periodic hollow steel trenches are analyzed on basis of the infinite unit cell mode, whereas the periodic wave barriers are finite in practical engineering. To verify the accuracy and efficiency of BG, two-dimensional finite element model is established and harmonic analyses with six rows of hollow steel trenches are carried out, as shown in Fig. 3. Perfectly matched layers (PML) are added on the boundaries of soils to prevent the reflection of vibration waves from the bound. A vertical harmonic load F_0 = 1000 N vibrates along the *y*-direction at the point A away from the left boundary of model to simulate the incident surface waves. l_2 is the distance from the source to the first row of trenches. l_3 is the distance from the last row of trenches to the detection point B for vibration response. The dimensions of the soil substrate are l_4 and l_5 respectively. In this section, the following parameters are considered: $l_1 = 5$ m, $l_2 = 20$ m, $l_3 = 3$ m, $l_4 = 40$ m, $l_5 = 15$ m, the geometrical parameters and material properties of two types of trenches are referred to Tables 1 and 2. The free triangular mesh is adopted for discretizing the model and a mapped mesh is used for the PMLs. The maximum element size is 0.225 m, which is consistent with that of the unit cell models used to calculate the dispersion relations in Section 3.1.

To assess the vibration isolation performance of periodic trenches, the transmission attenuation is defined: TA = $20\times\log_{10}(u_{y1}/u_{y0})$, the u_{y1} and u_{y0} represent the displacement at the detection point B with and without trenches respectively. The transmission attenuation curves together with the corresponding dispersion curves of two types of periodic hollow steel trenches are shown in Fig. 4, it can be found that the BGs are well coincide with that of attenuation zones (AZs). The interesting feature is that a new AZ2 appears around point A_1 ranging from 18 Hz to 25 Hz in Fig. 4 (a), it is because that Rayleigh waves are forced to transform into hybrid Rayleigh waves traveling at different phase velocity in the frequency region below the resonance (25.4 Hz) by the locally resonant trenches and portion of the surface energy leaks into the soil substrate, which results in a surface ground motion attenuation [38]. In addition, a new attenuation zone (AZ3) in Fig. 4 (b) exist above the AZ1. It is attributed to that pseudo surface wave modes exist in the area beyond the sound cone (the blue areas), which is contain small bulk-wave components that leak energy into the substrate [17,41]. Further information on pseudo surface waves in periodic structures can be found in references [41-43]. It is interesting to note that the transmission attenuation degree within the Bragg BG is larger than that within the locally resonant BG. As an example, the largest transmission attenuation degree of periodic hollow sealed steel trenches is approximately 23 dB for AZ1 and that for AZ2 is about 12 dB. The largest transmission attenuation degree of periodic hollow unsealed steel trenches is around 31 dB for AZ1, and that for AZ2 is about 12 dB. This occurs due to that the surface wave wavelength at low frequencies is longer than that at high frequencies, resulting in that the number of low-frequency surface waves propagating through the limited amount of unit cells is less than that of high-frequency surface waves. Generally, the transmission attenuation of low-frequency surface waves can be enhanced by growing the number of unit cells to contain more low-frequency surface wavelengths.

To further confirm the attenuation of surface waves within BGs, nephograms of displacement field for the system when vibrating at 30 Hz outside the BGs and 55 Hz inside the BG are given in Fig. 5 (a) and (b) respectively. The results indicate that when incident waves at 30 Hz outside the BGs pass through the periodic hollow sealed steel trenches, no obvious attenuation occurs the area behind periodic trenches. However, the incident surface waves at 55 Hz inside the BG are almost totally reflected and concentrated in the soil on the left side of periodic trenches. It is validated that the desired isolation performance can be obtained within BG. Fig. 6 illustrates the attenuation characteristics of the incident surface wave at 55 Hz where the shaded area represents the location of periodic hollow sealed steel trenches. It is clear that an exponential decay of displacement occurs inside the periodic hollow sealed steel trenches, which is an interference characteristic of Bragg scattering.

The comparative study is also conducted to validate the superiority of vibration isolation for two types of proposed periodic hollow steel trenches. Fig. 7 (a) and (b) compares the vibration isolation performance of two types of periodic hollow steel trenches and periodic geofoam-filled trenches by Pu and Shi. The geometrical parameters and material properties of periodic geofoam-filled trenches and is referred to [17]: the width of trench b is 0.3 m, the depth of trench d is 2 m, the lattice constant a is 1 m, the row of trenches is six, the $E_{geofoam}$ is 37 MPa, the $\rho_{geofoam}$ is 60 kg/m^3 and $v_{geofoam}$ is 0.32. The row and geometrical parameters of two types of periodic hollow steel trenches in the comparative study are the same as that of periodic geofoam-filled trenches. Furthermore, the thickness of hollow steel plate c is 0.02 m, and material properties of soils is show in Table 1. The results, as presented in Fig. 7 (a) and (b), indicate that the vibration isolation performances of two types of periodic hollow steel trenches are superior to that of periodic geofoam-filled trenches below 80 Hz. It is because that the impedance of hollow steel trenches is lower than that of geofoam-filled trenches, a smaller impedance means that fewer waves pass through materials [9]. The smaller impedance ratio between the barrier and the adjacent soil is contribute to the vibration reduction more [8,44]. Therefore, the value of TA with two types of periodic hollow steel trenches is bigger than that with periodic geofoam-filled trenches within the BG. Moreover, it is clear that the vibration isolation performance of open trench is better than other wave barriers, since the impedance of air is pretty low compared to the impedance of soil. Thus, the hollow unsealed steel trench, which is more similar to the open trench in structure form, can isolate more vibration waves than hollow sealed steel trench, so the value of TA with periodic hollow unsealed steel trenches is bigger than that with periodic hollow sealed steel trenches within the BG. Importantly, the use of periodic hollow steel trenches provides an AZ in the low frequencies below 20 Hz shown in the first shaded area caused by the local resonance of hollow steel trench. It means that the proposed periodic hollow steel trenches can be applied to the attenuation of vibration induced by trains (dominant frequency: 40-60 Hz), and attenuate seismic waves (dominant frequency: below 20 Hz) as well.

