Theoretical study on dynamic responses of an unlined circular tunnel subjected to blasting P-waves

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ABSTRACT

In conventional studies, the blasting seismic wave is always treated as a time-harmonic wave, which is not suitable in some situations due to its short duration. In this paper, the blasting P-wave is simplified as a triangular impulse. The distribution functions of dynamic stress concentration factor (DSCF) and the radial and hoop vibration velocity scaling factors (RVSF and HVSF) around the circular tunnel are derived based on the Fourier–Bessel expansion method. Then, the effects of the rising duration, the total duration and Poisson’s ratio on DSCF, RVSF and HVSF are discussed. Results show that (1) the maximum RVSF and HVSF are located at the incident side, and the location of the maximum DSCF will move from the incident side to the shadow side when the total duration increases; (2) the maximum DSCF increases with the increasing total duration, decreases with the increasing Poisson’s ratio, but is immune to the ratio of the rising to total duration; (3) the maximum RVSF decreases with the increase of the total duration and the ratio of the rising to total duration, but increases with the increasing Poisson’s ratio; (4) the maximum HVSF decreases with the increase of the total duration and the ratio of the rising to total duration, but is immune to Poisson’s ratio; (5) the RVSF and HVSF under triangular impulses gradually change from less than those under time-harmonic waves to greater than those under time-harmonic waves with the increasing total duration, but the DSCF shows the opposite trend.

KEYWORDS: dynamic response, blasting vibration, circular tunnel, triangular impulse

1. INTRODUCTION

In the past few decades, the drilling and blasting method was widely used in the construction of underground structures, such as metro tunnels and hydropower stations. These structures are always not far from existing underground tunnels, whose safety is significantly influenced by the blasting-induced vibration. As a consequence, the study on blasting dynamic responses of underground structures becomes increasingly critical to evaluate their safety.

In conventional theoretical studies, the blasting seismic wave is always treated as a time-harmonic plane P-, SV- or SH-wave. Under this assumption, the dynamic response of underground structures subjected to blasting seismic waves has been sufficiently studied. Pao and Mow \cite{1} and Yi et al. \cite{2} studied the dynamic stress concentration of lined and unlined circular tunnels subjected to plane P- and S-waves. Wang and Sudak \cite{3} studied the scattering of plane waves by multiple cylindrical cavities with imperfect interface. Liao et al. \cite{4} analyzed the responses of an elastic half-space with a buried tunnel subjected to obliquely incident waves. Yi et al. \cite{5} studied the peak particle velocity (PPV) threshold of the lining of a horseshoe-shaped tunnel subjected to plane P-waves. Manoogian and Lee \cite{6} studied the interaction of plane SH-waves and arbitrarily shaped inclusions by conformal transforms, and Wang et al. \cite{7} studied the scattering of plane waves by an arbitrarily shaped hole in porous medium by the similar means. Lee and Karl \cite{8,9} studied the ground displacement induced by the scattering of plane P- and SV-waves by underground cylindrical tunnels. Smerzini et al. \cite{10} studied the ground motions resulting from the diffraction of plane SH-waves by underground tunnels. Zhao and Qi \cite{11} studied the scattering of plane SH-wave from a debonded cylindrical elastic inclusion in half-space. Lin et al. \cite{12} studied the dynamic response of a circular underground tunnel in an elastic half-space under the incidence of plane P-waves. Qi et al. \cite{13,14} carried out the dynamic analysis for circular inclusion near interface impacted by SH-wave. Yi et al. \cite{15} studied the dynamic stress concentration factors (DSCFs) of circular lined tunnels with an imperfect interface subjected to cylindrical P-waves. Xu \cite{16} studied the dynamic stress and vibration velocities around a circular tunnel induced by plane P-waves in the background of Luxin coal mine. Lu et al. \cite{17,18} studied the dynamic stress concentration and the PPV response of a circular tunnel under the incidence of cylindrical P-waves in theory. Liu et al. \cite{19,20} studied the dynamic response of multiple holes and liquid-filled pipes subjected to blasting waves in theory. Fu et al. \cite{21} studied the soil–tunnel interactions under the incidence of plane SH-waves. In recent years, the experimental methods based on piezoceramic transducers were developed quickly, and they are always
used to study the response of underground structures [22–25]. Du et al. [26–28] studied the damage, crack detection and corrosion of pipelines by using piezoceramic transducers.

