Energy and Vibration Absorption Characteristics of Damping Holes under Explosion Dynamic Loading

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ABSTRACT: There are usually many buildings near the subway. In tunnel construction, the vibration caused by explosion affects the structure of buildings. The vibration and energy absorption characteristics of damping holes caused by tunnel blasting are investigated under explosion dynamic loading, experimentally and numerically. This paper, taking Yan’an Third Road Station as a case, verified the effectiveness of the damping hole on the vibration reduction of the ground building based on the simulation and experiment. Furthermore, the article examines the effect of distance between the damping hole and charging holes, diameters of the damping hole, and material of the medium on the damping performance. The results show that an increase in diameter improves the energy and vibration absorption performances of the damping hole better than a decrease in distance. In addition, damping performance in gas and liquid medium is better than that in solid medium. The optimum scheme for vibration and energy absorption under extreme conditions of tunnel blasting is to arrange an 80 mm damping hole above the charging holes, and the distance between the damping hole and the center axle wire of the two charging holes is 0.2 m. By using this scheme, the vibration and energy absorption characteristics of damping holes are better than that of other scheme: the damping efficiency is the highest, which is 10.83%, and the pressure-relief efficiency is 10.48%. Furthermore, the medium materials of the damping hole are preferably air or water. Finally, the tunnel excavation contour line is smooth by applying this method. It is concluded that if the damping system is developed with proper design guidelines, then it may reduce the transmission of energy and vibration with effective protection of ground buildings.

1. INTRODUCTION

With the acceleration of urban modernization, the subway has become the preferred mode of urban transportation. Although mechanical excavation has been greatly improved, drilling and blasting are still the most effective and economical method of excavation in tunnels.1 Tunnel excavation technology is the key to construction, especially tunnel blasting under special geological conditions.2 There are usually many structures near the subway. During the tunnel excavation, the vibration waves generated by the explosion propagate to the ground through rocks, which will have an impact on the structure of a building. Sometimes, structures suffer damage because of high ground vibration.

In this field, because of the high risk and cost, it is difficult to achieve the test in civil research. However, some researchers (Kutter et al.4) determined the dynamic response of the tunnel based on reduced centrifugal model techniques. They found that centrifugation is an effective method to simulate the effects of rock and soil explosions.

Recently, numerical techniques have been used, and they represent a good alternative to provide valuable information in a timely and cost-effective manner. Wang and Lu5 created a numerical three-phase soil model that is able to simulate an explosion wave propagation into soils. Lu et al.6 and Wang et al.7 utilized this model to study the response of buried structures subjected to underground explosions. Benselama et al.8 studied shock waves caused by explosions in typical constrained geometry by three-dimensional simulation. Ren et al.9 simulated the blasting dynamic loading intensity by a LS-DYNA dynamic finite element and proved that the vibration velocity, displacement, and plastic strain of slope obtained by this method could reflect the dynamic response objectively.

The structures around the tunnel include underground adjacent structures and structures above the ground. Meanwhile,
scholars have made a lot of research studies on blasting vibration control. For example, Lai et al.\textsuperscript{10} monitored the blasting vibration by a wireless sensor network and evaluated the impact of new tunnel blasting on the existing tunnel structure by concrete strain and peak particle velocity. Wang et al.\textsuperscript{11} analyzed the lining structures of existing tunnels affected by blasting seismic waves by field monitoring and calculation. Chu et al.\textsuperscript{12} put forward a blasting-vibration safety standard for fresh concrete by experiments based on the effects of damage accumulation. Taking the small-distance tunnel as the research object, Song et al.\textsuperscript{13} designed and developed a large-scale three-dimensional tunnel excavation simulation test system and analyzed the influence of blasting vibration on the stability of sandwiched rocks. Taking a highway tunnel in Shanghai as an example, Yu et al.\textsuperscript{14} evaluated the effects of blasting vibration on existing tunnels by the finite element software ABAQUS. Shin et al.\textsuperscript{15} identified the effect of blast-induced vibration on the immediately adjacent tunnels and put forward a preliminary guideline for evaluating the protection zone for the blast vibration. For the case of the Jinping-II diversion tunnel, Yang et al.\textsuperscript{16} studied the blasting vibration characteristics under high in situ stress conditions by numerical simulation and finally determined that at least 24.0 m of secondary shotcrete should be constructed behind the working face to avoid the vibration-induced failure.