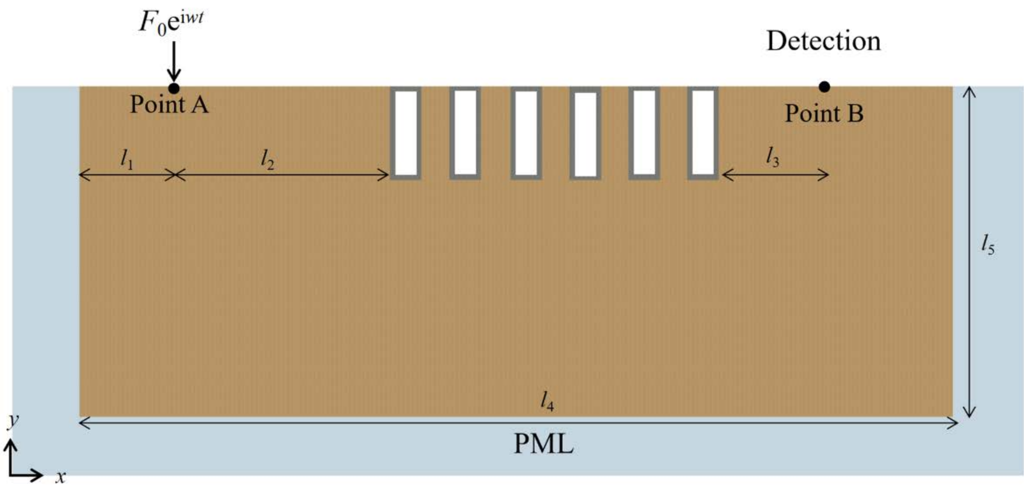


Fig. 3 Finite element model used for the numerical analysis.

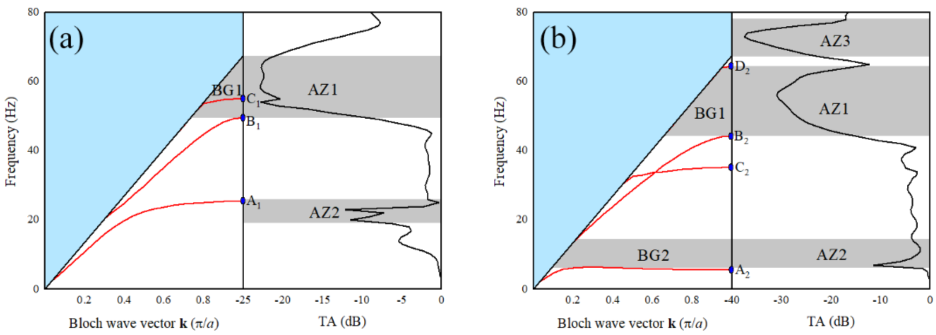


Fig. 4 Dispersion relations and transmission attenuation spectra of (a) periodic hollow sealed steel trenches, (b) periodic hollow unsealed steel trenches.

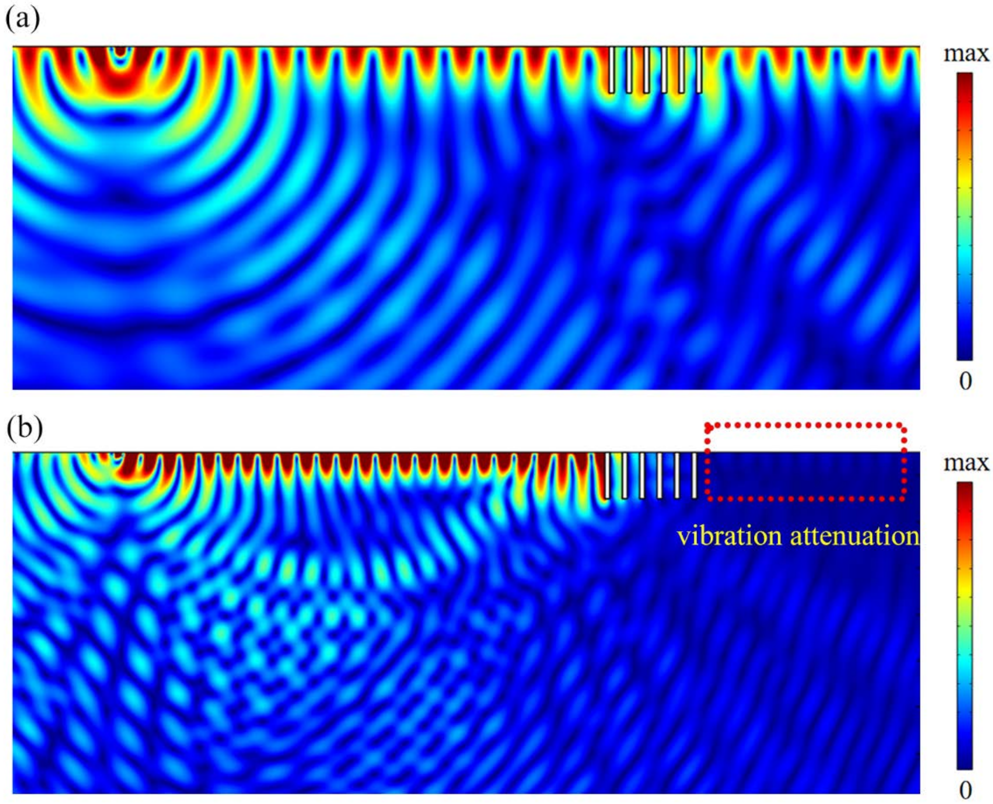


Fig. 5 The nephogram of displacement field for soil-periodic hollow sealed steel trenches system at frequencies of (a) 30 Hz and (b) 55 Hz.

