Research Article

A Microseismic/Acoustic Emission Source Location Method Using Arrival Times of PS Waves for Unknown Velocity System

Longjun Dong and Xibing Li

School of Resources and Safety Engineering, Central South University, Lushan South Road, Changsha 410083, China

Correspondence should be addressed to Longjun Dong; rydong001@csu.edu.cn

Received 28 July 2013; Accepted 30 August 2013

Academic Editor: Yong Jin

Copyright © 2013 L. Dong and X. Li. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To eliminate the location error of MS/AE (microseismic/acoustic emission) monitoring systems caused by the measurement deviations of the wave velocity, a MS/AE source location method using P-wave and S-wave arrivals for unknown velocity system (PSAFUVS) was developed. Arrival times of P-wave and S-wave were used to calculate and fit the MS/AE source location. The proposed method was validated by numerical experimentations. Results show that the proposed method without the need for a premeasured wave velocity has a reasonable and reliable precision. Effects of arrival error on location accuracy were investigated, and it shows location errors enlarged rapidly with the increase of arrival errors. It is demonstrated the proposed method can not only locate the MS/AE source for unknown velocity system but also determine the real time PS waves velocities for each event in rockmass.

1. Introduction

Geophysical methods, statistical analysis, microseismic monitoring, and in-seam seismic techniques, have shown an increased significance in rock physical mechanics and mining engineering in recent decades [1–21]. In particular, the developments of seismic monitoring provide a scientific basis for controlling the rockburst and seismic hazards.

The seismic location, one of the most important parameters for a seismic monitoring, is very important for rockburst control and warning in a mine through the seismological method of the prediction of the areal rockbursts, which could improve the safety performance of deep geotechnical engineering. Researchers have developed many acoustic emission or seismic source location techniques [1, 2, 7, 22–32]. The problem of locating a signal source using time difference of arrival (TDOA) measurements also has numerous applications in aerospace, surveillance, structural health, navigation, industrial process, speaker location, machine condition, and the monitoring of nuclear explosions [1, 33–45]. And some of which are mature technologies and are widely used in the location of acoustic emission or seismic source.

However, for the existing technologies based on AE or seismic source, a given wave velocity or practical pre-measured wave velocity of the propagation medium is required. It is well known that the wave velocity is influenced by the materials, size, and surface conditions of transmission media and other factors. When the input wave velocity is different from the real wave velocity of the measured object, an error would occur in the system [46]. The average wave velocity is different from that of various regions, and the actual location of the occurrence of rockburst is not necessarily in the predetermined wave velocity area. The measured wave velocity is affected significantly by the distance between sensors; the measured P-wave velocity of the general container is between 2800 and 3100 m·s⁻¹ when the distance is large while that is about 5000 to 6000 m·s⁻¹ when the distance is small [41]. The large location errors can be induced by inaccurate average wave velocity. Both of these conditions result in some errors between the pre-measured wave velocity as an input in the positioning system and the actual wave velocity of the area where the rockburst occurs; hence, it would result in a large positional error [41]. To quantitatively study the location errors induced by deviation of sonic speed, the line and plane location tests were carried out in [47], and some interesting conclusions were summarized: the results show that for line positioning, the maximum error of absolute distance is about 0.8 cm. With the speed difference of 200 m/s, the average value of absolute difference from the position error is about...
0.4 cm; for the plane positioning, in the case of the sensor array of 30 cm, the absolute positioning distance is up to 8.7 cm. It shows the sonic speed seriously impacts on the plane positioning accuracy; the plane positioning error is larger than the line positioning error, which means that when the line position can satisfy the need in practical engineering, it is better to use the line position instead of the plane location, and the plane positioning error with the diagonal speed is the minimum one. Dong et al. analyzed above drawbacks systematically in [48]. Velocities of P-wave and S-wave are obtained by blast experiments in existed methodologies. Two clear disadvantages were discussed. Firstly, active times are different because the premeasured velocity is obtained before the real-time seismic event. The fact is that the velocity in rockmass is changing all the time, and the velocity in different time would be not the same. Secondly, propagation traces are different (i.e., the traces of the wave propagation for blast experiments are always different from the wave propagation for real-time events), which would induce a big error because of the different average velocities in different propagation traces. The above drawbacks are further discussed in Figure 1, and the traces between blast source A and sensors were expressed as $A_1, A_2, A_3,$ and $A_4$, and the average velocity of the four traces is supposed as $V_A$; the traces between seismic source B and sensors were expressed as $B_1, B_2, B_3,$ and $B_4$, and the average velocity of the four traces is supposed as $V_B$. Considering the active time, $V_A$ is not equal to $V_B$ at different time; while considering the active space, propagation traces are different, and $V_A$ is also not equal to $V_B$.