However, the duration of blasting seismic waves is quite short and the approximation of blasting seismic waves is not suitable in some situations. It is necessary to consider the characteristic of short duration of blasting waves when studying the dynamic response of structures subjected to blasting waves. However, the related research is not sufficient. Li et al. [29] studied the dynamic stress concentration and energy evolution of deep-buried tunnels under triangular blasting loads.

The blasting waves are usually simplified as time-harmonic plane waves in theory to study the dynamic responses of structures under blasting waves. In fact, the pressure–time curve of blasting waves is more suitable to be considered as a double-exponential curve or a triangle-shaped curve. In this paper, the blasting P-wave is simplified as a plane triangular impulse. Based on the Fourier–Bessel expansion method, the formulas for dynamic responses of a circular tunnel under a time-harmonic P-wave are derived. Then, the dynamic responses of a circular tunnel under a unit Heaviside step load are studied by the inverse Fourier transform and the formulas under the incidence of a triangular blasting wave are derived by the Duhamel integral. Finally, the effects of duration of the triangular impulse and Poisson’s ratio of surrounding rock on the DSCF, and the hoop and radial velocity scaling factors (HVSF and RVSF) are investigated. The main goal is to reveal the dynamic responses of a tunnel subjected to blasting waves under different factors, including the rising duration, the total duration of the triangular impulse and the Poisson’s ratio of surrounding rock.

### 2. INTERACTION OF BLASTING P-WAVES AND SURROUNDING ROCK

According to the Duhamel integral equation, the entire loading history can be considered to consist of a succession of short impulses, each producing its own differential response, and the total response of a linear elastic system can then be obtained by summing all the differential responses developed during the loading history. Therefore, if we want to obtain the response of a circular tunnel subjected to blasting waves, we should obtain the transient response produced by an impulse load or a Heaviside step function load at first. The transient response can be obtained by the inverse Fourier transform of the response produced by a time-harmonic wave. So, the responses produced by a time-harmonic wave, by a unit Heaviside step load and by a blasting wave should be studied successively.

#### 2.1 Dynamic responses of circular tunnel under time-harmonic incident P-waves

We suppose that a circular tunnel of radius  in an unbounded rock mass, whose axis is coincident with , as shown in Fig. 1. The potential function of the harmonic plane P-wave can be expressed in terms of the displacement potential as

\[
\varphi^{(i)}(t) = \varphi_0 e^{i(\alpha z - \omega t)},
\]

where \(\varphi_0\) is the amplitude of incident wave, \(\alpha\) is the wavenumber of P-waves and \(\alpha = \omega / C_P\), \(\omega\) is the circular frequency of incident wave, \(C_P\) is the wave speed of P-waves and \(i\) is the unit of complex number.

In terms of the Bessel function expansion method, the incident wave can be expanded as

\[
\varphi^{(i)}(t) = \sum_{n=0}^{\infty} A_{0n} J_n(\alpha r) \cos n\theta e^{-i\omega t},
\]

where \(A_{0n} = \epsilon_n P \varphi_{0n}, \epsilon_0 = 1\) and \(\epsilon_n = 2\) for \(n > 0\).

