Propagation Characteristics of Medium-length Hole Blasting Air Wave in Mining Tunnel

Chuanbo Zhou
Professor, Faculty of Engineering, China University of Geosciences, Wuhan
cbzhou@cug.edu.cn

Nan Jiang*
Ph.D, Faculty of Engineering, China University of Geosciences, Wuhan
happyjohn@foxmail.com; tel: +8618164055091
*corresponding author

Wen Ping
Master student, Faculty of Engineering, China University of Geosciences, Wuhan
pingwen312@126.com

Ru He
Master student, Faculty of Engineering, China University of Geosciences, Wuhan
hr19901231@163.com

ABSTRACT

On the basis of reviewing the previous studies on empirical formulas of blasting air wave attenuation law, we solved the blasting air wave overpressures combining with the reality of the Daye iron ore mining project in China. Simultaneously, a model of medium-length holes blasting in mining tunnel was established, and the blasting air wave propagation characteristics were calculated by the finite element software LS-DYNA. The overpressure attenuation law formula is fitted in numerical simulation results. The comparative analysis of numerical simulation results with previous solving results with empirical formulas shows that the previous empirical formulas cannot fit propagation characteristics of medium-length hole blasting air wave in mining tunnel.

KEYWORDS: mining tunnel; medium-length hole; blasting air wave; overpressure; numerical simulation.

INTRODUCTION

Due to the efficiency of medium-length hole blasting mining method, many mines in the world have adopted it. The blasting air wave overpressure load may threaten the safety of operating personnel and equipment in mining operations process. In order to ensure the safety of
underground mining operations, analysis of propagation characteristics of medium-length hole blasting air wave in mining tunnel has an important practical significance.

Many scholars have conducted extensive research in the blasting air wave attenuation law (Wang, 2010; Haque, 2009; Wakabayashi, 2007), but more concentrated on blasting air wave propagation in the open air (Mori, 2004; Gel'fand, 2004; Lu, 2003; Brode, 1955; Li, 1992; Sadovskii, 1952; Henrych, 1979). The researches of blasting air wave’s propagation law in tunnel are relatively scarce and mainly adopt the numerical simulation methods (Chandra, 2012; Yang, 2003; Xiao, 2012). R. Rodriguez (2010), adopting Phonometric curve, predicted the air wave due to blasting inside tunnels. However, due to the charge structure of the mining blasting and form of the explosion, the blasting air wave propagation has a new feature.

In this paper, based on the reality of the Daye iron ore mining project in China, the blasting air wave overpressures are solved referring to the previous studies on empirical formulas of blasting air wave attenuation law. Simultaneously, the overpressures are calculated by the finite element software LS-DYNA. The numerical simulation results have been comparatively analyzed with the results which are adopting previous empirical formulas.

**EMPIRICAL FORMULAS OF BLASTING AIR WAVE OVERPRESSURE ATTENUATION LAW**

According to the laws of mass conservation, momentum conservation, energy conservation and the Hugoniot equation, the propagation law of blasting air wave in an ideal medium is distinct. However, there is not an actual blasting project in an infinite space. Some scholars propose the empirical formulas of blasting air wave overpressure for propagating in a limited air medium.

(a) The empirical formula proposed by H. L. Brode (Brode, 1955) is as follows:

\[
\Delta P = 0.975\left(\frac{\sqrt{W}}{r}\right) + 1.445\left(\frac{\sqrt{W}}{r}\right)^2 + 5.85\left(\frac{\sqrt{W}}{r}\right)^3 - 0.019
\]

where \(\Delta P\) is the maximum air overpressure (10^5Pa), \(W\) is explosion charge (kg), \(r\) is distance from the blasting point to the measurement point (m).

(b) The empirical formulas provided by the National Defense Engineering Design Specifications (NDEDS) in China are as follows (Li, 1992):

\[
\Delta P = 0.84\left(\frac{\sqrt{W}}{r}\right) + 2.7\left(\frac{\sqrt{W}}{r}\right)^2 + 7\left(\frac{\sqrt{W}}{r}\right)^3
\]
where $H$ is distance from the blasting point to the ground, and the other parameters are same as equation (1). When $\frac{H}{\sqrt{W}} \geq 0.35$ and $1 \leq \frac{r}{\sqrt{W}} \leq 15$, the equation (2) is applicable.