In present work, we proposed an innovative MS/AE source location method without the need for premeasured P-wave and S-wave velocities, which can calculate MS/AE source locations in unknown velocity networks.

2. Methodology

The microseismic $n$ sensors are placed in a location area, and they are not in the same plane. Three-dimensional coordinates of the microseismic sensors are known, which are $(x_1, y_1, z_1), (x_2, y_2, z_2), \ldots$, and $(x_i, y_i, z_i)$. When the microseismic event occurs, the sensor $i$ receives the MS/AE source signals and arrival times of PS waves are recorded as $t_{ai}$ and $t_{bi}$, respectively. The distance between MS/AE source and received station (sensor) $i$ is $R_i$. The average velocities of PS waves (P-wave and S-wave) are expressed as $\alpha$ and $\beta$, respectively.

The distance from MS/AE source to sensor $i$ can be expressed as

$$R_i = \alpha t_{ai} = \beta t_{bi}.$$  \hspace{1cm} (1)

The time difference of arrival times between PS waves is given by

$$t_{bi} - t_{ai} = \frac{R_i}{\beta} - \frac{R_i}{\alpha} = R_i \left( \frac{1}{\beta} - \frac{1}{\alpha} \right).$$  \hspace{1cm} (2a)

Supposing an equivalent parameter consider

$$\overline{v} = \left( \frac{1}{\beta} - \frac{1}{\alpha} \right)^{-1} = \frac{\alpha\beta}{\alpha - \beta}.$$  \hspace{1cm} (2b)

Equation (2a) and can be rewritten as

$$t_{bi} - t_{ai} = \frac{R_i}{\overline{v}} - \frac{R_i}{\alpha} = \frac{R_i}{\overline{v}} - \frac{R_i}{\alpha}.$$  \hspace{1cm} (2c)

Then, the distances between MS/AE source and received stations $i$, as well as the distance between MS/AE source and received stations $j$, are obtained as follows:

$$R_i = \overline{v} (t_{bi} - t_{ai}),$$  \hspace{1cm} (3a)

$$R_j = \overline{v} (t_{bj} - t_{aj}).$$  \hspace{1cm} (3b)

According to the distance formula of two point in the space, for sensors $i$ and $j$, (4) and (5) are given as follows:

$$(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2 = R_i^2,$$  \hspace{1cm} (4)

$$(x_0 - x_j)^2 + (y_0 - y_j)^2 + (z_0 - z_j)^2 = R_j^2.$$  \hspace{1cm} (5)

The left side and the right side of (4) added the left side and the right side of (5), it can be expressed as

$$[(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2]
+ [(x_0 - x_j)^2 + (y_0 - y_j)^2 + (z_0 - z_j)^2] = R_i^2 + R_j^2.$$  \hspace{1cm} (6)

Submitting (3a) and (3b) into (6), it can be rewritten as

$$[(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2]
+ [(x_0 - x_j)^2 + (y_0 - y_j)^2 + (z_0 - z_j)^2] \times \left( \frac{1}{\overline{v}} \right)^{-1} = (t_{bi} - t_{ai})^2 + (t_{bj} - t_{aj})^2.$$  \hspace{1cm} (7)

