Research Article

Numerical Analysis on the Ground Vibration Isolation of Duxseal

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1.Introduction

Traffic load, machine operation, engineering construction, and other human activities on grounds are known to induce large vibrations in the vicinity of the vibration source [1, 2]. Along with the rapid development of society and economy, this phenomenon has increasingly intensified and aroused widespread concern. For example, there were obvious furniture dislocation and wall cracking of surrounding buildings caused by the daily operation of the Beijing Subway DAXING Line. To reduce the vibration levels, many investigations have been conducted on active barriers such as piles, trenches (in-filled trench and open trench), and wave impeding blocks (WIBs).

Early research by Woods [3] illustrated that open trenches for both active and passive isolation cases could reduce vibration amplitudes by conducting several full-scale experiments. Cai et al. [4] investigated the results of the screening of elastic waves using a row of piles as an isolation barrier in a poroelastic medium with a set of cylindrical coordinate systems and Graff’s theorem for cylindrical Bessel functions. Arslan and Celebi [5] provided a special fiber retrofitting system to improve the masonry structures under earthquake loads. Gao et al. [6] conducted a series of field experiments and numerical studies to investigate the vibration isolation for a surface foundation using WIB in a multilayered ground under vertical loading. However, it has been often reported that the above traditional technologies could not always be sufficiently effective in screening the ground vibrations. For instance, the experimental results [6] showed that the WIB for screening ground vibrations becomes ineffective when the ground is relatively far away from the vibration source.

On account of the significance and necessity of vibration isolation, various new kinds of vibration damping materials and isolation technologies were developed gradually. In...
1983, a new isolation material called Duxseal was initially used for centrifuge modelling boundary at Princeton by Coe et al. [7] to reduce the reflection/refraction of energy and waves from the end walls of the test chamber; further, this study concluded that Duxseal possesses excellent damping properties. Based on the work conducted by Coe, Pak et al. [8] investigated the characteristics of Duxseal for absorbing vibration energy from the seismic free-field ground motion. Several literature [7, 8] are available regarding investigations on the damping properties. Based on the work conducted by Coe, Pak et al. [7] to reduce the reflection/refraction of energy and vibration energy from the seismic free-field ground motion. This study concluded that Duxseal possesses excellent damping properties.

2 Advances in Civil Engineering

2.3D Semianalytical Boundary Element Method (BEM) and Verification

2.1 3D Semianalytical BEM

2.1. Boundary Integral Equation of Elastodynamics. The boundary conditions can be expressed as follows:

\[ u_i = \overline{u}_i, \]
\[ t_i = \sigma_{ij} n_j = \overline{t}_i, \]  

(1)

where \( i = x, y, z; j = x, y, z; \overline{u}_i \) and \( \overline{t}_i \) are the known displacement and surface force components on the boundary, respectively; \( \sigma_{ij} \) is the stress; and \( n_j \) is the directional cosine of the outer normal vector on the boundary.

Assume that the displacement field \( u_i \) is generated under the body force \( f_i \) and surface force \( t_i \) in the elastomer \( V \) and that the displacement field \( u_i^* \) is generated under the body force \( f_i^* \) and surface force \( t_i^* \) in the same elastomer \( V \). An integral equation that can be proved by the Betti–Rayleigh dynamic reciprocal theorem is given as follows:

\[ \int_S t_i u_i^* dS + \int_V f_i u_i dV = \int_S t_i^* u_i^* dS + \int_V f_i^* u_i dV, \]

(2)

where \( S \) is the boundary of elastomer \( V \).

When the distance of the field point \( p \) and the source point \( q \), which are subjected to a concentrated force on the boundary, tend to approach 0, the displacement \( u_i^* \) and force \( t_i^* \) of the fundamental solution have primary and secondary singularity, respectively. We considered the source point \( q \) as the center and then created an arc segment with \( \varepsilon \) as the radius to eliminate the singular points; further, it is to be noted that the intersection of the arc segment and the elastomer was recorded as \( S_\varepsilon \). According to the Betti–Rayleigh dynamic reciprocal theorem, the integral equation can be derived as follows:

\[ \int_S t_i u_i^* dS + \lim_{\varepsilon \rightarrow 0} \int_S t_i^* u_i^* dS + \int_V f_i u_i dV = \int_S t_i^* u_i^* dS + \lim_{\varepsilon \rightarrow 0} \int_S t_i^* u_i^* dS + \int_V f_i^* u_i dV. \]  