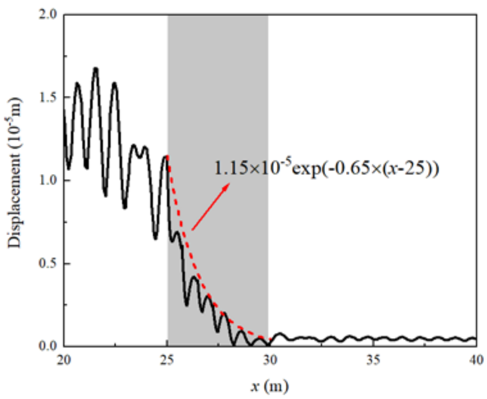


Fig. 6 Attenuation characteristics of the incoming surface waves at 55 Hz. (periodic hollow sealed steel trenches are situated in the shadow area)

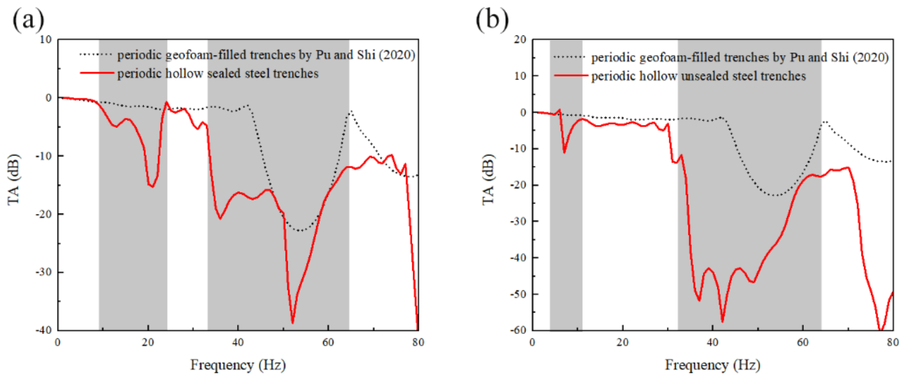


Fig. 7 Comparison of the vibration isolation effects of periodic in-filled trenches and (a) periodic hollow sealed steel trenches, (b) periodic hollow unsealed steel trenches.

3.3 Time domain analysis

In this section, the vibration isolation performance of two types of proposed periodic hollow trenches is analyzed in the time domain. PMLs in Fig. 3 are not suitable for the time domain analysis, so the low-reflective boundary condition is applied to the model to avoid the reflection of vibration waves in time domain analysis. The geometrical parameters and material properties of periodic hollow steel trenches in time domain analysis are also referred to Table 1 and 2, l_1, l_2, l_3, l_4, and l_5 are the same as described in Section 3.2. A 50 Hz (within the BG1 of periodic hollow unsealed steel trenches) and 7 Hz (within the BG2 of periodic hollow unsealed steel trenches) harmonic unit displacement load is applied to the point A along the *y*-direction using the model in Fig. 3 respectively. Fig. 8 and 9 present the displacement field nephogram of soils with periodic hollow unsealed steel trenches and without trenches at varying times as an example to show an explicit attenuation of the wave propagation through the trenches. The color bar represents the degree of the displacement, red stands for the maximum displacement. It is worth noting that the incident surface waves (50 Hz) within BG1 (Bragg BG) are almost completely reflected, while the incident surface waves (7 Hz) within BG2 (local resonance BG) are suppressed and confined inside unit cells resulting from the resonance.

In practice, ambient vibration is not harmonic such as vibration induced by trains and seismic vibration, theses vibrations are superposed by different frequency vibration. Therefore, this work conducts a field test to obtain practical traffic-induced ground vibrations in Dongguan (Guangdong Province, China) as shown in Fig. 10 (a) and (b), also acquire a practical seismic vibration record from the PEER Ground Database [45] as shown in Fig. 12 (a) and (b). Moreover, the measured acceleration data can be integrated twice to acquire the displacement load, which can be applied at point A along the y-direction in the model for time domain analysis. The type of daily operating elevated intercity train in the field test is CRH6. The INV3062-type vibration signal acquisition instruments and 941B-type ultra-low accelerometers are used. Fig. 10 (c) and (d) show the measured acceleration record and the corresponding Fourier spectrum at 10 m away from the pier in a field are measured when a train runs by approximately 100 km/h respectively. It is apparent that the main frequency domain of vibrations induced by this train is around 40-60 Hz. The acceleration data are integrated twice to acquire the displacement load to add to the point A along the *y*-direction. The rows, materials and geometric parameters of periodic hollow sealed steel trenches are the same as above. Fig. 11 (a) shows vertical acceleration responses at the detection point B with two kinds of periodic hollow steel trenches and without trenches subjected to railway excitation. It can be spotted that the accelerations behind the periodic hollow steel trenches are significantly reduced. Fig. 11 (b) presents the corresponding Fourier spectrum of acceleration responses and it can be found that the vibration induced by trains is dramatically reduced within the BGs. The acceleration amplitudes with periodic hollow sealed steel trenches and with periodic hollow unsealed steel trenches are reduced by 51% and 71% respectively, when comparing with that without trenches.