In general, when the incident P-wave arrives at the tunnel, two outward propagating reflected waves will be generated. They are the reflected P-wave (\(\varphi^{(r)}\)) and the reflected SV-wave (\(\psi^{(r)}\)). Both of them take the following forms:

\[
\varphi^{(r)}(t) = \sum_{n=0}^{\infty} A_n H_n^{(1)}(\alpha r) \cos n\theta e^{-i\omega t},
\]

\[
\psi^{(r)}(t) = \sum_{n=0}^{\infty} B_n H_n^{(1)}(\beta r) \sin n\theta e^{-i\omega t},
\]

where \(A_n\) and \(B_n\) are undetermined constants, \(H_n^{(1)}\) is the first kind of Hankel function in \(n\)th order, \(\beta = \omega / C_S\) and \(C_S\) is the wave speed of SV-waves.
Let \( \varphi = \varphi^{(l)} + \varphi^{(r)} \) and \( \psi = \psi^{(l)} \), then the relations between potentials, stresses and velocities can be expressed as

\[
\begin{align*}
\sigma_{rr} &= \lambda \nabla^2 \varphi + 2\mu \left( \frac{\partial^2 \varphi}{\partial r^2} + \frac{\partial^2 \varphi}{\partial \theta^2} \right), \\
\sigma_{\theta r} &= \lambda \nabla^2 \varphi + 2\mu \left( \frac{\partial \varphi}{\partial r} + \frac{1}{r} \frac{\partial \varphi}{\partial \theta} \right), \\
\sigma_{\theta \theta} &= \mu \left( 2 \left( \frac{\partial^2 \varphi}{\partial \theta^2} - \frac{1}{r} \frac{\partial \varphi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \varphi}{\partial r^2} \right), \\
v_r &= -i \omega \left( \frac{\partial \varphi}{\partial r} + \frac{1}{r} \frac{\partial \varphi}{\partial \theta} \right), \\
v_\theta &= -i \omega \left( \frac{\partial \psi}{\partial \theta} - \frac{1}{r} \frac{\partial \psi}{\partial r} \right),
\end{align*}
\]

where \( \lambda \) and \( \mu \) are Lame constants.

By substituting Eqs. (2)–(4) into Eq. (5) and considering the boundary conditions \( \sigma_{rr} \big|_{r=a} = 0 \) and \( \sigma_{\theta \theta} \big|_{r=a} = 0 \), we obtain the DSCF and velocity scaling factors at tunnel boundary as follows:

\[
\begin{align*}
\sigma_{\theta r}^* &= \frac{\sigma_{\theta r}}{\sigma_0} \bigg|_{r=a} = \frac{4}{\pi} \left( 1 - \frac{1}{\xi} \right) \sum_{n=0}^{\infty} \varepsilon_n \sin \frac{n \pi}{\alpha} \cos \eta \theta \ e^{-i \omega t}, \\
v_r^* &= \frac{v_r}{v_0} \bigg|_{r=a} = \frac{1}{\xi^2} \sum_{n=0}^{\infty} \varepsilon_n \sin \frac{n \pi}{\alpha} \cos \eta \theta \ e^{-i \omega t}, \\
v_\theta^* &= \frac{v_\theta}{v_0} \bigg|_{r=a} = \frac{1}{\xi^2} \sum_{n=0}^{\infty} \varepsilon_n \sin \frac{n \pi}{\alpha} \sin \eta \theta \ e^{-i \omega t},
\end{align*}
\]

where \( \xi = \sqrt{(1 - \nu)/(1 - 2\nu)} \), \( \sigma_0 = -\mu \xi^2 \varphi_0 \), and \( v_0 = \alpha \varphi_0 \).

\[
D_n = \left( n^2 - 1 \right) \kappa \alpha a H_{n-1} - \kappa \alpha a \right) - \left( n^2 - n - \frac{1}{2} \xi^2 a^2 \right) H_n - \kappa \alpha a H_{n-1},
\]

\[
M_n = \kappa \alpha a H_{n+1} - \kappa \alpha a H_{n-1}
\]

\[
N_n = n \left( (n + 1) H_n H_{n+1} - \kappa \alpha a H_{n-1} \right).
\]

2.3 Dynamic responses of circular tunnel under a blasting P-wave

For an arbitrary input \( P(\hat{t}) \), the response \( g(x, \hat{t}) \) of the system can be obtained by the Duhamel integral as

\[
g(x, \hat{t}) = \int_0^\hat{t} P(s) g_h(x, \hat{t} - s) \, ds.
\]