On the other hand, scholars have also studied the impact of new tunnel excavation on ground structures. For example, Ozer\textsuperscript{17} established an empirical relationship between the scale distance and the peak particle velocity for Istanbul Kadikoy-Karta and evaluated the particle velocity and frequency to predict the extent of the impact on a building structure. Based on Huolang-yu tunnel of Mixing road, Gao et al.\textsuperscript{18} proved that the vibration control of wedge cutting hole blasting is the key to reduce or eliminate shallow tunnel vibrating calamity. Amari et al.\textsuperscript{19} ensured the stability of the slope above the tunnel by controlling the vibration by tunnel excavation. Yilmaz et al.\textsuperscript{20} studied the effect of blasting vibration of Ordu-Mesudiye highway tunnel on an inclined penstock pipe (PP) of 35—400 slopping of Topçam Hydro-Electrical Power Plant (HEPP). Taking Beijing Metro Line 16 as an example, Jiang et al.\textsuperscript{21} established a mathematical model of the peak particle velocity (PPV) of the surface soil with the blasting depth of the tunnel by monitoring the blasting vibration on site and analyzed the response characteristic of the buried gas pipeline under the explosion vibration. Xia et al.\textsuperscript{22} adopted the parallel cut blasting method to ensure the safety of the DN1200 buried water supply pipeline under the blasting vibration influenced by subway tunnel excavation based on the Ling-Qing section of Tsingtao Metro Line 3. Jiang and Zhou\textsuperscript{23} established the relationship of dynamic stresses and PPVs of tunnel structures under the different blasting conditions and determined the safety criteria of PPV according to the maximum tensile strength theory and numerical calculation results. Zhang and Hu\textsuperscript{24} took the partial excavation method to protect ground buildings. Guan et al.\textsuperscript{25} studied the vibration velocity, main frequency, and safety evaluation methods by analyzing ground vibration data for shallow and deep buried tunnels.

Meanwhile, some scholars have continuously proposed vibration reduction schemes. For example, Song et al.\textsuperscript{26} combined traditional blasting technology with precutting technology to develop a vibration reduction method and studied the feasibility of this method by three-dimensional finite element analysis. Tian et al.\textsuperscript{27} used MATLAB to analyze the propagation law of blasting vibration of a super-large section shallow tunnel in the stratum and proposed a blasting damping scheme. Lee et al.\textsuperscript{28} made the blind end of the tunnel produce discontinuity around the central blasting area to reduce propagation due to vibration by a wire saw cutting method. Park and Jeon\textsuperscript{29} proposed an air-deck method for reducing blast-induced vibration in the direction of tunneling. Through people’s response to the vibration of the tunnel, Kuzu and Guçu\textsuperscript{30} practiced an optimization of the blast duration with an appropriate time sequencing based on PPV monitoring at experimental blasts of full-face and half-face blasting rounds. Navarro Torres et al.\textsuperscript{31} processed the collected data with multiple regression techniques to obtain the blasting vibration attenuation law to predict the levels of blasting-induced taken for the locality, and the blasting vibration is controlled by reducing the maximum blasting charge. The simulation results show that taking a bond can control the vibration better. Taking the diversion tunnel blasting of a hydropower station as an example, Liu et al.\textsuperscript{32} and Huang et al.\textsuperscript{33} put forward an effective control technology for blasting vibration by adjusting the construction method.

Experimentally and theoretically, the scholars have analyzed and calculated the blasting process from some views, such as tunnel diameter, the conditions of surrounding rocks, etc. They found out the regularity and conclusions about the vibration velocity and proposed measures to reduce vibration. But, there are few studies on the performance of the damping hole under the effect of multiple factors. In this paper, the blasting process in view of the peripheral holes will be analyzed and the effect of damping holes under different conditions will be studied.

2. ANALYSIS OF THE DAMPING MECHANISM

The mechanism of the damping hole is analyzed from the two perspectives, the minimum burden and the energy propagation.

2.1. Minimum Burden. According to the principle of rock blasting,\textsuperscript{34} seismic waves will propagate in the direction of the minimum burden. Setting the damping hole means creating a new free surface for the two charging holes. As shown in Figure 1, the ground is denoted as No.1 free surface and the damping hole is denoted as No.2 free surface. The vertical distance between the charging hole and No.1 free surface is $L_1$, and the vertical distance between the charging hole and No.2 free surface is $L_2$. Since $L_2$ is less than $L_1$, No.2 free surface is the nearest free surface to the charging hole. So, the minimum burden is the minimum distance between the charging hole and damping hole.
After the charging hole explodes, part of the detonation energy will be released to the direction of the damping hole, that is, the direction of the minimum burden. Therefore, the vibration can be reduced by releasing part of energy from the charging hole to damping hole.

### 2.2. Energy Propagation

Further analysis revealed that when the explosion pressure is generated by the charging hole, it will be introduced into the damping hole, as shown in Figure 2a. The explosion pressure makes the wall of the charging hole extrude outside. The pressure, which acts on the wall of the charging hole, makes the rock between two damping holes pull to the opposite direction, as shown in Figure 2b. Because of the low tensile strength, the rock between two damping holes breaks and creates crevices, as shown in Figure 2c. A damping crack is formed at the inside of damping holes, as shown in Figure 2d. Therefore, the free surface area will increase.