Data with respect to diverse earthquakes show that the dominant frequencies of seismic waves span the range of 1–20 Hz [31,46]. Fig. 12 (a) and (b) present the 2008 Iwate (Japan) AKT019UD records and the Fourier spectrum acquired from the PEER Ground Database [45]. It can be seen that the dominant frequencies of Iwate seismic waves are below 20 Hz. To verify the shielding capability of periodic hollow steel trenches for seismic vibration, the displacement load of Iwate AKT019UD records added on the point A along the *y*-direction. The rows, materials and geometric parameters of periodic hollow sealed steel trenches remain the same as above. Fig. 13 shows the acceleration responses and corresponding Fourier spectra under the excitation of Iwate (Japan) AKT019UD record with periodic hollow steel trenches and without trenches. The acceleration amplitudes with periodic hollow sealed steel trenches and with periodic hollow unsealed steel trenches are reduced by 32% and 31% respectively.

The time domain analysis indicates that the use of proposed periodic hollow steel trenches could effectively isolate the vibration induced by trains (dominant frequency: 40-60 Hz) and seismic waves (dominant frequency: below 20 Hz), as hollow steel trenches exhibit Bragg and local resonance BG in the middle and low frequency range respectively. Table 5 summarizes the vibration isolation results for the periodic hollow steel trenches in frequency and time domain analysis.

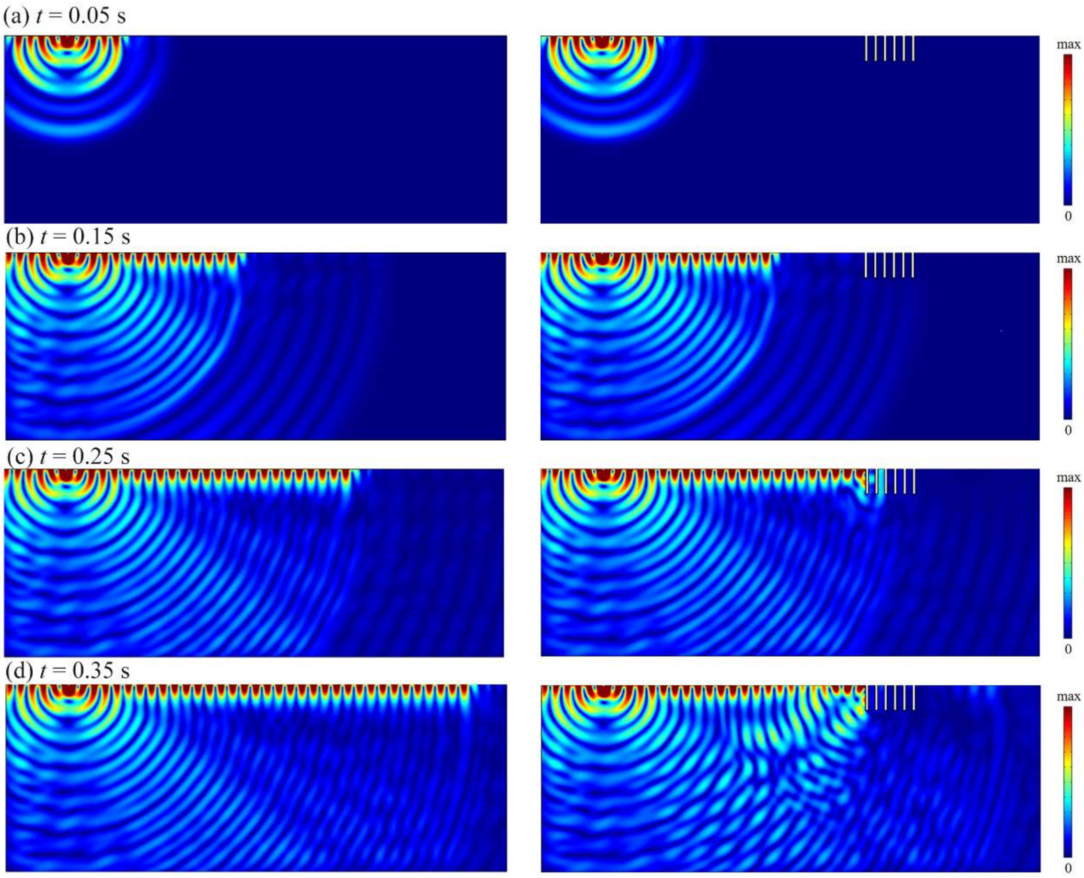


Fig. 8 Transient displacement field nephogram for soils with periodic hollow unsealed steel trenches and without trenches at frequencies of 50 Hz when (a) t = 0.05 s, (b) t = 0.15 s, (c) t = 0.25 s and (d) t = 0.35 s.