The blasting P-wave is always simplified as a triangular impulse with linear loading and unloading processes as shown in Fig. 2, which can be expressed as

\[
P(\hat{t}) = P_m f(\hat{t}) = \begin{cases} 
\frac{\hat{t}}{\tau_\text{r}} P_m, & 0 \leq \hat{t} < \hat{t}_\text{r}, \\
\frac{\hat{t}}{\tau_\text{s}} P_m, & \hat{t}_\text{r} \leq \hat{t} < \hat{t}_s, \\
0, & \hat{t}_s \leq \hat{t},
\end{cases}
\]

where \( P_m \) is the peak pressure of the blasting wave, and \( \hat{t}_r \) and \( \hat{t}_s \) are the rising and total durations, respectively.
Figure 3 Distributions of DSCF (a), RVSF (b) and HVSF (c) around the circular cylindrical tunnel for the case of $\nu = 0.25$.

\[
\tilde{d}_{\theta}(\hat{\tau}) = \frac{2P}{\pi} \left( \frac{\pi^2 - 1}{\pi^2} \right) \sum_{n=0}^{\infty} e_n e^{i\nu n \cos \theta} \quad 0 \leq \hat{\tau} \leq \hat{\eta}_1,
\]

\[
\times \left\{ \begin{array}{ll}
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_1}^{\hat{\eta}_0} \frac{e^{-i\nu \tilde{\tau}}}{\nu \tilde{\tau}} d\tilde{\tau}, & 0 \leq \tilde{\tau} \leq \tilde{\eta}_1, \\
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_0}^{\hat{\eta}_1} \frac{e^{-i\nu \tilde{\tau}} - e^{-i\nu \hat{\eta}_1}}{\nu \tilde{\tau} - \nu \hat{\eta}_1} d\tilde{\tau}, & \tilde{\eta}_1 \leq \tilde{\tau} \leq \tilde{\eta}_0, \\
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_0}^{\hat{\eta}_1} \frac{e^{-i\nu \tilde{\tau}} - e^{-i\nu \hat{\eta}_1}}{\nu \tilde{\tau} - \nu \hat{\eta}_1} d\tilde{\tau}, & \tilde{\eta}_0 \leq \tilde{\tau} \leq \tilde{\eta}_1.
\end{array} \right.
\]

\[
\tilde{v}_r(\hat{\tau}) = \frac{3D}{2\pi \rho c_r} \sum_{n=0}^{\infty} e_n e^{i\nu n \cos \theta} \quad 0 \leq \hat{\tau} \leq \hat{\eta}_1,
\]

\[
\times \left\{ \begin{array}{ll}
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_1}^{\hat{\eta}_0} \frac{e^{-i\nu \tilde{\tau}}}{\nu \tilde{\tau}} d\tilde{\tau}, & 0 \leq \tilde{\tau} \leq \tilde{\eta}_1, \\
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_0}^{\hat{\eta}_1} \frac{e^{-i\nu \tilde{\tau}} - e^{-i\nu \hat{\eta}_1}}{\nu \tilde{\tau} - \nu \hat{\eta}_1} d\tilde{\tau}, & \tilde{\eta}_1 \leq \tilde{\tau} \leq \tilde{\eta}_0, \\
\frac{e_n}{\pi c_r} \int_{\hat{\eta}_0}^{\hat{\eta}_1} \frac{e^{-i\nu \tilde{\tau}} - e^{-i\nu \hat{\eta}_1}}{\nu \tilde{\tau} - \nu \hat{\eta}_1} d\tilde{\tau}, & \tilde{\eta}_0 \leq \tilde{\tau} \leq \tilde{\eta}_1.
\end{array} \right.
\]

3. RESULTS AND DISCUSSION

The PPV is easy to be measured and has been an index to evaluate the vibration intensity and structural damage [30], which
has been one of the major concerns in the blasting field [31]. In fact, the dynamic stress is the most essential index. When the stress induced by external loadings exceeds the maximum that the structure can bear, the structure is considered to be damaged. Therefore, both the stress and the PPV responses of the tunnel should be considered. In order to obtain general results, some dimensionless parameters should be defined.

