Research on the propagation mechanism of the arrival time error and wave velocity error under sensor array

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Abstract. To study the propagation mechanism of the arrival time error and wave velocity error under sensor array is an urgent problem in microseismic (MS) source location. To solve it, based on the theory of source location, the elliptic governing equation of source location is established. Combining with the hyperbolic governing equation of source location, it is revealed that the arrival time error and wave velocity error make the source "jump" on the adjacent hyperbola and ellipse. Through the numerical simulation test, the seismogenic time error law under the influence of the arrival time error and the wave velocity error is revealed. It is concluded that the location error of the source inside 1.8 times the array radius is mainly caused by the arrival time error and the wave velocity error, while the location error of the source outside 1.8 times the array radius is mainly caused by the seismogenic time error. Finally, considering the seismogenic time error, the location error law of the source under the influence of the arrival time error and velocity error is studied. The research results improve the understanding of the propagation mechanism of the arrival time error and wave velocity error in MS source location.

Key words: microseismic, sensor array, elliptic equation, hyperbolic equation, location error, seismogenic time.

1. Introduction

In recent years, due to the depletion of shallow resources, the development of the western region in China and the implementation of “the Belt and Road” strategy, more and more deep high in-situ stress projects have been carried out. Therefore, the problem of rockburst is becoming more and more prominent, resulting in rock failure, damage of support equipment, delay of the construction period and even casualties [1, 2]. With the development of electronic, communication equipment and computer technology, the MS monitoring technique has become an advanced and effective in-situ stress monitoring means, which widely used in the ground pressure safety monitoring of deep mines and high in-situ stress tunnels around the world [3-12]. According to the principle of microseismic (MS) location, the key factors that affect the MS source location mainly include location method, the layout of MS network, first arrival time pickup of waveform signal, velocity model, etc. Among them, the MS network not only affects the reliability and effectiveness of MS monitoring data but also

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affects the location accuracy and stability of the MS source [13]. Therefore, to improve the location accuracy of the MS sources, it is necessary to study the MS network. Scholars around the world have done a lot of research on the MS network, achieving very fruitful results. The research contents are mainly reflected in the aspects of the network optimization, the network evaluation, and the network mechanism. In terms of the network optimization, Saot and Skoko [14] proposed a Monte Carlo algorithm for calculating numerically the monitoring ability of the seismic network and drew the error contour map of source parameters in the monitoring area. Hardy [15] studied the optimization layout of the MS monitoring network in Greenwich Coal Mine in Binzhou, aiming to design the optimal MS monitoring network. In terms of the network evaluation, kijko [16, 17] and mendekci [13] designed an MS network based on D-optimality and C-optimality theory, respectively, and the two methods were mainly used to evaluate the merits and demerits of the network. Based on the D-optimality theory, Gong SY [18] established the optimization and evaluation system of the MS network layout. In terms of the network mechanism, Cete [19] studied the influence of MS network layout on the MS source location under the given wave velocity and sensor coordinates, and the research results showed that the wave velocity error has a greater impact on the MS source location than the arrival time error. With the MS source far away from the center of the MS network, the location accuracy of the source continued to decline. Ge MC and Li N [20, 21] discussed two types of multi-solution problems of the MS source and analyzed the influence mechanism of the two-dimensional sensor network on the source location, obtaining the distribution law of the MS source location error of different sensor array.

At present, scholars around the world have done a lot of research on network optimization and evaluation, and put forward a series of optimization and comprehensive evaluation methods. However, there is little research on the mechanism of the sensor array, which mainly focuses on the geometric diffusion effect of the location error inside and outside the sensor array and the propagation characteristics of the arrival time error and wave velocity error on the two-dimensional plane. But how does the arrival time error and wave velocity error affect the location error of the MS source? There has not been a systematic study that the location error law of the MS source under the influence of the arrival time error and wave velocity error. Therefore, based on the hyperbolic governing equation, combined with the elliptic governing equation, the law of seismogenic time error under the influence of the arrival time error and wave velocity error is analyzed, and then the location error law of the MS source is further obtained. The research results reveal the mechanism of the arrival time error and wave velocity error on the MS source location error, and further improve the understanding of the MS source location error law.