According to the principle of rock blasting, the rock would break and move to the free surface after blasting. So, increasing the area of free surface can significantly improve the blasting effect and reduce the blasting vibration. With an increase in the area of free surface, peak vibration velocity of a particle would reduce during blasting. With the main frequency increasing, the peak energy decreases, the proportion of low frequency energy to total energy would reduce, and its duration would become shorter. Based on the above principles, it is known that the more the free surface is, the lower the damage performance of blasting vibration is. When there is no free surface nearby, the explosion energy of the charging hole spreads evenly outward, as shown in Figure 3a. When the damping crack is formed, more energy spreads into the damping crack, and then less energy spreads toward the ground, as shown in Figure 3b.

Obviously, the damping crack creates much more free surfaces, so the damping hole decreases the pressure and reduces the vibration.
3. RESULTS AND DISCUSSION

Most urban subway tunnels are shallow buried tunnels. In order to analyze the effect of blasting vibrations on the ground buildings above the shallow buried tunnel, the distance between the ground and the charging holes is shortened on the basis of the verification model. Furthermore, the effect of the position and diameter of the damping hole on the damping performance is further studied. The new model remains constant except that the distance between the charging holes and the ground becomes 2 m. The monitoring points are shown in Figure 4. As can be seen from Figure 4, the vibration velocities of the monitoring points 2#, 3#, and 4# are the same as those of the monitoring points 5#, 6#, and 7#. So, only the monitoring points 1#, 2#, 3#, and 4# are analyzed.

3.1. Effect of Distance on the Damping Performance.

To study the effect of distance on the damping performance, the damping holes are arranged at different distances to the center axle wire of the two charging holes, as shown in Figure 5. Since the upper space of the charging holes is limited, only one set of damping holes can be arranged above the charging holes, and the other damping holes are all arranged below the charging holes.

![Figure 4. Monitoring point location of simulation.](image)

3.1.1. Peak Vibration Velocity. Explosion vibration velocity of the ground building can be obtained by numerical simulation. When the damping hole is arranged at a distance of +0.2 m, the vibration velocity of a ground monitoring point as a function of time is shown in Figure 6. As can be seen from Figure 6, the peak vibration velocity reaches the maximum velocity at the beginning of the explosion and it gradually decreases with an increase in time. This is because the explosive energy transfers into the rock after the explosion, and the energy transfers in the form of vibration waves. The vibration wave gradually decays with time, and then the vibration velocity decreases. Figure 6 illustrates that the maximum peak vibration velocities of points 1#, 2#, and 3# appear at a time of 0.05−0.06 s. But, the maximum peak vibration velocity of 4# monitoring point appears at a time of 0.24 s. The maximum peak vibration velocities of points 1#, 2#, 3#, and 4# are 154, 128.99, 90.31, and 88.58 cm/s, respectively. Also, the maximum peak vibration velocity of points 1# and 2# is larger than that of points 3# and 4#.

According to the above function, the maximum peak vibration velocity of the ground under the action of the damping hole at different distances is obtained. The maximum peak vibration velocity as a function of distance to the axle wire is shown in Figure 7. Figure 7 illustrates that the maximum peak vibration velocity along the axle wire is varied with distance.

To accurately analyze the effect of the damping hole, the concept of damping efficiency is introduced. Damping efficiency is the ratio of the vibration velocity of the same point with and without the damping hole. Damping efficiency of each measuring point can be calculated by eq 1, which varies with the location of the damping hole, as shown in Table 1.

\[ \eta = \frac{V - V'}{V} \times 100\% \]  

(1)

At a distance of +0.2 m, the maximum explosion peak vibration velocity is lowest in the enclosure. When the damping hole is arranged away from the ground, the vibration velocities decrease with an increase in distance. The damping efficiency also increases with an increase in distance, but most of them vary from 2% to 3%. When the damping hole is arranged toward the ground, the vibration velocities decrease greatly, and the damping efficiency increases by 5%−6%. It can be seen that when the damping hole is arranged a distance of +0.2 m, the damping performance is excellent.

3.1.2. Peak Pressure. When the damping hole is arranged at a distance of +0.2 m, the dynamic pressure of the ground monitoring point as a function of time is shown in Figure 8. Figure 8 illustrates that the maximum peak pressure appears at a time of 0.116−0.120 s. As can be seen from Figure 8, the pressure fluctuates up and down on both sides. The pressure fluctuation ranges from ~39 to 44 MPa. In comparison, the maximum peak pressure of point 2# is the largest among the other four measuring points. Therefore, this law applies to selecting the other maximum peak pressure.

The maximum peak explosion pressure as a function of distance to the axle wire is shown in Figure 9. At a distance of ~0.9 m, the maximum peak pressure is the highest. At a distance of +0.2 m, the maximum peak pressure is the lowest, which is 43 MPa. Compared with the model without the damping hole, the ground pressure of the model with the damping hole is reduced to different extents. It is proven that the damping hole can relieve the pressure, and adjusting the position of the damping hole has an effect on the damping performance.