(3)

For equation (3), three integrals can be accumulated as follows:

\[ \int_V f_i^* u_i dV = 0, \]
\[ \lim_{\varepsilon \rightarrow 0} \int_S t_i u_i^* dS = 0, \]
\[ \lim_{\varepsilon \rightarrow 0} \int_S t_i^* u_i^* dS = C_i u_i(q). \]  

(4)  

(5)  

(6)

Substituting equations (4)–(6) into equation (3), the boundary integral equation of elastodynamics can be simplified as follows:

\[ Cu_i(q) + \int_S t_i^* (p, q) u_i(p) dS = \int_S u_i^* (p, q) t_i(p) dS + \int_V u_i^* (p, q) f_i(p) dV, \]

(7)

where \( C \) is the free term of the boundary integral equation, which is closely related to the geometric characteristics of the boundary surface at the source point \( q \). In this investigation, the boundary surface at the source point \( q \) is assumed to be smooth, that is, \( C = 1/2 \).

To simplify the work of calculation, the body force was neglected. For the boundary integral equation, the displacement component is a continuous function of the coordinate points on the boundary and the surface force component can be a discontinuous function of the coordinate points on the boundary. To avoid the complexity of solving the function of displacement and surface force components, the boundary integral equation is discretized in the following matrix form:

\[ \frac{1}{2} [u'] = [u^*'] [t'] - [t^*'] [u']. \]

(8)

All boundary nodes of the elastomer are numbered from 1 to \( N \) in order, and the surface force and displacement components of node \( n \) are then recorded as \( t_i^n \) and \( u_i^n \), respectively. Based on equation (8), the algebraic relationship between the displacement component and surface force component of boundary nodes can be expressed as
Unknown displacement and force components on the boundary can be obtained from equation (9). Using the discretized dynamic Somigliana integral, the displacement of any point in the elastomer can be obtained as follows:

\[ \{u_d\} = \left[u^*\right][t'] - \left[t^*\right][u']. \quad \text{(10)} \]

### 2.1.2. Basic Solution of Thin-Layer Method (TLM)

TLM is a semianalytical method that is used to solve the wave propagation problems in the elastic media in this investigation. This basic solution is used as Green’s function and is incorporated into the BEM to use in soil-structure interaction problems. In this method, as shown in Figure 1, the foundation is discretized into several thin layers in the vertical direction \( z \) by means of the finite element method (FEM); moreover, the analytical method is used along the horizontal direction \( x \). It is to be noted that the discretization is only required to be performed at the interface between the media and the structure, which can reduce the quantity of calculation rapidly.

In practical applications, the case of a harmonic vertical excitation that is applied at the midpoint of the surface foot can be idealized according to the model shown in Figure 1.

The dynamic equilibrium differential equation for the elastic media in the cylindrical coordinate system can be expressed as follows:

\[
\begin{cases}
\frac{\partial \sigma_r}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \tau_{rz}}{\partial z} + \sigma_r - \sigma_\theta + f_r = \rho \frac{\partial^2 u_r}{\partial t^2}, \\
\frac{\partial \tau_{r\theta}}{\partial r} + \frac{1}{r} \frac{\partial \sigma_r}{\partial \theta} + \frac{\partial \sigma_\theta}{\partial z} + 2 \tau_{rz} + 2 f_\theta = \sigma_z = \rho \frac{\partial^2 u_\theta}{\partial t^2}, \\
\frac{\partial \tau_{rz}}{\partial r} + \frac{1}{r} \frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{\partial \sigma_z}{\partial z} + \tau_{rz} + f_z = \sigma_z = \rho \frac{\partial^2 u_z}{\partial t^2},
\end{cases}
\quad \text{(11)}
\]

where \( \sigma_r, \sigma_\theta, \sigma_z, \tau_{rz}, \tau_{r\theta}, \tau_{z\theta} \) and \( \tau_{rz} = \tau_{z\theta} \) are defined as the normal stress and shear stress components, respectively; \( u_r, u_\theta \) and \( u_z \) are the radial, tangential, and vertical displacement, respectively; \( f_r, f_\theta \) and \( f_z \) are the radial, tangential, and vertical physical forces, respectively.