Equation (7) can be expressed as

$$\Delta t_{ij} = (t_{bi} - t_{ai})^2 + (t_{bj} - t_{aj})^2 = f \left( x_i, y_i, z_i, x_j, y_j, z_j, x_0, y_0, z_0, \overline{v} \right).$$  \hspace{1cm} (8)
In (8), sensor coordinates \((x_i, y_i, z_i), (x_j, y_j, z_j)\), and dependent variable \(t_{x_i}, t_{y_i}, t_{z_i}, t_{y_j}, t_{z_j}\) are known parameters, and \(x_0, y_0, z_0\) and \(\bar{v}\) are unknown parameters. There are four unknown parameters; therefore, it needs more than four sensors to get the solutions by solving the nonlinear equations. This method was called PSAFUUVS (MS/AE source location method using P-wave and S-wave arrivals for unknown velocity system).

Equation (8) is a nonlinear fitting problem with a single dependent variable. According to all the observed data \((x_i, y_i, z_i, x_j, y_j, z_j)\), (8) can determine a regression value

\[
\Delta t_{ij} = f(x_i, y_i, z_i, x_j, y_j, z_j, x_0, y_0, z_0, \bar{v}).
\]

The difference between \(\Delta t_{ij}\) and \(\Delta t_{ij}\) can describe the degree of deviation between the regression value and observed values.

Due to \((x_i, y_i, z_i, x_j, y_j, z_j)\), if the degree of deviation between \(\Delta t_{ij}\) and \(\Delta t_{ij}\) is smaller, it shows that the fitted line and experimental points could fit better. The sum of squared deviations of all observations and fitted values is

\[
Q(x_0, y_0, z_0, \bar{v}) = \sum_{i,j=1}^{n} [\Delta t_{ij} - \Delta t_{ij}]^2.
\]

Equation (10) describes the deviations between all observed and experimental values. Therefore, the MS/AE source parameters \((x_0, y_0, z_0, \bar{v})\) can have values such that the \(Q(x_0, y_0, z_0, \bar{v})\) will reach a minimum as follows:

\[
Q(x_0, y_0, z_0, \bar{v}) = \sum_{i,j=1}^{n} [\Delta t_{ij} - \Delta t_{ij}]^2 = \min.
\]

\(P_{ij}(x_0, y_0, z_0, \bar{v})\) is a parameter to express the fitting error for each set of observations and fitted values as follows:

\[
P_{ij}(x_0, y_0, z_0, \bar{v}) = (\Delta t_{ij} - \Delta t_{ij})^2 = \min_{ij}.
\]

Equations (11a) and (11b) are the nonnegative function of \(x_0, y_0, z_0, \bar{v}\), so it always has the minimum. The coordinates of the MS/AE source location and the equivalent velocity \((x_0, y_0, z_0, \bar{v})\) can be obtained by solving (11a) and (11b). According to \(\alpha = \sqrt{3}\beta\), (2b) can be rewritten as

\[
\bar{v} = \frac{\sqrt{3}\beta^2}{\sqrt{3} - 1},
\]

\(\alpha\) and \(\beta\) can be obtained by resolving (12).

For a simple MS/AE source location problem, only \(x_0, y_0, z_0\) should be solved. Equation (11a) is a nonlinear fitting problem with a single dependent variable. The commonly used nonlinear fitting methods include Levenberg-Marquardt (LM), Simplex Method (SM), Quasi-Newton Method (QN), Max Inherit Optimization (MIO), Self-Organizing Migrating Algorithms (SOMA), and Global Optimization (GO) [27, 31, 48]. Dong et al. discussed the location error of the different method [48], and analyzed results show that it is easy to trap a local optimum value using MIO, QN, and LM simply. It is suggested that the selection of MIO, QN, and LM simply should be careful. The joint use of GO as well as MIO, QN, and LM can significantly improve positioning accuracy. The SOMA, SM coupled with GO, MIO coupled with GO, and LM coupled with GO, which are more stable with the high positioning accuracy, should be recommended preferred methods to locate MS/AE source coordinates. Therefore, in present work, The SOMA coupled with GO was used to fit the MS/AE source locations using (11a) and (11b).