When explosives detonate on the ground, the formula is as follows:

$$\Delta P = 1.06\left(\frac{\sqrt{W}}{r}\right) + 4.3\left(\frac{\sqrt{W}}{r}\right)^2 + 14\left(\frac{\sqrt{W}}{r}\right)^3$$  \hspace{1cm} (3)

where $\frac{H}{\sqrt{W}} \leq 0.35$ and $1 \leq \frac{r}{\sqrt{W}} \leq 15$ must be met.

(c) The empirical formula proposed by M.A. Sadovskyi is as follows (Sadovskii, 1952):

$$\Delta P = 0.95\left(\frac{\sqrt{W}}{r}\right) + 3.9\left(\frac{\sqrt{W}}{r}\right)^2 + 13\left(\frac{\sqrt{W}}{r}\right)^3$$  \hspace{1cm} (4)

where all parameters are same as equation (1).

(d) The empirical formulas proposed by Henrych (1979) is as follows:

$$\Delta P = 14.0717\left(\frac{\sqrt{W}}{r}\right) + 5.5397\left(\frac{\sqrt{W}}{r}\right)^2 - 0.3572\left(\frac{\sqrt{W}}{r}\right)^3 + 0.00625\left(\frac{\sqrt{W}}{r}\right)^4$$  \hspace{1cm} (5)

where $0.05 \leq \frac{r}{\sqrt{W}} \leq 0.3$ must be met;

$$\Delta P = 6.1938\left(\frac{\sqrt{W}}{r}\right) - 0.326\left(\frac{\sqrt{W}}{r}\right)^2 + 2.1324\left(\frac{\sqrt{W}}{r}\right)^3$$  \hspace{1cm} (6)

where $0.3 \leq \frac{r}{\sqrt{W}} \leq 1$ must be met;

$$\Delta P = 0.662\left(\frac{\sqrt{W}}{r}\right) + 4.05\left(\frac{\sqrt{W}}{r}\right)^2 + 3.288\left(\frac{\sqrt{W}}{r}\right)^3$$  \hspace{1cm} (7)

where $1 \leq \frac{r}{\sqrt{W}} \leq 10$ must be met. All the parameters in the equation (5), (6) and (7) are same with equation (1).

The above formulas are about blasting air wave propagating in an open space. There are many blasting projects in the trenches and tunnels. Due to the space in tunnels is confined, the blasting air wave overpressure propagation attenuation law has a great variation. Yang and Xiao provide the empirical formulas of blasting overpressure in tunnels, which are as follows:
\[ \Delta P = 1.692 \left( \frac{W}{rS} \right)^{1/3} + 0.269 \left( \frac{W}{rS} \right)^{2/3} + 2031 \frac{W}{rS} \]  

\[ \Delta P = 14 \left( \frac{W}{rS} \right)^{0.846} \left( \frac{D'}{W^{1/3}} \right)^{0.563} \]  

where \( S \) is the cross-sectional area of tunnel, \( D' \) is equivalent diameter of the cross-section, and the other parameters are same as equation (1).

**GENERAL INFORMATION OF THE DAYE IRON ORE MINING PROJECT**

Daye Iron Mine is located in Huangshi City, Hubei Province, China. It was founded in 1890, and was mined underground from open pit in 2003. The mine adopts sublevel pillarless caving underground mining method. Its stage is 60 m high and the segmentation is 12 m height. The distance between mining tunnels is 10m. The shape of mining tunnel’s cross-section is three centers arch. It is 3.6 m wide, 3 m height, and its area is 10.22 m². The mining adopts medium-length hole blasting method. The holes are distributed fanned, their row spacing is 1.6m, the distance between hole bottoms is 2.5m, nine holes in each row, and the hole diameter is 80 mm. The cross-section of mining tunnel is shown in Figure 1.

![Cross-section of mining tunnel](image)

**Figure 1:** Cross-section of mining tunnel  
1- mullocks, 2-blast holes, 3-ores, 4-mining tunnel

**NUMERICAL MODELING**

No.34 mining tunnel at -84 m level is selected as the simulate area. The blasting air wave propagation characteristics are calculated by LS-DYNA. In order to achieve the simulation about
medium-length hole blasting air wave propagation, the model can be simplified. A row of medium-length holes which are distributed fanned are merged into a rectangle blast hole. And it is 18 cm in length, 10 cm in wide, and 1000 cm in depth. Due to the model which is built symmetrically, Half the model is calculated to reduce the size of the research object. Mining tunnel is taken along the axial direction of 15m, and there is a transportation tunnel at the axial direction of 10m which is perpendicular with the mining tunnel. The cross-section of mining tunnel and numerical calculation model are shown in Figure 2 and Figure 3.