The geometric equation in the cylindrical coordinate system can be expressed as follows:

\[
\begin{bmatrix}
\frac{h_0^1}{h_1^1} & h_2^1 & \cdots & h_{3N-2}^1 & h_{3N-1}^1 & h_{3N}^1 \\
\frac{h_0^2}{h_1^2} & h_2^2 & \cdots & h_{3N-2}^2 & h_{3N-1}^2 & h_{3N}^2 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
\frac{h_0^N}{h_1^N} & h_2^N & \cdots & h_{3N-2}^N & h_{3N-1}^N & h_{3N}^N
\end{bmatrix}
\begin{bmatrix}
u_1^1 \\
u_2^1 \\
\vdots \\
u_1^N \\
u_2^N \\
\vdots
\end{bmatrix}
= \begin{bmatrix}
g_{11}^1 & g_{12}^1 & \cdots & g_{13N-2}^1 & g_{13N-1}^1 & g_{13N}^1 \\
g_{21}^1 & g_{22}^1 & \cdots & g_{23N-2}^1 & g_{23N-1}^1 & g_{23N}^1 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
g_{11}^N & g_{12}^N & \cdots & g_{13N-2}^N & g_{13N-1}^N & g_{13N}^N \\
g_{21}^N & g_{22}^N & \cdots & g_{23N-2}^N & g_{23N-1}^N & g_{23N}^N \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
g_{31}^N & g_{32}^N & \cdots & g_{33N-2}^N & g_{33N-1}^N & g_{33N}^N
\end{bmatrix}
\begin{bmatrix}
t_1^1 \\
t_2^1 \\
\vdots \\
t_1^N \\
t_2^N \\
\vdots
\end{bmatrix}. \quad \text{(9)}
\]

where \( \varepsilon_r, \varepsilon_\theta, \varepsilon_z, \gamma_r, \gamma_{r\theta}, \gamma_{z\theta} \) and \( \gamma_{rz} \) are the normal strain and shear strain components, respectively, and \( \varepsilon_r \) is the volumetric strain.

The constitutive equation can be expressed as follows:

\[
\begin{align*}
\sigma_r &= \lambda \varepsilon_r + 2 \mu \varepsilon_r, \\
\sigma_\theta &= \lambda \varepsilon_\theta + 2 \mu \varepsilon_\theta, \\
\sigma_z &= \lambda \varepsilon_z + 2 \mu \varepsilon_z, \\
\tau_{rz} &= \mu \gamma_{rz}, \\
\tau_{r\theta} &= \mu \gamma_{r\theta}, \\
\tau_{z\theta} &= \mu \gamma_{z\theta},
\end{align*}
\quad \text{(13)}
\]

where \( \lambda \) and \( \mu \) are the Lame’ elastic constants of medium.

Considering the effect of soil damping on wave propagation, the complex Lame’ elastic constant is applied in this investigation, which can be expressed as \( \lambda = (1 + 2i\beta)\lambda \) and \( \mu_c = (1 + 2i\beta)\mu \), where \( \beta \) is the damping ratio of soil.

Substituting equations (12) and (13) into equation (11), the Navier–Cauchy equation can be obtained as follows:
The original elastic layered medium can be divided into \( N \) thin sublayers in the vertical direction by means of finite element discretization. The displacements of each point within a thin layer can be then obtained using a linear interpolation function method when the thickness of the thin layer is sufficiently small. The displacements \( u \) of each point in the \( n^{th} \) thin layer can be obtained as follows:

\[
\begin{align*}
\mu \left[ \nabla^2 u_r - \frac{1}{r} \left( \frac{2}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r} \right) \right] + (\lambda + \mu) \frac{\partial^2 u_\theta}{\partial r^2} + f_r &= \rho \frac{\partial^2 u_r}{\partial t^2}, \\
\mu \left[ \nabla^2 u_\theta - \frac{1}{r} \left( \frac{1}{r} \frac{\partial u_r}{\partial \theta} - \frac{2}{r} \frac{\partial u_\theta}{\partial \theta} \right) \right] + (\lambda + \mu) \frac{\partial^2 u_r}{\partial r^2} + f_\theta &= \rho \frac{\partial^2 u_\theta}{\partial t^2}, \\
\mu \nabla^2 u_z + (\lambda + \mu) \frac{\partial^2 u_z}{\partial z^2} + f_z &= \rho \frac{\partial^2 u_z}{\partial t^2},
\end{align*}
\]

where

\[
\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}.
\]

The boundary conditions of the \( n^{th} \) thin layer can be expressed as follows:

\[
\begin{align*}
T_{Sn} \big|_{z=z_n} &= F_{iun}, \\
T_{Sn} \big|_{z=z_{n+1}} &= F_{iun}.
\end{align*}
\]

where \( F_{iun} \) and \( F_{iun} \) are the external forces acting on the upper and lower surfaces of the \( n^{th} \) thin layer, respectively, and \( T_{Sn} \) is the stress acting on the surface of the \( n^{th} \) thin layer.