3.1 Definitions of dynamic stress concentration and velocity scaling factors

The DSCF is defined as follows:

\[
\text{DSCF} = \max \left\{ \left| \bar{\sigma}_{\theta \theta}(\hat{\tau}) / P_m \right| \right\}.
\]

The RVSF is defined as follows [14]:

\[
\text{RVSF} = \max \left\{ \left| \bar{v}_r(\hat{\tau}) / v_0 \right| \right\},
\]

where \( v_0 \) is the maximum vibration velocity of the incident wave in its propagating direction, and \( v_0 = P_m / \rho C_p \).

The HVSF is defined as follows:

\[
\text{HVSF} = \max \left\{ \left| \bar{v}_\theta(\hat{\tau}) / v_0 \right| \right\}.
\]

3.2 Parametric studies and discussion

The DSCF, RVSF and HVSF are relevant to the total duration \( \hat{\tau}_s \), the rising duration \( \hat{\tau}_r \) and Poisson’s ratio \( \nu \). As a consequence, the influence of \( \hat{\tau}_s \), \( \nu \) and \( \hat{\tau}_r / \hat{\tau}_s \) on the DSCF, RVSF and HVSF is investigated.

The distributions of DSCF, RVSF and HVSF around the tunnel under different \( \hat{\tau}_s \) are shown in Fig. 3, where \( \nu = 0.25 \). It can be observed from Fig. 3 that the distributions of DSCF, RVSF and HVSF at the tunnel boundary are similar under different \( \hat{\tau}_s \). There are two same peak values of DSCF occurring at about \( \theta = \pi / 2 \) and \( \theta = 3\pi / 2 \) due to the symmetry. However, the RVSF at \( \theta = \pi \) is obviously larger than that at other locations. The locations of the maximum HVSF are at the incidence side. It can also be observed that the DSCF, RVSF and HVSF all increase with the increasing \( \hat{\tau}_s \), but the DSCF changes most apparently.

The variations of DSCF, RVSF and HVSF at different locations with the change of \( \hat{\tau}_s \) are shown in Fig. 4. It can be found from Fig. 4a that the DSCF increases with the increasing \( \hat{\tau}_s \), except that at \( \theta = 0 \). The DSCFs at \( \theta = \pi / 3 \) and \( \pi / 2 \) increase rapidly when \( \hat{\tau}_s < 0.1\pi \), which suggests that the DSCFs at the two locations are greatly affected by \( \hat{\tau}_s \). When \( \hat{\tau}_s \geq 0.1\pi \), the increasing rates of DSCF at \( \theta = \pi / 3 \) and \( \pi / 2 \) gradually decrease. The DSCFs at \( \theta = \pi / 3 \), \( \pi / 2 \) and \( 2\pi / 3 \) are obviously larger than those at other locations. It can be seen from Fig. 4b that the RVSFs at \( \theta = 0 \), \( \pi / 6 \) and \( \pi / 3 \) increase with \( \hat{\tau}_s \), increasing first and then tend to constant values, which is contrary to that at \( \theta = \pi / 2 \). The RVSFs at \( \theta = 2\pi / 3 \), \( 5\pi / 6 \) and \( \pi \) decrease linearly with the increasing \( \hat{\tau}_s \). It can be seen from Fig. 4c that the variation of HVSF with the change of \( \hat{\tau}_s \) is not apparent, which indicates that HVSF is immune to \( \hat{\tau}_s \).