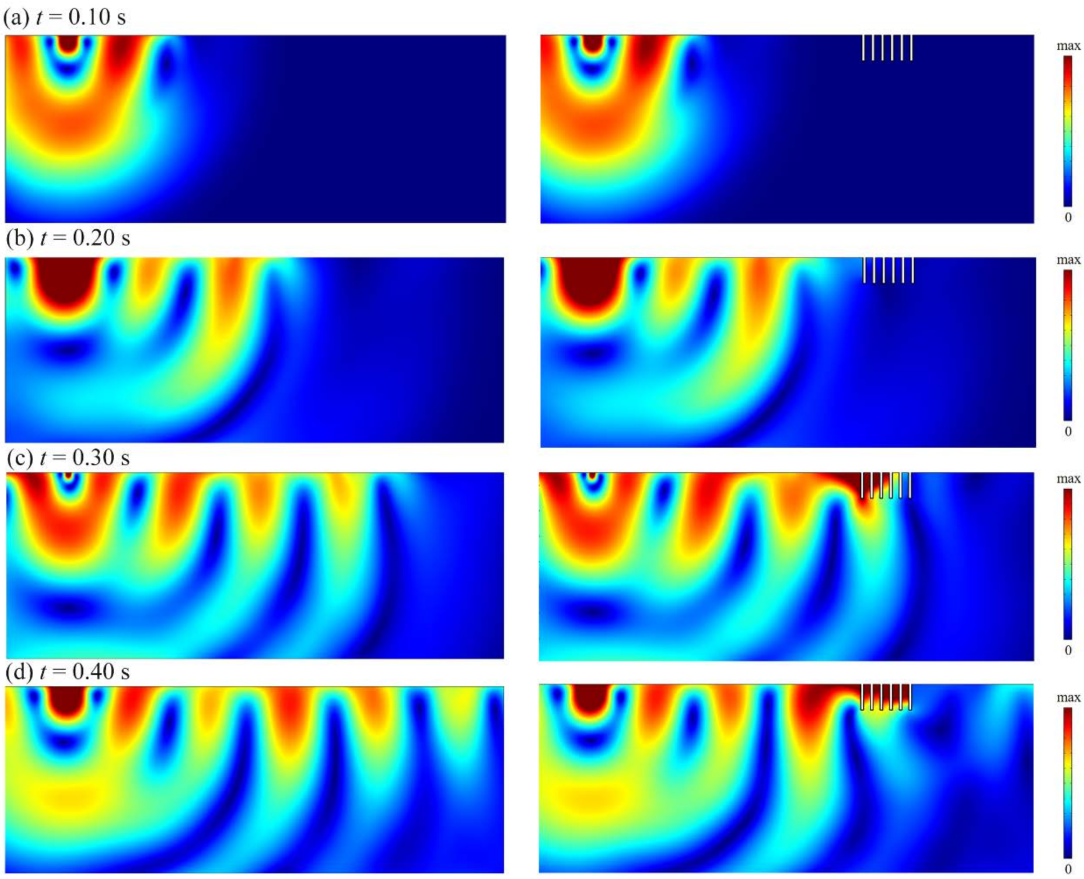


Fig. 9 Transient displacement field nephogram for soils with periodic hollow unsealed steel trenches and without trenches at frequencies of 7 Hz when (a) t = 0.10 s, (b) t = 0.20 s, (c) t = 0.30 s and (d) t = 0.40 s.

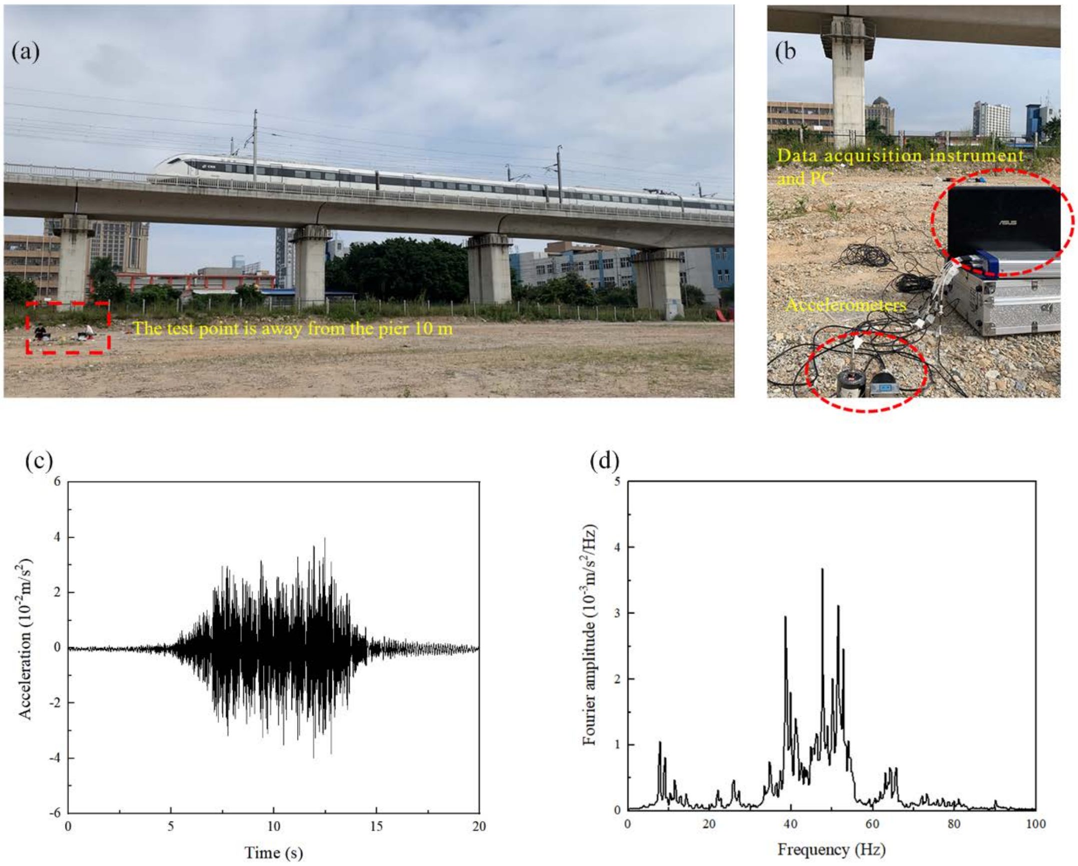


Fig. 10 Vibration response in the field induced by the intercity railway: (a) (b) field measure; (c) vertical acceleration record; (d) Fourier spectrum.