2. Governing equation of source location

2.1. The hyperbolic governing equation of source location

Taking two-dimensional plane as an example, the observed arrival time of any two sensors $T_i, T_j$ are respectively set to $t_i, t_j$, then the travel time equation of the two sensors is given by,

$$t_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} / v + t_0$$  \hspace{1cm} (1)

$$t_j = \sqrt{(x_j - x_0)^2 + (y_j - y_0)^2} / v + t_0$$  \hspace{1cm} (2)

$v$ is the propagation velocity of P-wave, $t_0$ is the seismogenic time, $(x_0, y_0, z_0)$ is the source coordinate; $(x_i, y_i, z_i)$ is the coordinate of the $i$th sensor; $(x_j, y_j, z_j)$ is the coordinate of the $j$th sensor.

By subtracting equations (1) and (2), we can get

$$\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} - \sqrt{(x_j - x_0)^2 + (y_j - y_0)^2} = v(t_i - t_j)$$  \hspace{1cm} (3)

From the perspective of plane geometry, equation (3) represents the hyperbola with the sensor $T_i$ and $T_j$ as the focuses, and the distance difference between any point on the hyperbola and the two focuses
is a constant. The hyperbola determined by the two sensors is shown in figure 1. The direction of the real axis is set to $X$ axis, the direction of the imaginary axis is set to $Y$ axis, and the midpoint of the two sensors is the origin $O$. When the distance between the two sensors is set to $2c$, the focal length of the hyperbola is set to $2c$, and the imaginary axis length of the hyperbola is set to $2b$, the real axis of the hyperbola can be expressed as

$$2a = \sqrt{\left| v(t_i - t_j) \right|}$$  \hspace{1cm} (4)

The standard equation of the hyperbola is given by,

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1$$  \hspace{1cm} (5)

The real axis length, imaginary axis length, and focal length of the hyperbola satisfy

$$a^2 + b^2 = c^2$$  \hspace{1cm} (6)

Therefore, when $a = 0$, the MS source is located on $Y$ axis. When $a = c$, the MS source is located on $X$ axis.

2.2. The elliptic governing equation of source location

By adding equations (1) and (2), we can get

$$\sqrt{(x_i-x_0)^2 + (y_i-y_0)^2} + \sqrt{(x_j-x_0)^2 + (y_j-y_0)^2} = v(t_i + t_j - 2t_0)$$  \hspace{1cm} (7)

Equation (7) represents an ellipse with sensors $T_i$ and $T_j$ as the focuses, and the sum of the distances from any point on the ellipse to the two focuses is a constant. The schematic diagram of the ellipse determined by the two sensors is shown in figure 1. When the focal length of the ellipse is set to $2c$, the short axis length of the ellipse is set to $2f$, and the long axis length of the ellipse can be expressed as

$$2e = v(t_i + t_j - 2t_0)$$  \hspace{1cm} (8)

t_0 is the theoretical seismogenic time, which is generally replaced by the calculated seismogenic time $t_0^c$. The calculated seismogenic time can be expressed as $t_0^c = t_0 + t_e$, where $t_e$ is the seismogenic time error.

$$\frac{x^2}{c^2} + \frac{y^2}{f^2} = 1$$  \hspace{1cm} (9)

The long axis length, short axis length, and focal length of the ellipse satisfy
The coordinate of intersection point of elliptic and hyperbolic is given by,

\begin{align}
  x &= \pm \frac{ae}{c} \\
  y &= \pm \frac{bf}{c}
\end{align}

(10)

(11)

(12)

In addition to equation (3), the source location should also satisfy equation (7). When there are the arrival time error and wave velocity error, the MS source position "jumps" on the adjacent hyperbola and ellipse (figure 2). The ellipse is affected by the seismogenic time error, while the hyperbola is not affected by the seismogenic time error.

2.3. The influence of the arrival time error and wave velocity error on location result without considering the seismogenic time error

For the convenience of analysis, \( t_0 \) is set to 0, and equation (8) without considering the seismogenic time error can be expressed as

\[ 2e = v(t_i + t_j) \]

(13)

The arrival time error of any sensor is taken as a small increment \( dt \), and the increment of the real axis \( a \) and long axis \( e \) are given by,

\begin{align}
  da &= v|dt|/2 \\
  de &= v|dt|/2
\end{align}

(14)

(15)

\textbf{Figure 3.} Schematic diagram of hyperbola and ellipse with an arrival time error of 0.2c/v.