According to the weighted residual approach, substituting the displacement of the \( n^{th} \) thin layer into equations (14) and (17), the corresponding residual stress can be derived. Considering the work performed by these residual stresses on the possible displacements \( \delta^*_n \) which are considered as a reasonable set of displacements is weighted to zero in the whole region, then the following equation can be obtained. Considering the harmonic vibration \( (e^{-i\omega t}) \), the governing equations for the \( n^{th} \) thin layer in a matrix form can be expressed as

\[
\mathbf{P}_m = k\mathbf{U}_m,
\]

where \( P \) is the nodal force vector, \( U \) is the nodal displacement vector, the subscript \( m \) is the \( m^{th} \) term of the Fourier series decomposition, and \( K = k^2A - kB + C \), in which \( A, B, \) and \( C \) are the matrices determined by the material properties.

By solving the eigenvalue using equation (18), the relationship between the internal force and displacement in the frequency-wave-number domain in the elastic layered media can be obtained. Conducting the Fourier series decomposition on the given force \( p \) along the tangential coordinate \( \theta \) and using the Hankel transformation on the obtained equations along the radial coordinate \( r \), the displacement expression in the frequency-wave-number domain is then obtained. Finally, the displacement expressed in the Cartesian coordinates can be fulfilled by means of the inverse Hankel transformation and Fourier synthesis.

In the above TLM calculation, a solution of paraxial approximation is used as the infinite boundary at the bottom of the media to overcome the problem that TLM can only work in a finite depth.

### 2.2. Verification for BEM

The method for investigating the vibration isolation of the Duxseal material is 3D semi-analytical BEM combined with a TLM [6]. To test the performance of a 3D semianalytical BEM combined with TLM used in this investigation, we compared it with the closed solution of the classic Lamb’s problem obtained by Wang [9]. The problems of dynamic response induced by the vibration on the surface of a half-space model are collectively called Lamb’s problem. In the numerical calculation, the soil parameters and excitation force are presented as follows: density of soil: \( \rho_w = 1800 \text{ kg/m}^3 \), shear modulus of soil: \( G_w = 53 \text{ MPa} \), Poisson ratio of soil: \( \nu_w = 0.25 \), and excitation frequency: \( f_w = 16 \text{ Hz} \).

Figure 2 shows the comparison between the solution of the proposed 3D semianalytical BEM combined with TLM in this study and the exact solution of the method used by Wang. The vertical displacements of the ground at distances from 1 m to 18 m away from the vibration source solved by BEM agree well with those in ref. [9], about only a 1.8% difference, as shown in Figure 2. And the vertical displacements at distances from 19 m to 40 m away from the vibration source obtained by the proposed method are a little bit bigger than the exact solution of Wang, about a 5.3% difference, which maybe due to the differences of element discretization. The above comparison of two solutions convincingly validated the adopted 3D semianalytical BEM combined with TLM in this study.
As shown in Figure 3, Duxseal is a putty-like, brown to gray-green colored rubber mixture compound, which possesses high fire resistance and excellent corrosion resistance and damping ratio. Furthermore, the stability of Duxseal is good, it does not generate any polymerize or decompose reaction with water. Figure 4 presents the schematic of Duxseal used for vibration isolation in a layered elastic soil. As shown in Figure 4, a harmonic vertical excitation is applied on the midpoint of the surface foot that is considered as a rigid foundation without any mass and Duxseal is embedded in the layered elastic soil below the surface foot. Based on the 3D semianalytical BEM combined with TLM, the interface between the elastic soil and the foot, and the elastic soil and the Duxseal is discretely divided into nodes as shown in Figure 4. The dimensionless diameter, thickness, and embedded depth for Duxseal are, respectively, denoted as $B = b / \lambda_R$, $D = d / \lambda_R$, and $H = h / \lambda_R$, the dimensionless width for rigid foundation is denoted as $W = w / \lambda_R$, the dimensionless depth for the topsoil layer is denoted as $H_T = h_T / \lambda_R$, the dimensionless depth for the subsoil layer is denoted as $H_S = h_S / \lambda_R$, and the dimensionless distance away from the vibration source is denoted as $S = s / \lambda_R$, in which $\lambda_R$ (10 m) is the wavelength of the Rayleigh wave corresponding to the shear modulus of the topsoil layer. In this section, the vertical loading is 500 N, the frequency of excitation is 16 Hz, the dimensionless width of the rigid foundation is $W = 0.2$, the dimensionless depth for the topsoil layer is $H_T = 1$, and the dimensionless depth for the subsoil layer is $H_S = 5$. In addition, the dimensionless distance for calculation points on the ground surface is from 0.1 to 4 away from the vibration source, with an interval of 0.05. The detailed calculation parameters of soil and Duxseal which refer to the works of Pak et al. [8] and Chakrabortty and Popescu [10] are listed in Table 1.