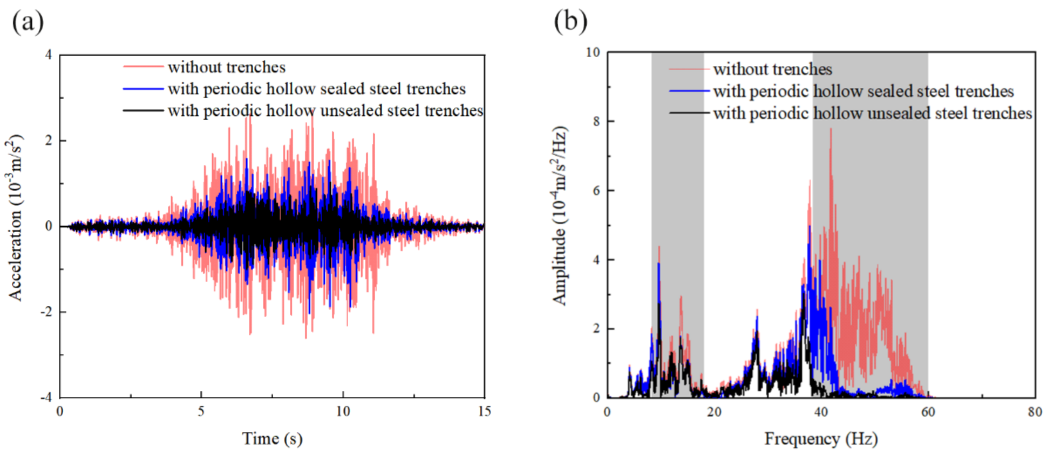


Fig. 11 (a) Vertical acceleration responses at the detection point B and (b) corresponding Fourier spectra with and without trenches.

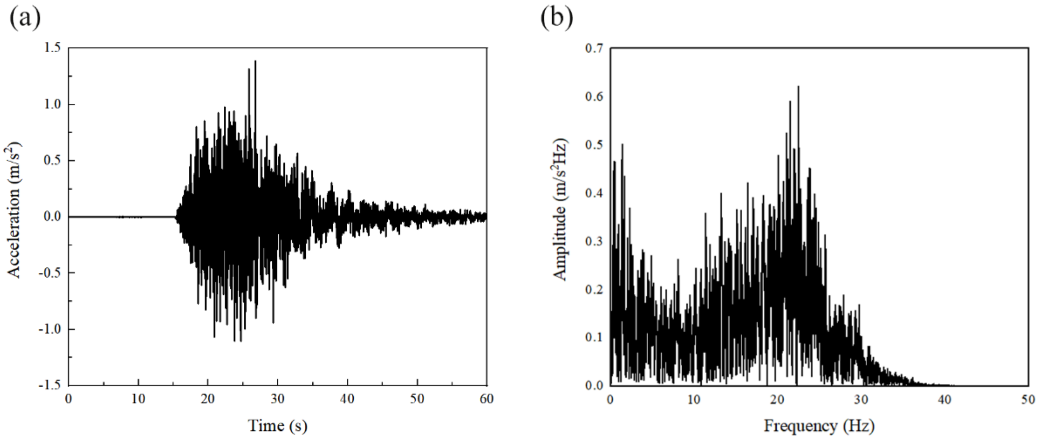


Fig. 12 (a) Iwate (Japan) AKT019UD record; (b) Fourier spectrum.