\textbf{Figure 4.} Schematic diagram of hyperbola and ellipse with wave velocity error of 0.1v.

The arrival time error \( dt \) is set to 0.2c/v, then \(|da| = 0.1c, |de| = 0.1c\) and the hyperbola and ellipse diagram with the arrival time error of 0.2c/v is shown in figure 3. The denser the hyperbola near the source in the MS monitoring area, the higher the location accuracy of the source [13]. The farther the source on the X axis and Y axis from the origin O, the location error in the x- and y-direction decreases first and then increases.

By calculating the partial derivatives of equations (11) and (12), the location error increment in x- and y-direction is given by,

\begin{align}
  |dx| &= \frac{eda + aed}{c} = \frac{(a + e)v|dt|}{2c} \\
  |dy| &= \frac{fbd + bfd}{c} = \left( \frac{af}{eb} + \frac{eb}{cf} \right) v|dt|/2
\end{align}

(16)

(17)

The location error of the MS source in the x-direction is proportional to the real axis \( a \), long axis \( e \) and the arrival time error \( dt \), while the location error of the MS source in the y-direction is proportional to
the arrival time error $dt$ and related to the real axis $a$ and the long axis $e$. The position of the MS source can be determined by the real axis $a$ and the long axis $e$, so the location error in the $x$- and $y$-direction of the source is related to the source position. $t_0$ is set to 0, and the wave velocity error is set to a small increment $dv$. According to equations (4) and (13), without considering the seismogenic time error $te$, the increment of the real axis $a$ and long axis $e$ is given by,

$$\frac{da}{2} = \frac{(t_i - t_f)}{dv}$$

$$\frac{de}{2} = \frac{(t_i + t_f)}{dv}$$

The wave velocity error $dv$ is set to 0.1$v$, and the hyperbola and ellipse diagrams with the wave velocity error of 0.1$v$ is shown in figure 4. The farther the source on the X axis is from the origin $O$, the location error in the $x$-direction increases gradually, and the location error in the $y$-direction decreases first and then increases. The farther the source on the Y axis is from the origin $O$, the location error in the $x$-direction is almost zero, and the location error in the $y$-direction first decreases and then increases.

By calculating the partial derivatives of equations (11) and (12), the location error increments in $x$- and $y$-directions is given by,

$$|dx| = \frac{eda + ade}{c} = \frac{2ae}{cv}|dv|$$

$$|dy| = \frac{fdh + bdf}{c} = (-\frac{a^2f}{cv} + \frac{e^2b}{cfv})dv$$

The location error in the $x$-direction is proportional to the real axis $a$, the long axis $e$, and the wave velocity error $dv$, while the location error in the $y$-direction is proportional to the wave velocity error $dv$ and related to the real axis $a$ and the long axis $e$.

3. The seismogenic time error law in the source location

3.1. Numerical simulation test

To study the seismogenic time error law in the MS source location, a cube sensor array with a side length of 100m is selected (Table 1). The central coordinates of the cube sensor array are (50, 50, 50), and the unit is m. 71 MS sources are set in the straight line vertically upward the center of the cube, starting from the center of the sensor array and ending at the point (50, 50, 750), and the distance between adjacent the MS sources is 10 m. The seismogenic time is set to 20 ms at 12:00 on a certain day. In the numerical simulation test, the expected velocity of the P-wave in the medium is set to 5500 m/s. Two kinds of simulation tests are carried out: 1) the mean of the arrival time error is 0, and the variances are $0.0002s, 0.0004s, 0.0006s, 0.0008s, 0.001s$, respectively; 2) the mean of the wave velocity error is 0, and the variances are $50m/s, 100m/s, 150m/s, 200m/s, 250m/s$, respectively. The repeated number $N_m$ of the simulation test is set to 2000 for each MS source, and it is assumed that the vibration can be received by all sensors. The average seismogenic time error and the average location error is obtained.

| Sensor | Coordinate(m) |
|--------|---------------|
|       | $x$ | $y$ | $z$ |
| A      | 0   | 0   | 0   |
| B      | 100 | 0   | 0   |
| C      | 100 | 100 | 0   |
3.2. The seismogenic time error law under the influence of the arrival time error and wave velocity error

According to simulation test 1, the relationship between the seismogenic time error $t_e$, the location error and the distance $l$ from the source to the center of the sensor array can be obtained under the influence of arrival time error, as shown in figure 5 and figure 6. The seismogenic time error and location error increase with the increase of the arrival time error and the distance $l$. When the distance $l$ is within 90 m (50 m reaches the boundary of the array and 90 m is 1.8 times the array radius), the seismogenic time error is less than the given arrival time error. When the distance $l$ is beyond 1.8 times the array radius, the seismogenic time error is greater than the given arrival time error and increases sharply with the increase of the distance $l$.