Figure 2: Cross-section of mining tunnel
The JWL state equation can simulate the relationship between pressure and specific volume in the explosion process (Lee et al., 1986). The equation is as follows:

\[
p = A(1 - \frac{w}{R_1 V})e^{-p/R_1} + B(1 - \frac{w}{R_2 V})e^{-p/R_2} + \frac{\omega E_0}{V}
\]

(10)

where \(A, B, R_1, R_2, W\) are material constants, \(p\) is pressure, \(V\) is relative volume and \(E_0\) is specific internal energy. The physical and mechanical parameters of the dynamite are the same with that of the field test and are listed in Table 1.

**Table 1: Material parameters of explosive**

<table>
<thead>
<tr>
<th>Density (g.cm(^{-3}))</th>
<th>Detonation Velocity (cm.μs(^{-1}))</th>
<th>(A) (GPa)</th>
<th>(B) (GPa)</th>
<th>(R_1)</th>
<th>(R_2)</th>
<th>(\omega)</th>
<th>(E_0) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.01</td>
<td>0.4</td>
<td>214.4</td>
<td>18.2</td>
<td>4.2</td>
<td>0.9</td>
<td>0.15</td>
<td>4.192</td>
</tr>
</tbody>
</table>

In order to simulate the propagation of blasting air waves in the tunnel, we fully fill the tunnel with air, which is simulated using the MAT_NULL model and calculated by the linear polynomial state equation EOS_LINEAR_POLYNOMIAL (Eq.11, Eq.12) (Jiang, 2012).

\[
p = C_0\mu + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E
\]

(11)
\[ \mu = \rho / \rho_0 - 1 \] (12)

In Eq.11 and Eq.12, \( E \) is the internal energy of unit volume, \( \rho \) is density, \( \rho_0 \) is reference density, and \( C_0, C_1, C_2, C_3, C_4, C_5, C_6 \) are real constants. The linear polynomial state equation follows the Gamma law. The parameters of air are listed in Table 2.

**Table 2**: Material parameters of air

<table>
<thead>
<tr>
<th>( P ) (kg·m(^{-3}))</th>
<th>( C_0 )</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( C_3 )</th>
<th>( C_4 )</th>
<th>( C_5 )</th>
<th>( E_0 ) (MPa)</th>
<th>( V_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.290</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.25</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**ANALYSIS OF THE CALCULATION RESULTS**

To analyze the propagation process of medium-length hole blasting air wave in the tunnel, the air overpressure changes with time in the tunnel are monitored, which are shown in Figure 4.

![Figure 4](image-url)
Fig. 4 shows that:

When the time is 2048.3us, blasting air wave propagates in a spherical form from the blast hole into the mining tunnel, the blast hole equals to the explosives center.

When the time is 7449.4us, blasting air wave has transmitted to the medium part of mining tunnel, the maximum overpressure is $2.559 \times 10^5$ Pa which locates at the center of tunnel, blasting air wave propagates still in the spherical form.

When the time is 15849us, blasting air wave propagates to the tunnel wall. And it is not as the spherical form due to the reflection influence of the tunnel wall, the maximum overpressure is near the tunnel floor.

When the time is 36399us, blasting air wave propagates to the junction of mining tunnel and transport tunnel, the overstress further reduces than before.

When the time is 42449us, blasting air wave passes by the junction and propagates in transport tunnel. Due to the reflection influence of the transport wall, there are an overpressure strengthened region in the right corner near the junction and an overpressure weakened region in the left corner near the junction.

When the time is 48349us, blasting air wave propagates to the end of mining tunnel, the overpressure at the junction of mining tunnel and transport tunnel is lower than other parts of the mining tunnel.

To investigate the propagation law of blasting air wave in the tunnel, we select a series of elements along the blast hole below and the axis of mining tunnel to monitor the overpressure. The positions of the selected elements below the blast hole are shown in Fig. 5, and the overpressure values are listed in Table 3.