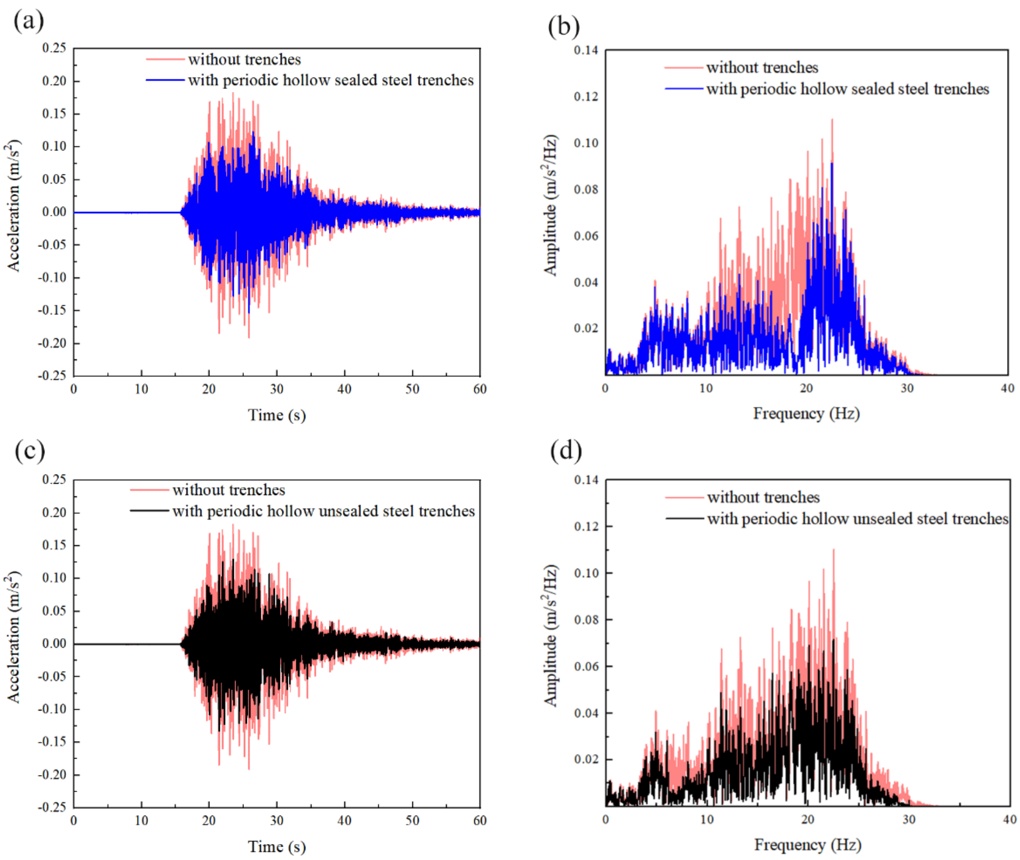


Fig. 13 Vertical acceleration responses under the excitation of Iwate (Japan) AKT019UD record with and corresponding Fourier spectra: (a-b) with periodic hollow sealed steel trenches and without trenches, (c-d) with periodic hollow unsealed steel trenches and without trenches.

Table 5. Summary of vibration isolation results for the periodic hollow steel trenches. (geometrical parameters and material properties are referred to Table 1 and 2)

Types of wave barriers	Frequency domain (largest TA degree)		Time domain (reduction of acceleration amplitudes)	
	AZ1	AZ2	seismic load	train load
Periodic hollow sealed steel trenches	12 dB	23 dB	32%	51%
Periodic hollow unsealed steel trenches	12 dB	31 dB	31%	71%

3.4 Effect of geometric parameters

The frequency domain and time domain analysis above demonstrate that the proposed periodic hollow steel trenches can be appropriate for the application in isolating vibration induced by trains and attenuating seismic waves. To further illustrate the mechanism of BG and explore the optimization of structure design, the influence of geometrical parameters on the BGs of hollow steel trench are discussed in this section. The variation of the bound frequency of two types of periodic hollow steel trenches with the change of a single geometrical parameter is analyzed in Fig. 14. The other materials and geometric parameters of periodic hollow sealed steel trenches are referred to Table 1 and 2. When a single parameter is changed, the other parameters remain unaltered.

Fig 14 (a) shows the effect of the ratio b/a on the BGs. As the increase of b/a, the upper and lower bound of BG1 for two types of periodic hollow steel trenches are moved to higher and lower frequencies respectively, so the width of BG1 increases with the b/a increases. However, the upper boundary decreases of periodic hollow unsealed steel trenches as the b/a increases, the width of BG2 decreases. Additionally, though the transmission attenuation spectrums in Fig. 4 (a) demonstrates that periodic hollow sealed steel trenches can be used to attenuate vibration at lower frequencies (18-25 Hz) as shown in AZ2, there is no BG2 for periodic hollow sealed steel trenches at lower frequency in the dispersion curves in Fig. 2 (a). Therefore, we do not discuss the effect of materials and geometric parameters on lower frequency BGs of periodic hollow sealed steel trenches. Fig 14 (b) presents the effect of the ratio *c*/*a* on the BGs, it is observed that the increase of *c*/*a* leads to the shifting toward the higher frequency bound of BG1 for periodic hollow steel trenches and narrowing of the BG width. However, the BG2 widens with the increase of *c*/*a*, because the upper frequency bound of BG2 increases when the lower bound frequency is basically unchanged. It means that the increase of thickness of steel plate *c* is more significant for isolating lower frequency waves such as seismic waves in practical engineering. In Fig 14 (c), the upper frequency bound of periodic hollow unsealed steel trenches decreases when *d*/*a* is greater than 2, the BG1 width of that also reduces with the increase of *d*/*a*. Whereas, the BG1 of periodic hollow sealed steel trenches widens with the rise of *d*/*a*. In addition, the BG2 of periodic hollow unsealed steel trenches shift the lower frequency bound but the width tends to narrow with the increase of *d*/*a*.

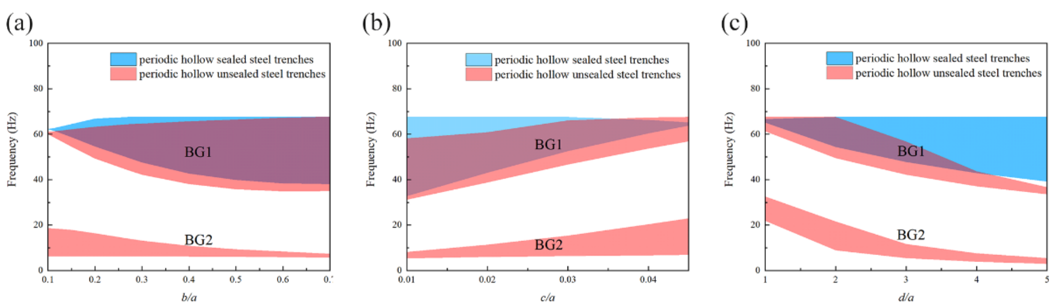


Fig. 14 Effect of different geometric parameters for two types of periodic hollow steel trenches on the BGs: (a) ratio of the width *b* to the lattice constant *a*; (b) ratio of the thickness *c* to the lattice constant *a*; (c) ratio of the depth *d* to the lattice constant *a*.

3.5 Effect of material parameters

The relation between geometric parameters and BGs are analyzed in the previous section and it is available for modifying the geometric parameters to tune the properties of the BG, especially its location and width. In this section, the effect of material parameters of soils and steel on the BGs are discussed as shown in Fig. 15.