![Figure 5. Damping hole layout at different distances.](image)
Pressure-relief efficiency of each measuring point can be calculated by eq 2, which varies with the location of the damping hole, as shown in Table 2.

\[
\tau = \frac{p - p_i}{p} \times 100\%
\]  

(2)

When the damping hole is arranged away from the ground, the pressure reduces less. But, when the damping hole is arranged toward the ground, the pressure reduces more, and the pressure-relief efficiency of four measuring points are 6.29%, 5.53%, 5.54%, and 10.29%. This shows that when the damping hole is arranged toward the ground, more explosion pressure will enter into the damping hole, and the pressure-relief efficiency is greatly improved, which is similar to the results of explosion vibration velocity.
3.2. Effect of Diameter on the Damping Performance.

In order to understand the effect of the diameter of the damping hole on the damping performance, the models are established by changing the diameter of the damping hole. The distance of the damping hole is +0.2 m. Then, the optimal damping scheme is further studied only by changing the diameter of the damping hole. The diameters of the damping hole are 20, 40, 50, 60, and 80 mm. Due to the complicated construction factors on the site and the limited blasting working face area, the maximum diameter of the damping hole is 80 mm.

3.2.1. Peak Vibration Velocity. Explosion vibration velocity of the ground building can be obtained by numerical simulation. When the diameter of the damping hole is 80 mm, four monitoring points were taken from the ground to measure the vibration velocities. The vibration velocity of the 80 mm damping hole as a function of time is obtained, as shown in Figure 10. Figure 10 illustrates that the peak vibration velocity reaches the maximum value at the beginning of the explosion and it gradually decreases with an increase in time. The peak vibration velocities of points 1# and 2# have reached the maximum value at a time of 0.059 s, while the velocities of points 3# and 4# have reached the maximum value at a time of 0.189 s. Also, the maximum vibration velocity of 1# monitoring point is 144.25 cm/s, which is larger than the vibration velocities of the other three monitoring points. Therefore, the vibration velocity of 1# monitoring point needs to receive more attention.

According to the above function, the maximum peak vibration velocity of the ground building under the action of the damping hole of different diameters is obtained. The maximum peak vibration velocity as a function of the diameter of the damping hole is shown in Figure 11. Figure 11 illustrates that the peak vibration velocity of 1# monitoring point needs to receive more attention.

Table 2. Pressure-Relief Efficiency at Different Distances to the Axle Wire

| monitoring point | distance to the axle wire (m) | −0.9 | −0.7 | −0.5 | −0.2 | 0 | 0.2 |
|------------------|-------------------------------|-----|-----|-----|-----|---|-----|
| 1#               | 0.19%                         | 2.13% | 2.63% | 4.36% | 5.10% | 6.29% |
| 2#               | 0.11%                         | 0.91% | 2.18% | 2.72% | 3.21% | 5.53% |
| 3#               | 0.38%                         | 0.99% | 2.11% | 2.69% | 3.03% | 5.54% |
| 4#               | 0.43%                         | 1.44% | 3.34% | 4.42% | 5.12% | 10.29% |

Figure 9. Peak dynamic pressure versus distance to the axle wire.

Figure 10. Vibration velocity at a diameter of 80 mm versus time.

Figure 11. Peak vibration velocity versus the diameter of the damping hole.
vibration velocity is varied with the diameter of the damping hole. At a diameter of 20 mm, the explosion peak vibration velocity is larger than the other velocities of different-diameter damping holes in the enclosure. At a diameter of 80 mm, the maximum peak vibration velocity is the lowest in the enclosure. When the diameter of the damping hole is between 20 and 60 mm, the maximum peak vibration velocities of all measuring points decrease linearly with an increase in diameter. When the diameter reaches 60 mm, the peak vibration velocity of points 1# and 2# still decreases linearly. Similarly, the peak vibration velocity of points 1# and 2# decreases but only slightly. The vibration velocity decreases as the diameter of the damping hole increases, and the damping efficiency also increases up to 10%. When the diameter is 80 mm, the damping efficiency is 10%, and the vibration velocity is greatly reduced. It can be seen that when the diameter of damping hole is 80 mm, the damping effect is excellent.

Damping efficiency of each measuring point can be calculated by eq 12, which varies with the diameter of the damping hole, as shown in Table 3.