### 3. Validation with Numerical Experimentations and Discussion

In numerical experimentations, the location network includes 6 sensors \(S_1, S_2, S_3, S_4, S_5,\) and \(S_6\). Their coordinates are \((600, 100, 500), (300, -500, 200), (400, 300, -250), (-300, -200, 400), (200, 600, -300),\) and \((-350, -450, -550)\), respectively. The average P-wave velocity and S-wave velocity in the medium are 5500 and 3175 m/s, respectively. The original times of MS/AE sources are supposed as 0 s. According to the relationship between distance formula, the coordinates of MS/AE sources \(A, B, C, D,\) and \(E\) as well as their arrivals are obtained and listed in Table 1. The sensor and the spatial distribution of MS/AE source locations are shown in Figure 2 (all coordinates are in the length unit: meter). The MS/AE source locations were calculated by the PSAFUUVS using arrivals in Table 1 and coordinates of sensors. The arrivals is accurate result with a accuracy...
The location results calculated by accurate arrivals were expressed as $E_0$ (the error is approximately equal to 0) and listed in Table 2. Compared results between authentic values and fitting results of dependent variables were listed in Table 3. It shows that the calculated coordinates $(C)$ of $A$, $B$, $C$, and $D$ using PSAFUVS are consistent with authentic results $(T)$, and the fitting values are approximately equal to authentic values. To further verify the proposed method, the $\alpha$ and $\beta$ were recalculated using (12), and the calculated results were compared with the authentic $\alpha$ and $\beta$. $\bar{v}$ is 7510.767. $\alpha$ and $\beta$ are 5497.88 and 3174.30 m/s which are approximately equal to authentic values 5500 and 3175 m/s, respectively. Results prove that the proposed PSAFUVS is reasonable and reliable with a high precision for the unknown velocity system.

As we all know, it is always difficult to read the accurate arrivals because of limitations of technologies, personal error, or machine error. In present work, the errors are considered as three levels within $E_1$ [0.000001, 0.00001], $E_2$ [0.00001, 0.0001], and $E_3$ [0.0001, 0.001], which are randomly generated by random function of Microsoft Excel. The calculated location results of the three levels were also listed in Table 2. Compared results between authentic values $(T)$ and fitting results of MS/AE sources $A$, $B$, $C$, $D$, and $E$ for error levels $E_0$, $E_1$, $E_2$ and $E_3$ are shown in Figure 3. From Table 2 and Figure 3, we can conclude that the location errors enlarged rapidly with the increase of arrival errors. The error $E_1$ results in errors within 3 m, and the minimum and maximum are $-0.28$ and $-2.98$ m, respectively. The error $E_2$ results in errors within 55 m, and the minimum and maximum are $-3.99$ and 54.08 m, respectively. The error $E_3$ could induce errors more than 500 m, and the minimum and maximum are $-1.62$ and 530.39 m, respectively. Figure 3 also shows that the differences between fitted values and authentic values increased with the enlarging of arrival errors. The induced location errors were further investigated by absolute distance errors between real MS/AE sources and fitted MS/AE sources in Figure 4. It also clearly shows the absolute distance errors enlarging exponentially with the increase of arrival errors, and the location errors for $A$, $B$, $C$, $D$, and $E$ are increased from 0.19, 0.13, 0.28, 0.64, and 0.47 m to 82.49, 331.61, 656.54, 576.49, and 266.39 m, respectively.