The distributions of DSCF, RVSF and HVSF around the circular tunnel under different \( \nu \) are shown in Fig. 5. The rising and total durations of the triangular impulse are chosen as \( \hat{\tau}_s = 2\pi \) and \( \hat{\tau}_s = 10\pi \), respectively. It can be observed from Fig. 5a that there are two peak values of DSCF occurring at about \( \theta = \pi / 2 \) and \( \theta = 3\pi / 2 \) when \( \nu = 0.3 \) and \( \nu = 0.4 \), but there are four peak values when \( \nu = 0.1 \) and \( \nu = 0.2 \), which suggests that \( \nu \) exerts a significant influence on DSCF. It can be observed from Fig. 5b that two peak values of RVSF occur at \( \theta = 0 \) and \( \theta = \pi \), and the maximum RVSF appears at \( \theta = \pi \). The distribution of RVSF is similar under different \( \nu \). However, the value is basically identical...
Figure 6 Variations of DSCF (a), RVSF (b) and HVSF (c) with $v$ when $\hat{\tau}_r = 2\pi$ and $\hat{\tau}_s = 10\pi$.

Figure 7 Distributions of DSCF (a), RVSF (b) and HVSF (c) around the circular tunnel for the case of $\hat{\tau}_r = 10\pi$ and $v = 0.25$.
of DSCF are nearly identical, which suggests that DSCF is little affected by $\hat{\tau}_r / \hat{\tau}_s$. Figure 7b and c shows that the distributions of RVSF and HVSF at the shadow side are also basically identical, but they change obviously at the incident side.

The variations of DSCF, RVSF and HVSF with $\hat{\tau}_r / \hat{\tau}_s$ at different locations are shown in Fig. 8. Figure 8a shows that the DSCF at different locations changes little. Figure 8b and c shows that only the RVSF and HVSF at $\theta = \pi / 2, 2\pi / 3$ and $5\pi / 6$ decrease quickly when $\hat{\tau}_r / \hat{\tau}_s$ is $< 0.3$ and then change little with $\hat{\tau}_r / \hat{\tau}_s$.

The variations of DSCF, RVSF and HVSF indicate that only the RVSF and HVSF at the incident side are influenced by $\hat{\tau}_r / \hat{\tau}_s$, and the DSCF is immune to $\hat{\tau}_r / \hat{\tau}_s$.

3.3 Comparison study of dynamic responses

In order to compare the dynamic responses of a tunnel under time-harmonic wave and triangular impulse wave, the variations of DSCF, RVSF and HVSF of the circular tunnel subjected to the two blasting waves with different $\nu$ and $\hat{\tau}_s$ are investigated.
3.3.1 Comparison of dynamic responses under different durations

When the Poisson’s ratio of the surrounding rock remains unchanged, the variations of DSCF, RVSF and HVSF around the circular tunnel subjected to the time-harmonic wave and triangular impulse wave with $\tau_s$ are shown in Figs 9–11. The Poisson’s ratio of the surrounding rock is set as 0.25.

It can be seen that when the total duration of blasting wave is short (such as $\tau_s = 0.5\pi$ and $\tau_s = \pi$), the RVSF and HVSF of the tunnel under the time-harmonic wave are larger than those under the triangular impulse wave. With the increasing total duration (e.g. $\tau_s = 10\pi$), the RVSF and HVSF of the tunnel under the triangular impulse wave are larger than those under the time-harmonic wave. The DSCF shows the opposite trend.
3.3.2 Comparison of dynamic responses under different Poisson's ratios

When the total duration $\tau_s$ of blasting waves remained unchanged, the variations of DSCF, RVSF and HVSF around the circular tunnel under the time-harmonic wave and triangular impulse wave with various Poisson's ratios are shown in Figs 12–14. The total duration $\tau_s$ of blasting waves is set as $10\pi$.