Table 3. Damping Efficiency at the Different Diameters of the Damping Hole

| monitoring point | diameter of the damping hole (mm) | 20  | 40  | 50  | 60  | 80  |
|------------------|----------------------------------|-----|-----|-----|-----|-----|
| 1#               | 1.90%                            | 4.81%| 6.53%| 8.02%| 10.83%|
| 2#               | 2.54%                            | 5.09%| 6.67%| 7.95%| 10.99%|
| 3#               | 3.25%                            | 3.83%| 7.15%| 10.05%| 10.55%|
| 4#               | 0.10%                            | 0.36%| 3.84%| 6.87%| 8.13%|

3.2.2. Peak Pressure. The dynamic pressure of the 80 mm-diameter damping hole as a function of time is shown in Figure 12. Figure 12 illustrates that the pressure of points 1# and 2# appears at a time of 0.117 s. The maximum peak pressure of points 3# and 4# appears at times of 0.239 and 0.594 s, respectively. The maximum peak pressure of point 1# is the negative pressure, while the maximum peak pressures of points 2#, 3#, and point 4# are the positive pressure. In comparison, the maximum peak pressure of point 2# is the largest.

The maximum peak explosion pressure as a function of the diameter of the damping hole is shown in Figure 13. At a diameter of 20 mm, the maximum peak pressure is higher than other pressure. At a diameter of 80 mm, the maximum peak pressure is the lowest, which is 41.25 MPa. Compared with the model without the damping hole, the ground pressure of the model with the damping hole is reduced to different extents. It is proven that the damping hole can relieve the pressure, and adjusting the diameter of the damping hole has an effect on the damping performance. Point 1# is the monitoring point of the maximum pressure. From the pressure peak curve of point 1#, it is known that when the diameter of the damping hole increases from 40 to 60 mm, the pressure reduces from 43.18 to 41.82 MPa.

Pressure-relief efficiency can be calculated by eq 13, which varies with the diameter of the damping hole, as shown in Table 4.

When the diameter of the damping hole increases from 40 to 60 mm, the pressure-relief efficiency increases from 6.29% to 9.24%. When the diameter increases from 60 to 80 mm, the pressure-relief efficiency is increased from 9.24% to 10.48%. This shows that when the diameter increases from 60 to 80 mm, the pressure-relief is not remarkable. This is consistent with the vibration law.

3.3. Effect of Filling Materials on the Damping Performance. Seismic waves propagate differently in different media, and the filtration of different media is also different. It is important to study the effect of the medium on the damping performance. The distance of the damping hole is +0.2 m, and the diameter is 80 mm. Then, the optimal damping scheme is further studied only by changing the filling material of the
The filling material of the damping hole is soil, water, and air.

3.3.1. Peak Vibration Velocity. Seismic waves produced by explosion in rocks include transverse waves and longitudinal waves. According to the propagation theory of seismic waves in medium, the transverse wave causes shear deformation of medium, which has the characteristics of long period and large amplitude. Because the shear modulus of the fluid is zero, the shear wave only exists in the solid medium, and there is no transverse wave in the fluid medium. Therefore, the transverse wave generated by explosion could not propagate in the air medium and aqueous medium. As shown in Figure 14, the vibration velocities of the model with soil medium damping holes are much larger than those of the model with aqueous medium and air medium damping holes, while the vibration velocities of the model with aqueous medium damping holes are similar to those of the model with air medium damping holes.

It can be known that damping performance in solid medium is worse than that in gas and liquid medium. Also, water has the function of dust fall and smoke absorption. In the field, the aqueous medium damping hole can be used to reduce vibration and dust.

3.3.2. Peak Pressure. The maximum peak explosion pressure as a function of the filling material of the damping hole is shown in Figure 15. When the medium of the damping hole is soil, the maximum peak pressure is higher than other pressure. But, when the medium of the damping hole is air, the maximum peak pressure is the lowest. It can be seen that aqueous medium and air medium damping holes also have better pressure-relief performance.

4. CONCLUSIONS

By using a damping hole, the vibration produced by two adjacent peripheral charging holes would be controlled. The damping performance of the damping hole under the coupling effect of multifactors was analyzed. According to the accounts by the numerical simulation and experiment, the following conclusions are drawn:

(1) Using a damping hole could control the vibration produced by two adjacent peripheral charging holes during the blasting. The maximum vibration velocity was reduced from 0.375 to 0.249 cm/s by simulation. Also, the velocity was reduced from 0.349 to 0.221 cm/s by experiments. Meanwhile, overbreak—underbreak had diminished. It is proven that this method is effective and practical.

(2) When the damping hole is arranged at a distance of +0.2 m from the center axle wire of the two charging holes, it formed the best control performance on vibration compared with the other distance. In this scheme, the damping efficiency of four monitoring points can reach 4.89%, 5.09%, 5.92%, and 3.73%. The pressure-relief efficiency can reach 6.29%, 5.53%, 5.54%, and 10.29%.

(3) When the diameter of the damping hole is 80 mm, it formed the best control performance on vibration compared with the other diameter. In this scheme, the damping efficiency of four monitoring points can reach 8.13%, 10.83%, 10.99%, and 13.23%. The pressure-relief efficiency can reach 10.48%, 13.23%, 17.16%, and 20.83%.