To evaluate the isolation effectiveness of Duxseal, the amplitude attenuation ratio $A_R$ at a certain point was proposed by Woods [3]. This ratio is defined as the ratio of the displacement component of the ground vibration in the presence of Duxseal to that in the absence of Duxseal, which can be expressed as follows:

$$A_R = \frac{\text{displacement amplitude of ground surface with Duxseal}}{\text{displacement amplitude of ground surface without Duxseal}}.$$  \hspace{1cm} (19)

$A_R$ represents deamplification if it is $< 1$ and amplification if it is $> 1$. In addition, the amplitude attenuation ratio equal to 1 indicates that the barrier becomes completely ineffective in isolating the ground vibrations.
Table 1: Calculation parameters of soil and Duxseal.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Young's modulus (MPa)</th>
<th>Poisson's ratio</th>
<th>Damping ratio</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil</td>
<td>1800</td>
<td>140.98</td>
<td>0.33</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>Subsoil</td>
<td>1522</td>
<td>59.04</td>
<td>0.44</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>Duxseal</td>
<td>1650</td>
<td>8</td>
<td>0.46</td>
<td>0.18–0.0003 × (σ_mean/0.001)</td>
<td>—</td>
</tr>
</tbody>
</table>

σ_mean is the average effective stress. The relationship curves of G–σ_mean and D–σ_mean are provided by Pak et al. [8].

\[
\bar{A}_R = \frac{1}{A} \int A_R dA, \quad (20)
\]

where \(A\) is the isolation influenced area of the Duxseal material from the dimensionless distance 0.1 to 4 away from the vibration source.

In the same meaning, in this note, \(\bar{A}_R\) represents amplitude deamplification if it is <1 and amplitude amplification if it is >1 within the whole influenced area of the Duxseal material. Furthermore, the average amplitude attenuation ratio equal to 1 indicates that the isolating effectiveness of ground vibrations within the whole influenced area of the Duxseal material is 0.

3.1. Effect of the Diameter of Duxseal. Figure 5 depicts the variation curve of the average amplitude attenuation ratio of ground displacement at a dimensionless distance of 0.1–4 from the vibration source with diameter, with the thickness of Duxseal, \(D = 0.12\), and the embedded depth, \(H = 0.60\). It is noted that the changing dimensionless diameter, thickness, and embedded depth are based on the changing dimension of the model. As observed in Figure 5, Duxseal performed exceedingly well in screening ground vibrations as an active isolation barrier in the free field. The minimum value of the average amplitude attenuation ratio of ground displacement occurred at \(B = 1.2\), about 0.67. When \(0.5 < B \leq 1.2\), the average amplitude attenuation ratio is decreasing rapidly to the minimum value in a linear trend as the diameter of Duxseal increases. When \(B > 1.2\), the average amplitude attenuation ratio tends to increase in a relatively fluctuant form with the increase in the diameter.