**Figure 5.** The relationship between the seismogenic time error and the distance $l$ under the influence of the arrival time error.

**Figure 6.** The relationship between the location error and the distance $l$ under the influence of the arrival time error.

**Figure 7.** The relationship between the seismogenic time error and the distance $l$ under the influence of wave velocity error.

**Figure 8.** The relationship between the location error and the distance $l$ under the influence of the wave velocity error.
According to simulation test 2, the relationship between the seismogenic time error $t_e$, the location error and distance $l$ from the source to the center of the sensor array can be obtained under the influence of wave velocity error, as shown in figure 7 and figure 8. The seismogenic time error and location error increase with the increase of the wave velocity error, and the location error increases with the increase of the distance $l$. When the distance $l$ is within 1.8 times the array radius, the seismogenic time error is small and decreases with the increase of the distance $l$. When the distance $l$ is more than 1.8 times the array radius, the seismogenic time error increases sharply with the increase of the distance $l$.

For further comparison, the location procedure is modified by changing the location parameters $x_0, y_0, z_0$ to $x_0, y_0, z_0$ and setting the seismogenic time $t_0$ to the theoretical seismogenic time. The relationship between the location error and the distance $l$ from the source to the center of the sensor array under the influence of the arrival time error and wave velocity error is shown in figure 9 and figure 10. When the distance $l$ is within 1.8 times the array radius, the location results in figure 6 and figure 9 are on the same order of magnitude, and the location results in figure 8 and figure 10 are on the same order of magnitude. It is indicated that the arrival time error and wave velocity error have a great influence on the location result while the impact of seismogenic time error on the location result is small when the distance $l$ is within 1.8 times the array radius. When the distance $l$ is beyond 1.8 times the array radius, the location result in figure 6 is two orders of magnitude greater than figure 9 and the location result in figure 8 is two orders of magnitude greater than figure 10 with the increase of the distance $l$. It shows that the influence of the arrival time error and wave velocity error on source location is attenuated, while the seismogenic error is gradually dominant with the increase of the distance $l$. Combined with the position relationship between the source and the sensor, it can be seen that the sensor is close to the source and the sensor coordinate can limit the seismogenic time error in three directions within 1.8 times the array radius. Therefore the seismogenic error is small, and the location error is mainly caused by the arrival time error and wave velocity error. Outside 1.8 times the array radius, the source is far away from the sensor array, so the sensor array can not limit the seismogenic time error in three directions. Therefore the seismogenic time error has gradually become the main factor affecting the location error.

![Figure 9. The diagram of location error under the influence of the arrival time error.](image)

![Figure 10. The diagram of location error under the influence of wave velocity error.](image)

The Logistic function is expressed as $y = k/(1 + e^{(a-bx)})$. The Logistic function is used to fit five seismogenic time error curves affected by the arrival time error (as shown in figure 5), and the correlation coefficient $R^2$ are about 1, 1, 0.99, 0.99, 0.97, respectively, which are not less than 0.97. The Logistic function is used to fit the five seismogenic error curves affected by the wave velocity error (as shown in figure 7), and the correlation coefficient $R^2$ are about 1, 0.99, 0.99, 0.98, 0.97, respectively, which are not less than 0.97. Therefore, to simplify the calculation, the Logistic function is used to fit the relationship between the seismogenic time error $t_e$ and distance $l$. 
4. Location error law of the source under the influence of the arrival time error and wave velocity error

4.1. Location error law under the influence of the arrival time error

t_0 is set to 0. Considering that the seismogenic time error t_e varies with the arrival time error and the distance l from the source to the center of the sensor array, t_e can be expressed as

\[ t_e = f(l, \ dt) \]  

(22)