### 4. Conclusions

A new MS/AE source location method PSAFUVS was developed to address the difficult problem of the location errors for microseismic monitoring system induced by wave velocity measurement deviation. The proposed method was validated by numerical experimentations. Results show that the proposed method without the need for a premeasured wave velocity has a reasonable and reliable precision. It is demonstrated that the proposed method can not only locate the MS/AE source for unknown velocity network but
Figure 3: Comparisons between authentic values and fitting results: (a) source $A$, (b) source $B$, (c) source $C$, (d) source $D$, and (e) source $E$. 
Table 3: Comparisons between authentic values and fitting results for the E0 condition.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>T</th>
<th>C</th>
<th>T</th>
<th>C</th>
<th>T</th>
<th>C</th>
<th>T</th>
<th>C</th>
<th>T</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>i( j = 1)</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>E</td>
</tr>
<tr>
<td>1</td>
<td>0.010636</td>
<td>0.010636</td>
<td>0.02641</td>
<td>0.02641</td>
<td>0.044296</td>
<td>0.044296</td>
<td>0.003347</td>
<td>0.003347</td>
<td>0.030323</td>
<td>0.030323</td>
</tr>
<tr>
<td>2</td>
<td>0.014891</td>
<td>0.014891</td>
<td>0.01705</td>
<td>0.01705</td>
<td>0.049295</td>
<td>0.049295</td>
<td>0.01377</td>
<td>0.01377</td>
<td>0.035961</td>
<td>0.035961</td>
</tr>
<tr>
<td>3</td>
<td>0.012453</td>
<td>0.012453</td>
<td>0.019363</td>
<td>0.019363</td>
<td>0.035654</td>
<td>0.035654</td>
<td>0.008709</td>
<td>0.008709</td>
<td>0.032158</td>
<td>0.032158</td>
</tr>
<tr>
<td>4</td>
<td>0.011618</td>
<td>0.011618</td>
<td>0.023644</td>
<td>0.023644</td>
<td>0.033554</td>
<td>0.033554</td>
<td>0.014799</td>
<td>0.014799</td>
<td>0.030682</td>
<td>0.030682</td>
</tr>
<tr>
<td>5</td>
<td>0.014713</td>
<td>0.014713</td>
<td>0.026268</td>
<td>0.026268</td>
<td>0.030682</td>
<td>0.030682</td>
<td>0.012175</td>
<td>0.012175</td>
<td>0.030075</td>
<td>0.030075</td>
</tr>
<tr>
<td>6</td>
<td>0.029205</td>
<td>0.029205</td>
<td>0.021703</td>
<td>0.021703</td>
<td>0.047833</td>
<td>0.047833</td>
<td>0.036948</td>
<td>0.036948</td>
<td>0.045188</td>
<td>0.045188</td>
</tr>
</tbody>
</table>

Note: 1, 2, 3, 4, 5, and 6 indicating the values calculated using (8), and i is equal to 1, 2, 3, 4, 5 and 6, while j is equal 1.

Figure 4: Comparisons of absolute distance error for different arrival errors.

also determine the PS wave real-time velocities for each event. Effects of arrival errors on location accuracy were investigated using PSAFUUVS, and it shows location errors enlarged rapidly with the increase of arrival errors. The absolute distance errors between real MS/AE sources and fitted MS/AE sources were further discussed, and results show the absolute distance errors enlarging exponentially with the increase of arrival errors.

Conflict of Interests

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

Acknowledgments

The authors gratefully acknowledge the financial support of National Natural Science Foundation of China (50934006,41272304), National Basic Research (973) Program of China (2010CB732004), China Scholarship Council (CSC), Doctoral Candidate Innovation Research Support Program by Science & Technology Review (kjdb201001-7), Scholarship Award for Excellent Doctoral Student from Ministry of Education of China (105501010), and Support Program for Cultivating Excellent Ph.D. Thesis of Central South University.

References


L. Dong and X. Li, “Closed-form solutions of acoustic emission source location for minimal element monitoring arrays of rectangular pyramid and circular column,” *Disaster Advances*, vol. 6, no. 13, p. 11, 2013.