(4) Damping performance in gas and liquid media is better than that in solid medium.

Therefore, using this damping scheme as a natural “shock absorber” is an energy-saving vibration control method. It effectively protects the structure of ground buildings. It has significant economic and environmental benefits.

5. MODELS

5.1. Mathematical Models. A finite element computational code for explosion dynamics, suitable for tunnel blasting and vibration hazard problems, was adopted to calculate the explosive propagation in rocks. The code solves Navier—Stokes partial differential equations numerically by means of the finite volume formulation. The explosion process of emulsion...
dynamite was expressed by the following governing equations using the Cartesian tensor notation.

The mass conservation equation described by Lagrange is

$$\rho(X, t)J(X, t) = \rho_0(X)$$  \hspace{1cm} (3)

The momentum conservation equation is

$$D\rho_{\mathbf{x}}(x, t)dt \int_V \rho v(x, t) dV = \int_V \rho b(x, t) dV + \int_A t(x, t) dA$$ \hspace{1cm} (4)

The differential equation for the object motion in the current configuration is

$$\rho(Dv_i/Dt) = \rho b_i - \partial\rho/\partial x_j = 0$$ \hspace{1cm} (5)

The differential equation for the object motion in the initial configuration is

$$\rho_0\rho_0/\partial t = \rho_0 b_i + \sum_a \partial/\partial x_j = 0$$ \hspace{1cm} (6)

The equation of conservation of energy is

$$D\rho_{\mathbf{x}}(x, t)dt \int_V \left(\rho \dot{\omega} + 1/2 \rho v^2\right) dV = \int_V \rho v \dot{\omega} dV + \int_A \rho v^2 dA$$ \hspace{1cm} (7)

\[\text{Table 5. Emulsion Explosive Performance Parameters}\]

| Material          | $\rho$ (kg·m$^{-3}$) | $D$ (m·s$^{-1}$) | $P_{\infty}$ (GPa) | $A$   | $B$  | $R_1$ | $R_2$ | $\omega$ | $E_{\text{em}}$ (GPa) |
|-------------------|----------------------|-----------------|---------------------|-------|------|-------|-------|---------|---------------------|
| Emulsion explosive | 1150                 | 3500            | 4.2                 | 214.4 | 0.182| 4.2   | 0.9   | 0.152   | 4.192               |

\[\text{Table 6. Physical and Mechanical Parameters of Rock}\]

| Material       | Density (kg·cm$^{-3}$) | Elastic Modulus (GPa) | Shear Modulus (GPa) | Poisson’s ratio | Tensile Strength (MPa) | Internal Friction Angle |
|----------------|-------------------------|------------------------|---------------------|------------------|------------------------|------------------------|
| Rock           | 2580                    | 5.99                   | 2.5                 | 0.20             | 1.2                    | 37°                    |

\[\text{Table 7. Physical and EOS Parameters of Air}\]

| Material       | $\rho$ (kg·m$^{-3}$) | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $V_0$ | $E_{\text{air}}$ (MPa) |
|----------------|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|------------------------|
| Air            | 1.29                 | 0     | 0     | 0     | 0     | 0     | 0     | 1     | 0.25             |

**Figure 16.** Layout of the damping hole diagram.

**Figure 17.** Blasting model 1 of two adjacent peripheral charging holes without a damping hole.

where in eqs 3–7, $\rho_0$ is the density of the initial configuration; $\rho$ is the density of the current configuration; $X = X_0 + \mathbf{E}$, where $X$ is the vector component of the particle $X$ in the reference configuration and $\mathbf{E}$ is the base vector of the Cartesian

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**Table 8. Physical Parameters of Soil**

| Material       | $\rho$ (kg·m$^{-3}$) | $a_0$ | $a_1$ | $a_2$ | $G$  | $K_s$ | $P_{\text{max}}$ (MPa) |
|----------------|----------------------|-------|-------|-------|------|-------|------------------------|
| Soil           | 1255                 | 0     | 0     | 0.8702 | 1.7240 | 5.5160 | 0                      |

**Table 9. Sandy Soil Triaxial Hydrostatic Compression Data**

| True volumetric strain (0.05) | 0.1 | 0.15 | 0.2 | 0.25 | 0.3 | 0.33 |
|-------------------------------|-----|------|-----|------|-----|------|
| Pressure (MPa)                | 0.02| 0.05 | 0.07| 0.12 | 0.2 | 0.34 | 0.5     |