**Table 3:** Blast air wave overpressures below the blast hole

<table>
<thead>
<tr>
<th>Distance(m)</th>
<th>Overpressure ($10^5$ Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>6.52</td>
</tr>
<tr>
<td>0.6</td>
<td>0.54</td>
</tr>
<tr>
<td>0.9</td>
<td>0.11</td>
</tr>
<tr>
<td>1.2</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Figure 5: Positions of selected elements below the blast hole

Figure 6: Overpressure curve of selected elements below the blast hole
Figure 6 shows that the propagation law of blasting air wave overpressure below blast hole below is the same as explosion in a single medium, and they both attenuate quickly in near zone, but then gently.

To investigate the propagation law of blasting air wave overpressure in transport tunnel, we select two series of elements alone both sides of transport tunnel walls that are shown in Fig.7. And the overpressures are listed in Table 4.

![Figure 7: Positions of selected elements in transport tunnel](image)

<table>
<thead>
<tr>
<th>Number</th>
<th>Left elements Overpressure(Pa)</th>
<th>Right elements Overpressure(Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6944#</td>
<td>132.7</td>
<td>7084# 148.6</td>
</tr>
<tr>
<td>6942#</td>
<td>32.0</td>
<td>7082# 43.6</td>
</tr>
<tr>
<td>6940#</td>
<td>12.3</td>
<td>7080# 26.0</td>
</tr>
<tr>
<td>6938#</td>
<td>7.3</td>
<td>7078# 13.3</td>
</tr>
<tr>
<td>6936#</td>
<td>7.1</td>
<td>7076# 9.2</td>
</tr>
<tr>
<td>6934#</td>
<td>0.0</td>
<td>7074# 6.8</td>
</tr>
<tr>
<td>6932#</td>
<td>0.0</td>
<td>7072# 4.0</td>
</tr>
<tr>
<td>6930#</td>
<td>0.0</td>
<td>7070# 3.9</td>
</tr>
<tr>
<td>6928#</td>
<td>0.0</td>
<td>7068# 2.6</td>
</tr>
<tr>
<td>6926#</td>
<td>0.0</td>
<td>7066# 0.5</td>
</tr>
</tbody>
</table>

Table 4 shows that the overpressures of the left elements (closer to the blast hole) are all smaller than the other side. And there are greatly different values which are closer to the mining tunnel. According to the contour in Fig.4 (the time is 42449us), due to the reflection influence of the transport wall, there is an overstress strengthened region in the right corner near the junction.
of mining tunnel and transport tunnel and an overstress strengthened region in the left corner, which is proved by the data in Table 4.

**Figure 8:** Overpressure curve of selected elements along the mining tunnel centerline

We select elements along the mining tunnel centerline to monitor the overpressure. According the previous studies, which are shown in Eqs. (1) to (9), there is a relationship between the blasting air overpressures and scaled charges ($W^{1/3}/r$). So, we draw the relationship between the blasting air overpressures and scaled charges in Fig. 8.

Figure 8 shows that there are tremendous differences between medium-length hole blasting air wave propagating in mining tunnel and blasting air wave overpressure propagating in a limited air medium.

The maximum overpressure of medium-length hole blasting air wave in mining tunnel is $0.9 \times 10^5$ Pa. When the scaled charges are smaller than 0.5, the overpressures attenuate quickly. But, when the scaled charges are larger than 0.5, the overpressures attenuate gently. When the scaled charge is 1.7, where is located at the junction of mining tunnel and transport tunnel, the overpressure drops suddenly. It indicates that the transport tunnel accelerates the blasting air wave attenuation.

Figure 8 shows that there is an index relationship between the overpressures and scaled charges. We fit the data and get the attenuation law formula which is as follows:
According to the project blasting parameters, we calculate the overpressures by Eqs. (1) to (9) and compare them with the simulation results, which are listed in Table 5.