Then equation (13) is given by,

\[ 2e = v(t_i + t_j + t_k) \]  

(23)

t_e is a Logistic function of the distance l and the increment of arrival time error dt. Therefore, considering the influence of seismogenic time error t_e, the hyperbola and ellipse schematic diagram with an arrival time error of 0.2c/v is shown in figure 11. Compared with figure 3, for the source at the same position, the curve density in figure 11 becomes sparser and the location error increases. The farther the source on the X axis and Y axis is from the origin O, the location error becomes smaller first and then larger. Taking the real axis a and the long axis e as variables and considering the seismogenic time error t_e, combined with equations (16), (17), and (23), the cloud charts of location error under the influence of the arrival time error are shown in figure 12. Figures 12(a) and 12(b) show the relationship between the location error in the x-direction, y-direction and the real axis a, the long axis e, respectively. When the increment of arrival time error is determined, the location error of the MS source in the x-direction is proportional to the real axis a and long axis e, indicating that the location error in x-direction increases uniformly on the same hyperbola or ellipse. The location error in the y-direction is related to the real axis a and the long axis e, which is related to the source position.

![Hyperbola and ellipse diagram with an arrival time error of 0.2c/v considering the seismogenic time error.](image1)

![Cloud charts of location errors considering the seismogenic time error under the influence of arrival time error.](image2)

4.2. Location error law under the influence of the wave velocity error

t_0 is set to 0. Considering that the seismogenic time error t_e varies with the wave velocity error and the distance l from the source to the center of the sensor array, t_e can be expressed as

\[ t_e = f(l, \ dv) \]  

(24)

t_e is a Logistic function of the distance l and the increment of wave velocity error dv. Therefore, considering the influence of wave velocity error and seismogenic time error t_e, the hyperbola and ellipse schematic diagram with wave velocity error of 0.1v is shown in figure 13. Compared with figure 4, the farther the source on the X axis is from the origin O, the location error in the x-direction increases gradually, and the location error in the y-direction decreases first and then increases. The farther the source on the Y axis is from the origin O, the location error in the x-direction is almost zero,
and the location error in the y-direction first decreases and then increases. Taking the real axis $a$ and the long axis $e$ as variables and considering the seismogenic time error $t_e$, combined with equations (20), (21), and (24), the cloud charts of location error under the influence of the wave velocity error is shown in figure 14. Figures 14(a) and 14(b) show the relationship between the location error in the x-direction, y-direction and the real axis $a$, the long axis $e$, respectively. When the increment of wave velocity error is determined, the location error of the MS source in the x-direction is proportional to the real axis $a$ and long axis $e$, indicating that the location error in the x-direction and y-direction increases uniformly on the same hyperbola or ellipse. The location error in the y-direction is related to the real axis $a$ and the long axis $e$, which is related to the source position.

Figure 13. Hyperbola and ellipse diagram considering the seismogenic time error with a wave velocity error of 0.1u.

Figure 14. Cloud charts of location errors considering the seismogenic time error under the influence of wave velocity error.

5. Conclusion
The elliptic governing equation of source location, it is revealed that the arrival time error and wave velocity error make the source position "jump" on adjacent hyperbola and ellipse. Through numerical simulation tests, it is concluded that the location error of the source in x- and y-directions is proportional to the arrival time error and wave velocity error. When the distance between the source and the center of the sensor array is within 1.8 times the array radius, the seismogenic time error is small and the location error is mainly caused by the arrival time error and the wave velocity error. When the distance from the source to the center of the sensor array is more than 1.8 times the array radius, and the seismogenic time error gradually increases with the increase of the distance from the source to the center of the sensor array, and the seismogenic time error gradually becomes the main factor affecting the location error. It is concluded that under the influence of the arrival time error, the farther the source on the X axis and Y axis is from the origin $O$, the location error in the x- and y-direction becomes smaller first and then larger. Under the influence of wave velocity error, the farther the source on the X axis is from the origin $O$, the location error in the x-direction gradually increases, and the location error in the y-direction first becomes smaller and then becomes larger; The farther the source on the Y axis is from the origin $O$, the location error in the x-direction is almost zero, and the location error in the y-direction first becomes smaller and then becomes larger. Under the influence of the arrival time error and the wave velocity error, the source in other positions of the plane, the location error in the x- and y-direction depend on the source coordinates.

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