Figure 6 shows the variation curves of the amplitude attenuation ratio \(A_R\) of ground displacement with the increasing distance away from the vibration source for different representative values of Duxseal diameters \(B = 0.5, 1.0, 1.2, 1.4,\) and 1.6. As observed in Figures 6(a) and 6(b), the variation of the amplitude attenuation ratios of radial displacement is more complicated with the increase in the distance away from the vibration source, while the variation of the amplitude attenuation ratios of vertical displacement is relatively stable. It is also found that the amplitude attenuation ratios of both radial and vertical displacements far from the vibration source are relatively lower than that near the vibration source. In addition, when the diameter of the embedded Duxseal is smaller \((B \leq 1)\) or bigger \((B \geq 1.6)\), the amplifications of vertical and, especially, radial displacements occurred at certain points at a distance of 0.1–4 from the vibration source (i.e., \(A_R > 1\)). Irregularity in the result of \(A_R\) occurred at Figure 6 attributes to the layered characteristic of the soil medium and the isolation barrier, Duxseal. When the incident wave induced by vertical excitation encounters the isolation barrier, Duxseal, embedded in the soil foundation, Duxseal acts as a secondary wave source, resulting in a shorter wavelength, which increases the attenuation of the wave propagation. Meanwhile, part of the elastic wave produces scattered wave and reflected wave due to the layered soil and Duxseal, resulting in the phenomenon of amplitude amplification of the ground displacement.

3.2. Effect of the Thickness of Duxseal. Figure 7 depicts the variation curve of the average amplitude attenuation ratio of ground displacement at dimensionless distances of 0.1–4 from the vibration source with thickness, with the diameter of Duxseal, \(B = 1.2\), and the embedded depth, \(H = 0.60\). As observed in Figure 7, the first valley value of the average amplitude attenuation ratio occurred at \(D = 0.14\) (about 0.66) and the second valley value of the average amplitude attenuation ratio occurred at \(D = 0.34\) (about 0.64). When the thickness is smaller \((D < 0.01)\), Duxseal causes amplitude amplification of ground displacement \((\bar{A}_R > 1)\). When \(0.01 < D \leq 0.14\), the average amplitude attenuation ratio of ground displacement is decreasing rapidly to the first valley value in a linear trend as the thickness increases. When \(D > 0.14\), the average amplitude attenuation ratio of ground displacement tends to increase in a relatively fluctuant form with the increase in the thickness.
Figure 8 shows the variation curves of the amplitude attenuation ratio \( AR \) of ground displacement with the increasing distance away from the vibration source for different representative values of Duxseal thicknesses \( D = 0.02, 0.08, 0.10, 0.12, 0.14, \) and 0.16. As observed in Figures 8(a) and 8(b), when the thickness of the embedded Duxseal is smaller \((D \leq 0.08)\), the amplifications of radial displacement occurred at certain points at distances of 0.1–4 from the vibration source \((i.e., AR > 1)\), while the amplitude attenuation ratios of vertical displacement are almost less than 1 at a distance of 0.1–4 from the vibration source.

3.3. Effect of the Embedded Depth of Duxseal. Figure 9 depicts the variation curve of the average amplitude attenuation ratio of ground displacement at a dimensionless distance of 0.1–4 from the vibration source with embedded depth, with the diameter of Duxseal, \( B = 1.2 \), and the thickness, \( D = 0.12 \). As observed in Figure 9, the minimum value of the average amplitude attenuation ratio occurred at \( H = 0.60 \) (about 0.67). When the embedded depth is smaller \((H < 0.24)\), Duxseal causes amplitude amplification of ground displacement \((AR > 1)\). This result may attribute to the poor rigidity of Duxseal. When \( 0.24 < H \leq 0.60 \), the average amplitude attenuation ratio of ground displacement is decreasing rapidly to the minimum value in a linear trend as the embedded depth increases. When \( H > 0.60 \), the average amplitude attenuation ratio of ground displacement increases rapidly with the increase of the embedded depth.

Figure 10 shows the variation curves of the amplitude attenuation ratio \( AR \) of ground displacement with the increasing distance away from vibration source for different representative values of embedded depths of Duxseal \( H = 0.45, 0.50, 0.55, 0.60, \) and 0.65. It can be noticed that the embedded depth is a critical factor for the vibration screening effectiveness of Duxseal, as a result of the poor rigidity of Duxseal. When the embedded depth of Duxseal is smaller \((H \leq 0.55)\), the amplifications of radial displacement occurred at certain points, especially at a distance of 2.2–2.7 from the vibration source \((i.e., AR > 1)\), while the amplitude attenuation ratios of vertical displacement are almost less than 1 at a distance of 0.1–4 from the vibration source.
4. Comparison with Wave Impeding Block (WIB)

For the purpose of comparatively exploring the vibration isolation effectiveness of Duxseal in the free field, the vibration screening effectiveness of the common isolation material, WIB, [12] as an active barrier in a layered elastic soil is considered. The excitation frequency is 16 Hz, and the other material parameters of the soil, WIB, and Duxseal that were required for the simulation are listed in Table 2.