Table 5: Overpressure calculation results

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Simulation results</th>
<th>Eqs. (8)</th>
<th>Eqs. (9)</th>
<th>NDEDS</th>
<th>M.A. Sadovskyi</th>
<th>J.Henrych</th>
<th>H.L. Brode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.864</td>
<td>371.150</td>
<td>126.555</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>198.112</td>
</tr>
<tr>
<td>2.00</td>
<td>0.395</td>
<td>187.112</td>
<td>70.406</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>62.867</td>
</tr>
<tr>
<td>3.00</td>
<td>0.216</td>
<td>125.590</td>
<td>49.961</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24.718</td>
</tr>
<tr>
<td>4.00</td>
<td>0.179</td>
<td>94.756</td>
<td>39.169</td>
<td>44.827</td>
<td>45.674</td>
<td>14.091</td>
<td>20.709</td>
</tr>
<tr>
<td>5.00</td>
<td>0.174</td>
<td>76.217</td>
<td>32.430</td>
<td>24.384</td>
<td>24.766</td>
<td>10.647</td>
<td>11.361</td>
</tr>
<tr>
<td>6.00</td>
<td>0.132</td>
<td>63.833</td>
<td>27.795</td>
<td>14.993</td>
<td>15.181</td>
<td>6.949</td>
<td>7.062</td>
</tr>
<tr>
<td>7.00</td>
<td>0.085</td>
<td>54.972</td>
<td>24.396</td>
<td>10.031</td>
<td>10.126</td>
<td>4.894</td>
<td>4.784</td>
</tr>
<tr>
<td>8.00</td>
<td>0.075</td>
<td>48.316</td>
<td>21.790</td>
<td>7.137</td>
<td>7.183</td>
<td>3.641</td>
<td>3.451</td>
</tr>
<tr>
<td>9.00</td>
<td>0.069</td>
<td>43.130</td>
<td>19.724</td>
<td>5.321</td>
<td>5.341</td>
<td>2.821</td>
<td>2.610</td>
</tr>
<tr>
<td>10.00</td>
<td>0.048</td>
<td>38.975</td>
<td>18.042</td>
<td>4.116</td>
<td>4.120</td>
<td>2.257</td>
<td>2.048</td>
</tr>
<tr>
<td>11.00</td>
<td>0.037</td>
<td>35.570</td>
<td>16.644</td>
<td>3.279</td>
<td>3.273</td>
<td>1.852</td>
<td>1.656</td>
</tr>
<tr>
<td>12.00</td>
<td>0.026</td>
<td>32.729</td>
<td>15.463</td>
<td>2.676</td>
<td>2.665</td>
<td>1.551</td>
<td>1.371</td>
</tr>
<tr>
<td>13.00</td>
<td>0.019</td>
<td>30.322</td>
<td>14.451</td>
<td>2.228</td>
<td>2.213</td>
<td>1.321</td>
<td>1.158</td>
</tr>
<tr>
<td>14.00</td>
<td>0.014</td>
<td>28.256</td>
<td>13.572</td>
<td>1.887</td>
<td>1.870</td>
<td>1.141</td>
<td>0.995</td>
</tr>
<tr>
<td>15.00</td>
<td>0.002</td>
<td>26.463</td>
<td>12.803</td>
<td>1.621</td>
<td>1.604</td>
<td>0.998</td>
<td>0.866</td>
</tr>
</tbody>
</table>

Table 5 shows that there is a huge difference between the simulation results and other calculation results. It indicates that the empirical formulas based on previous researches have some limitations, and do not suit the project of medium-length hole blasting in mining tunnel.

Eqs. (8) and (9) describe the propagation laws of blasting air wave in tunnel, but they are based on explosive blasting in the tunnel. It is different from medium-length hole blasting in mining tunnel on charge structure and form. And the other formulas all describe blasting propagation in infinite air medium, are also different from medium-length hole blasting in mining tunnel. The simulation results are smaller than the other results which indicate that most of the explosives energy adopted from medium-length hole blasting is used for crushing the ore mass, and a small part of explosive energy is transformed into the energy of blasting air wave.
CONCLUSION

(1) We can analyze the propagation process of medium-length hole blasting air wave in the tunnel by LS-DYNA.

(2) The propagation law of blasting air wave overpressure below blast hole below is the same as explosive in a single medium, and they both attenuate quickly in near zone, but then gently.

(3) The overpressures of the left elements (closer to the blast hole) are all smaller than the other side. And there are greater the difference values which are closer to the mining tunnel.

(4) There is an index relationship between the overpressures and scaled charges of the elements along the mining tunnel centerline.

(5) There is a huge difference between the simulation results and other calculation results that indicates the empirical formulas based previous researches have some limitations, and do not suit the project of medium-length hole blasting in mining tunnel.

ACKNOWLEDGMENT

We thank the National Natural Science Foundation of China (Grant No. 41072219) for financial support. We are also grateful to Gang Luo, Yangbo Liu for their help during the paper writing.

REFERENCES