**Table 10. Physical and EOS Parameters of Water**

| Material | $\rho$ (kg·m$^{-3}$) | $C$  | $S_1$  | $S_2$  | $S_3$  | $\gamma$ | $A$  | $E$  |
|----------|----------------------|------|--------|--------|--------|----------|------|------|
| Water    | 998.2                | 1480 | 2.56   | −1.986 | 0.227  | 0.5      | 0.47 | 0    |
coordinate system; $t$ is the time coordinate; $J$ is the Jacobin determinant, where $J = \frac{dV}{dV_0} = \rho_0 / \rho$, when the medium is incompressible ($J = 1$); $V$ is the volume of the current configuration; $x$ is the space coordinate; $v_i$ is the instantaneous velocity at $t$ time; $b_i$ is the force acting on the unit mass of the object; $t_i$ is the surface force; $i$ and $j$ are the coordinate directions; $A$ is the panel element of the configuration; and $\sigma_{ji}$, called Euler stress tensor is the stress acting on the per unit area of the current configuration. In eqs 4 and 5, $\omega_{int}$ is the unit mass internal energy; $\sum_{ji}$ is the Piola–Kirchhoff stress, and its expression is

$$\sum_{ji} = \sum_{i} \frac{\partial \chi_j}{\partial x_i} \sigma_{ji}$$  \hspace{1cm} (8)

where $\chi_j$ is the space coordinate.

**5.2. Material Models.** Emulsion explosive was used as the explosive material. Their parameters are shown in Table 5. The parameters of the wall rock material are shown in Table 6.

The flow behaviors of gas products after explosion will lead to the change in pressure and volume. JWL (Jones–Wilkins–Lee) state equation is used to describe the relationship between pressure, volume, and internal energy after the detonation Chapman–Jouguet state. JWL state equation is as follows.\(^{37}\)

$$P = A \left[ 1 + \frac{\omega}{R_1 V} \right]^{-R_2 V} + B \left( 1 - \frac{\omega}{R_3 V} \right)^{-R_4 V} + \frac{\omega E_{int}}{U}$$ \hspace{1cm} (9)

where $P$ is the pressure (GPa); $E$ is the initial specific internal energy (GPa); $U$ is the relative volume of detonation products; and $A$, $B$, $R_1$, $R_2$, and $\omega$ are the explosive parameters. The parameters of emulsion explosive in the simulation are shown in Table 5.

The air is modeled as (MAT_Null)\(^{37}\) with a linear polynomial equation of state (EOS), and it is as follows.

$$p = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_5 \mu + C_6 \mu^2) E_{int}$$ \hspace{1cm} (10)

where $P$ is the pressure on the air (GPa); $C_0$, $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, and $C_6$ are constants; $E_{int}$ is the initial internal energy per volume; and $\mu = \rho / \rho_0 - 1$, where $\rho$ is the current density of air and $\rho_0$ is the initial density. The linear polynomial equation denotes an ideal gas with the gamma law EOS, where $C_0 = C_1 =
$C_2 = C_3 = C_6 = 0$ and $C_4 = C_5 = \gamma - 1$. Therefore, the pressure can be written as

$$p = (1 - \gamma) \frac{\rho E_{\text{air}}}{\rho_0}$$  \hspace{1cm} (11)$$

where $\gamma$ is the adiabatic constant for air behaving as an ideal gas and equal to 1.4. The parameters of air in the simulation are shown in Table 7.

The soil is modeled as (MAT_soil_and_foam), which is considered to be a simple model that works in some ways like a fluid. The parameters of soil are shown in Tables 8 and 9.

Equation of state for water (Table 10) is as follows.

$$P = \frac{\rho_0 C^2}{1 - \left(S_1 - 1\right)\mu - \frac{S_2}{S_3 + 1}} - \frac{\rho_2}{S_3 + 1}$$  \hspace{1cm} (12)$$
where $P$ is the pressure on the water (GPa); $\gamma_0$ is the Grüneisen coefficient; $\alpha$ and $\gamma_0$ are the first-order volume correction; $C$, $S_1$, $S_2$, and $S_3$ are the material constants; $E$ is the initial internal energy; and $\mu = \rho / \rho_0 - 1$, where $\rho$ is the current density of water and $\rho_0$ is the initial density.

According to the Sdovsk algorithm (eq 13), if the other conditions are unchanged, the shorter the distance to the protected objects is, the larger the vibration disturbance is. Because the marked charging holes are located on the top of the tunnel contour line as shown in Figure 16, the distance between the marked charging holes and the protected objects is the shortest. In order to simplify the operation, the models with two peripheral charging holes at the top of the tunnel were built in this paper.

$$v = \frac{K}{R^\alpha} \times Q^{\mu/3}$$

where $v$ is the safety vibration velocity of the protected object (cm/s); $R$ is the distance between the explosive source and the protected object (m); $Q$ is the maximum amount of charge amount per delay interval (kg); and $K$ and $\alpha$ are the coefficient and attenuation index related to the geological and topographical conditions, respectively.

In this paper, two models for tunnel working face with and without the damping hole are built by LS-DYNA simulation software. Since the shape of blasting working face has no effect on blasting vibration, two rectangular models with holes are built. The peripheral hole is the charging hole. Model 1 (Figure 17) is the peripheral hole working face model without the damping hole, and model 2 (Figure 18) is the peripheral hole working face model with the damping hole.