It can be found that the DSCF and HVSF of the tunnel under the time-harmonic wave are basically the same as those under the triangular impulse wave when the Poisson’s ratio increases, which suggests that the DSCF and HVSF of the tunnel obtained...
from the time-harmonic wave and triangular impulse wave are little influenced by the Poisson's ratio. The RVSF of the tunnel subjected to the triangular impulse wave is larger than that subjected to the time-harmonic wave under different Poisson's ratios. The difference between the RVSF obtained from the time-harmonic wave and triangular impulse wave increases with the increasing Poisson's ratio. This indicates that the time-harmonic wave has an amplification effect on the RVSF of the tunnel compared with the triangular impulse wave, and the amplification effect increases with the increasing Poisson's ratio of surrounding rock.

4. CONCLUSIONS

The following conclusions can be made from the above results:

(1) The formulas of DSCF, RVSF and HVSF are derived based on the Bessel–Fourier expansion and the Duhamel integral.

(2) The locations of the maximum DSCF are different from those of the maximum RVSF and HVSF. The maximum RVSF and HVSF are located at the incident side, and the location of the maximum DSCF will move from the incident side to the shadow side when the total duration increases.

(3) The maximum DSCF increases with the increasing total duration of the incident triangular impulse, but the maximum RVSF and HVSF decrease.

(4) The maximum DSCF decreases with the increasing Poisson's ratio, the maximum RVSF increases and the maximum HVSF is immune.

(5) Only the RVSF and HVSF at the incident side are obviously influenced by the ratio of the rising to total duration, but the DSCF is immune.

(6) The RVSF and HVSF under triangular impulses gradually change from less than those under time-harmonic waves to greater than those under time-harmonic waves with the increasing total duration, but the DSCF shows the opposite trend.

(7) The time-harmonic wave has an increasing amplification effect on the RVSF with the increasing Poisson’s ratio, but the DSCF and HVSF are immune.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

REFERENCES

1. Pao YH, Mow CC. The Diffraction of Elastic Waves and Dynamic Stress Concentrations. New York: Crane, Russak & Company, Inc., 1973.

2. Yi C, Lu W, Zhang P, Johansson D, Nyberg U. Effect of imperfect interface on the dynamic response of a circular lined tunnel impacted by plane P-waves. Tunnelling and Underground Space Technology 2016; 51:68–74.

3. Wang X, Sudak L. Scattering of elastic waves by multiple elastic circular cylinders with imperfect interface. Waves in Random and Complex Media 2007; 17:159–187.
4. Liao W, Yeh CS, Teng TJ. Scattering of elastic waves by a buried tunnel under obliquely incident waves using T matrix. *Journal of Mechanics* 2008;24(4):405–418.

5. Yi C, Lu W, Zhang J, Zhang A. Study on critical failure vibration velocity of arch with vertical wall lining subjected to blasting vibration. *Rock and Soil Mechanics* 2008;29:2203–2208.

6. Manoogian ME, Lee W. Diffraction of SH-waves by subsurface inclusions of arbitrary shape. *Journal of Engineering Mechanics* 1996;122:123–129.

7. Wang JH, Lu JF, Zhou XL. Complex variable function method for the scattering of plane waves by an arbitrary hole in a porous medium. *European Journal of Mechanics, A: Solids* 2009;28:582–590.

8. Lee VW, Karl J. Diffraction of SV waves by underground, circular, cylindrical cavities. *Soil Dynamics and Earthquake Engineering* 1992;11:445–456.

9. Lee VW, Karl J. On deformation near a circular underground cavity subjected to incident plane P waves. *European Journal of Earthquake Engineering* 1993;7:29–35.

10. Smerzini C, Aviles J, Paolucci R, Sánchez-Sesma F. Effect of underground cavities on surface earthquake ground motion under SH wave propagation. *Earthquake Engineering & Structural Dynamics* 2009;38:1441–1460.

11. Zhao JX, Qi H. Scattering of plane SH-wave from a partially debonded shallow cylindrical elastic inclusion. *Journal of Mechanics* 2009;25(4):411–419.

12. Lin CH, Lee VW, Todorovska MI, Trifunac MD. Zero-stress, cylindrical wave functions around a circular underground tunnel in a flat, elastic half-space: incident P-waves. *Soil Dynamics and Earthquake Engineering* 2010;30:879–894.