Fig. 15 (a) and (b) presents the variation of the bound frequency of two types of periodic hollow steel trenches with the change of Young's modulus and mass density of soil respectively. When the Young's modulus of soil increases from 20 MPa to 100 MPa, the upper and lower frequencies of BG1 for two types of periodic hollow steel trenches rise dramatically, while the BG1 width enlarges significantly. Although the BG2 width of periodic hollow unsealed steel trenches remain basically constant with the increase of Young's modulus of soil, its location is moved to the higher frequencies gradually. From Fig. 15 (b), as the mass density of soil increases from 1600 kg/m^3 to 2200 kg/m^3, the upper and lower bound frequencies of BG1 for two types of periodic hollow steel trenches decrease substantially and the bound frequency of BG2 for periodic hollow unsealed steel trenches keep almost unchanged. Fig. 15 (c) and (d) present effects of the Young's modulus and mass density of steel on BG2 for two types of periodic hollow steel trenches. The rise of Young's modulus of steel causes the increase of upper and lower bound frequencies of BG1 for periodic hollow unsealed steel trenches in Fig. 15 (c), and it can contribute to the enlarging of BG2 width, which means that increasing Young's modulus of steel is a desired method to widen the width of low frequency BG to attenuate vibration such as seismic waves. As can be seen from Fig. 15 (d), BG1s descend gradually and steadily are shifted toward the lower frequency as the increase of mass density of steel. Though the lower bound of BG2 for periodic hollow unsealed steel trenches keeps basically unchanged, the BG2 width is turned to be narrower because the upper bound frequency moves toward lower frequencies.

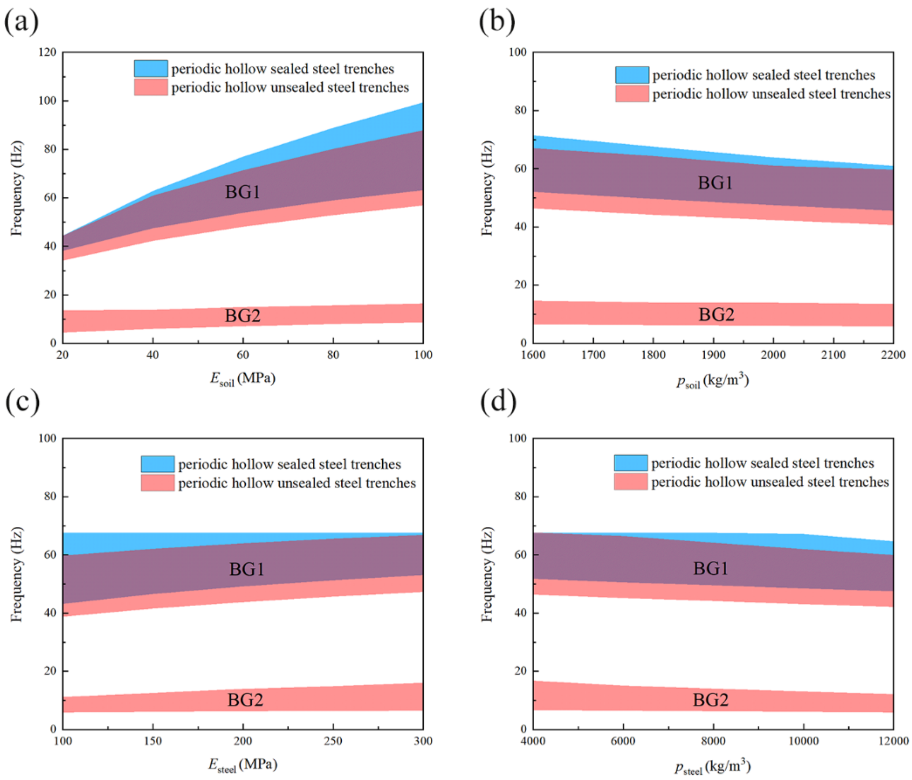


Fig. 15 Effect of soil and steel material parameters: (a) the Young's modulus of soil; (b) the mass density of soil; (c) the Young's modulus of steel; (d) the mass density of steel.

4. Conclusion

In summary, two novel types of periodic hollow steel trenches with Bragg band gap and locally resonant BG are proposed. Based on Bloch theory and finite element method, the dispersion relations are calculated and the generation mechanism of BGs are clarified. The effectiveness of the periodic hollow steel trenches on the surface waves attenuation is confirmed by both frequency domain and time domain analysis. Furthermore, the effects of several significant geometric parameters (the width and depth of trenches, the thickness of steel plates) and several materials parameters (Young's modulus and mass density of soils and steel) on the the BGs have been analyzed respectively. The conclusions drawn are as follows:

(1) The proposed periodic hollow steel trenches feature both a Bragg BG and a local resonance BG simultaneously. The Bragg BG around middle frequencies is induced stemming from system's periodicity, which is of interest for control ambient vibration such as vibrations induced by trains. The local resonance BG appears below 20 Hz due to occurrence of unit cell local resonance, which can contribute to the isolation of seismic vibration.

(2) When the frequencies of incident surface waves fall into the local resonance BG, wave energy is confined and suppressed inside the unit cell structures. If the frequencies of incident surface waves are within the Bragg BG, incident surface waves can be almost fully reflected and an exponential decay of the transmission occurs inside the periodic hollow sealed steel trenches.

(3) The Bragg BG width of two types of periodic hollow steel trenches increases with an increase of trench width or decrease of steel plate thickness, while the local resonance BG width decreases with such the variation of parameters. The rise of depth of trenches results in the decline of both Bragg BG and local

resonance BG width of periodic hollow unsealed steel trenches, but causes the increase of Bragg BG of periodic hollow sealed steel trenches.

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