Figure 11 presents the comparisons of the variation curves of the amplitude attenuation ratio $AR$ of the radial and vertical displacements between Duxseal and WIB at a dimensionless distance of 0.1–3 from the vibration source under the influence of a harmonic vertical excitation. It is observed that the curves of both Duxseal and WIB show the irregularities of $AR$. By comparing the results shown in Figure 11, we can obtain that the average amplitude attenuation ratio of ground displacement for WIB and Duxseal is 0.52 and 0.64, respectively. Therefore, the vibration isolation of Duxseal is marginally less than that of the WIB, at approximately 84% of the WIB, while the material use of Duxseal is apparently less than that of the WIB, i.e., approximately 60% of the dimensions of WIB. This finding shows the Duxseal is much more effective than the traditional WIB for isolating ground vibration. Additionally, it is also observed that $AR$ bounces upward when the distance away from the vibration source increases for the ground with the WIB isolation system. In contrast, the performance of Duxseal in isolating ground vibration is relatively stable along the distance away from the vibration source.
Figure 10: Variation curve of $A_R$ of ground displacement with distance for various Duxseal embedded depths: (a) radial displacement and (b) vertical displacement.

Table 2: Calculation parameters of soil, WIB, and Duxseal.

<table>
<thead>
<tr>
<th></th>
<th>Density (kg/m$^3$)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Damping ratio</th>
<th>Diameter</th>
<th>Thickness</th>
<th>Embedded depth</th>
</tr>
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<td>140.98</td>
<td>0.33</td>
<td>0.05</td>
<td>—</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Subsoil</td>
<td>1522</td>
<td>59.04</td>
<td>0.44</td>
<td>0.05</td>
<td>—</td>
<td>5</td>
<td>—</td>
</tr>
<tr>
<td>WIB</td>
<td>2400</td>
<td>18316.8</td>
<td>0.20</td>
<td>0.05</td>
<td>1</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Duxseal</td>
<td>1650</td>
<td>8</td>
<td>0.46</td>
<td>0.18–0.0003×($\sigma_{\text{mean}}$/$0.001$)</td>
<td>1</td>
<td>0.06</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 11: Comparison of $A_R$ of ground displacement between Duxseal and WIB: (a) radial displacement and (b) vertical displacement.
5. Conclusions

An active isolation barrier, Duxseal, was utilized to screen the vibrations caused by dynamic loads in the free field, based on its significant damping performance. The influence of width, thickness, and embedded depth of Duxseal on ground displacement was initially investigated using a 3D BEM. Subsequently, the isolation effectiveness of Duxseal in ground vibration is compared with traditional WIB. The principal conclusions are as follows:

(i) Duxseal can reduce dynamic responses such as ground displacement as an active isolation barrier when subjected to dynamic loads in the free field, owing to its high damping ratio. The vibration screening effectiveness of Duxseal increases with the increase in the values of width, thickness, and embedded depth of the Duxseal material within a certain range.

(ii) The embedded depth is a critical factor for the vibration screening of Duxseal. Considering its poor rigidity, it is recommended that the dimensionless embedded depth $H$ should be set to more than 0.25 to achieve isolation effectiveness.

(iii) Duxseal is much more effective than the traditional WIB for isolating ground vibration. Additionally, the performance of Duxseal in isolating ground vibration is relatively stable along the distance away from the vibration source, while $A_R$ bounces upward when the distance away from the vibration source increases for the ground with the WIB isolation system.

(iv) The isolation laws pertaining to the increasing distance from the vibration source for Duxseal and WIB demonstrated a complementary phenomenon. That is, the amplitude attenuation ratios of Duxseal at a distance far from the vibration source are relatively lower than that near the vibration source, while the amplitude attenuation ratios of WIB near the vibration source are relatively lower than that at a distance far from the vibration source. Based on its relationship, therefore, efforts will be directed towards the performance of a newly designed barrier, i.e., the basic WIB blocks are drilled with multiple cylindrical holes which are then packed with Duxseal, for isolating ground vibrations in the future study. In addition, the adaption and accordance of the results trend of Duxseal will be compared with other similar material in the future study.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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