13. Qi H, Yang J, Shi Y, Tian JY. Dynamic analysis for circular inclusion near interfacial crack impacted by SH-wave in half space. *Journal of Mechanics* 2012;28(1):143–151.

14. Qi H, Yang J, Shi Y. Scattering of SH-wave by cylindrical inclusion near interface in bi-material half-space. *Journal of Mechanics* 2011;27(1):37–45.

15. Yi C, Zhang P, Johansson D, Nyberg U. Dynamic response of a circular lined tunnel with an imperfect interface subjected to cylindrical P-waves. *Computers and Geotechnics* 2014;55:165–171.

16. Xu T. Blasting vibration safety criterion of surrounding rock of a circular tunnel. *Geotechnical and Geophysical Engineering* 2019;37:3077–3084.

17. Lu S, Zhou C, Zhang Z, Jiang N. Dynamic stress concentration of surrounding rock of a circular tunnel subjected to blasting cylindrical P-waves. *Geotechnical and Geophysical Engineering* 2019;37:2363–2371.

18. Lu S, Zhou C, Zhang Z, Jiang N. Particle velocity response of surrounding rock of a circular tunnel subjected to cylindrical P-waves. *Tunnelling and Underground Space Technology* 2019;83:393–400.

19. Liu Y, Geng M, Xu B, Li J. Dynamic response of multiple holes in half saturated space impacted by seismic waves. *Chinese Journal of Geotechnical Engineering* 2013;35:399–405.

20. Liu Y, Qiao L, Xu B. Dynamic response of liquid-filled pipe embedded in saturated soil due to P waves. *Rock & Soil Mechanics* 2013;34:3151–3158.

21. Fu J, Liang J, Du J. Analytical solution of dynamic soil–tunnel interaction for incident plane SH wave. *Chinese Journal of Geotechnical Engineering* 2016;38:588–598.

22. Zhang J, Huang Y, Chen Y, Du G, Zhou L. Numerical and experimental study on seismic behavior of concrete-filled T-section steel tubular columns and steel beam planar frames. *Journal of Central South University* 2018;25:1774–1785.

23. Zhang J, Huang Y, Zheng A. Feasibility study on timber damage detection using piezoceramic-transducer-enabled active sensing. *Sensors* 2018;18:1563.

24. Zhang J, Li Y, Zheng Y, Wang Z. Seismic damage investigation of spatial frames with steel beams connected to L-shaped concrete-filled steel tubular (CFST) columns. *Applied Sciences* 2018;8:1713.

25. Zhang J, Zhang C, Xiao J, Jiang J. A PZT-based electromechanical impedance method in monitoring the soil freeze–thaw process. *Sensors* 2019;19:1107.

26. Du G, Huo L, Kong Q, Song G. Damage detection of pipeline multiple cracks using piezoceramic transducers. *Journal of Vibration Engineering* 2016;18:2828–2838.

27. Du G, Kong Q, Wu F, Ruan J, Song G. An experimental feasibility study of pipeline corrosion pit detection using a piezoceramic time reversal mirror. *Smart Materials & Structures* 2016;25:037002.

28. Du G, Kong Q, Zhou H, Gu H. Multiple cracks detection in pipeline using damage index matrix based on piezoceramic transducer-enabled stress wave propagation. *Sensors* 2017;17:1–11.

29. Li X, Li C, Cao W, Tao M. Dynamic stress concentration and energy evolution of deep-buried tunnels under blasting loads. *International Journal of Rock Mechanics and Mining Sciences* 2018;104:131–146.

30. Liang Q, An Y, Zhao L, Li D, Yan L. Comparative study on calculation methods of blasting vibration velocity. *Rock Mechanics & Rock Engineering* 2011;44(1):93–101.

31. Yang J, Lu W, Li P, Yan P. Evaluation of rock vibration generated in blasting excavation of deep-buried tunnels. *KSCE Journal of Civil Engineering* 2017;22(7):2593–2608.