In order to simplify calculation of the model, some basic assumptions were made: (1) There is no other volumetric heat source in the roadway except the heat source of the chemical reaction. (2) The simulated wall rock is adiabatic and smooth. (3) The wall rock is not moving, and the thickness is not considered. The top boundary of the model is fixed boundary, and the bottom is a nonreflecting free boundary. Also, the other side edges are defined as a nonreflecting boundary to reduce the influence of the boundary reflection wave under a dynamic load.

5.3. Validation of the Method. 5.3.1. Simulation. The model used for verification is 1 m (long), 1 m (wide), and 7 m
There are two charging holes with 1 m deep and 0.6 m spacing at a distance of 0.5 m from the bottom in models 1 and 2. Also, the charging holes were detonated at the same initiation time. In addition, model 2 was arranged with a 0.5 m-deep damping hole. The damping hole is located at the center of the two charging holes. Distance from the damping hole to the connection center of two charging holes is 0.2 m.

As shown in Figure 19, the monitoring points are selected on the center line at the ground surface along the axis direction of the charging hole. Distances from monitoring points to the center vertical surface of the charging hole are 0, 0.1, 0.2, 0.3, 0.4, and 0.5 m.

The maximum peak vibration velocities of two models were obtained. The change in the maximum peak vibration velocity with distance is shown in Figure 20.

Figure 20 shows that with an increase in distance, most of the peak velocities decrease continuously. This shows that when the excavation distance is 0–0.4 m, the peak vibration velocity curve experiences a descending process. When the distance is 0.5 m, the peak vibration slightly rises. But, it is much lower than the peak vibration velocity at 0 m. So, the maximum vibration velocity is at an excavation distance of 0 m (center vertical surface of the charging hole). In model 1, the maximum peak vibration velocity is 0.375 cm/s. In model 2, the maximum peak vibration velocity is 0.358 cm/s. The vibration velocity of model 2 is reduced by 2.26% compared with model 1.

The pressures of the two models were obtained by LS-PREPOST software, and they are shown in Figures 21 and 22. The pressure between the two charging holes increases first and then decreases radially outward. Also, the pressure waves propagate through rocks to the ground. As can be seen from Figures 21 and 22, compared with model 1, the pressure of areas I, II, and III in model 2 is significantly reduced. Especially when $t = 270$ ms, the pressure of zone 1 in model 2 is lower than that in model 1, that is, less pressure spreads toward the ground. It is proven that the damping hole can release the explosion pressure between the two charging holes.

5.3.2. Experiments. There is an arched subway station to be excavated, as shown in Figure 23. Ground buildings are densely distributed in the construction area of the station. No.166 building located on the west side of the station is the key building to be protected. It is a seven-story (partly six-story) brick and concrete structure with poor anti-seismic performance. The upper excavation working face on the main station is 7.8 m wide and 3.9 m high, and its area is 18.7 m². The bedrock in this area is mostly coarse-grained granite. Also, the rock grade is IV–V.

To determine whether the simulation results accord well with the practical ones and the vibration reduction is obvious, the blasting effects with and without the damping hole were compared by experiments. This experiment followed the principle of a single variable. As shown in Figure 24, for scheme 1, the peripheral hole was set in a traditional way along with the tunnel outline. The distance of two holes is 0.6 m. The depth of the hole is 1.1 m. The interpolation angle is 3°. The charge mass is 0.2 kg. Also, the initiation time of every two charging holes is the same. As shown in Figure 24, scheme 2 is the vibration reduction design program. On the basis of scheme 1, it was arranged with a 0.5 m-deep damping hole in scheme 2. The distance from the damping hole to the center of two charging holes is 0.2 m.

Vibration data could be acquired using a TC-4850 vibration measurer, as shown in Figure 25. The instrument is placed near No.166 building. The horizontal distance between the monitoring point and the blast is 7.35 m. The vibration velocities generated by the charging holes in schemes 1 and 2 were measured and analyzed. As shown in Figure 24, the number of delay detonators in the charging holes is 6–9, and delay times are 150–310 ms. The vibration velocity could be obtained by the blasting vibration analysis software.

The maximum vibration velocity was reduced from 0.375 to 0.358 cm/s by simulation. Also, the velocity was reduced from 0.349 to 0.221 cm/s by experiments. It can be seen that both the simulation and the experiment can confirm that the damping hole can release the explosion pressure between the two charging holes. Especially when $t = 270$ ms, the pressure of zone 1 in model 2 is lower than that in model 1, that is, less pressure spreads toward the ground. It is proven that the damping hole can release the explosion pressure between the two charging holes.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS
The authors wish to express thanks to the National Natural Science Foundation of China (grant no. 10672091).

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