A new location method without pre-measuring wave velocity based on particle swarm optimization

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Abstract. To deal with the impact of the typical microseismic (MS) location (TMSL) method with the velocity measurement error on location accuracy, a new location method without pre-measuring wave velocity based on particle swarm optimization (PSO), named the TM-PSO method, is proposed. Then, based on the arrival time of the MS source, combining the sensor array and the expression of the TM-PSO method, the convergence and correlation of objective functions of the TM-PSO method are analyzed theoretically. The field test of the Beijinghe iron mine in Hebei province and the headrace tunnel in the Neelum-Jhelum hydropower station in Pakistan show that the TM-PSO method has great location effect and stability, which has important practical application value.

Key words: microseismic, objective function, sensor array, correlation; convergence.

1. Introduction

Since the microseismic (MS) phenomenon [1, 2] was discovered, scholars around the world had done a lot of research about it. To capture and analyze the MS signals generated by rock mass rupture, many advanced MS monitoring systems have been developed worldwide, such as the Institute of Mine Seismology (ISS) MS monitoring system in Australia [3], Engineering Seismology Group (ESG) MS monitoring system in Canada [4], and SinoSeism (SSS) MS monitoring system jointly developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, and Hubei Seake Technology Co., Ltd. [5], finally forming a set of mature MS monitoring techniques. At present, MS monitoring techniques have been widely used in domestic and foreign projects, such as mines, hydropower stations, rock slopes, hydraulic fracturing, etc. [6, 7]. In the MS research, the MS source localization directly affects the calculation of radiant energy, the analysis of MS activity, and the warning of rockbursts. Therefore, MS source localization is one of the most basic and core issues [8-11]. The location accuracy of the MS sources is directly related to the analysis and prediction of rock engineering disasters.

Scholars around the world have done a lot of research on the MS source location method and put forward a variety of location methods, such as the Geiger method, simplex method, Powell algorithm,
genetic algorithm, etc. [12-15]. The above method achieves good location results, but the wave velocity of the monitoring area needs to be inverted in advance. When there is a certain error between the pre-measuring wave velocity and that of the actual monitoring area, a large location error will occur [16, 17]. Therefore, to improve the location accuracy of MS events in the monitoring area, a new location method without pre-measuring wave velocity based on particle swarm optimization (PSO), named TM-PSO, is proposed, and the convergence and correlation of the proposed method are systematically analyzed and studied. The proposed method provides a new research idea for the improving location accuracy of MS source.

2. A new location method without pre-measuring wave velocity based on particle swarm optimization

2.1. The objective function of the traditional location method

In the rock engineering, the arrival time of the P-wave is easy to pick up because it is the first to arrive. The P-wave and S-wave are overlapped, making it hard to pick up the S-wave arrival time accurately. Therefore, the arrival time of the P-wave is generally for locating. The most widely used method in MS source location is the typical MS location (TMSL) method. This method assumes that the rock mass is a homogeneous medium, and its used velocity model is uniform. The velocity of P-wave is assumed to be known, and is set to \( c \). The objective function of the TMSL method is given by,

\[
Q(x_0, y_0, z_0, t_0) = \sum_{i=1}^{n} (t_i^c - t_i^c)^2
\]

\[
t_i^c = \frac{l_i}{c} + t_0
\]

\[
l_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}
\]

Where \( t_0 \) is the seismogenic time, and \( l_i \) is the distance from the \( i \)-th sensor to the MS source; \( n \) is the number of sensors, and \((x_0, y_0, z_0)\) is the coordinates of the MS source, and \((x_i, y_i, z_i)\) is the coordinates of the \( i \)-th sensor; \( t_i \) is the observed arrival time of the \( i \)-th sensor, and \( t_i^c \) is the theoretical arrival time of the \( i \)-th sensor.

The pre-measurement of wave velocity is the key in the TMSL method, which is generally inverted by the artificial blasting events. When there is a big difference between the pre-measuring wave velocity in the MS source location and the average wave velocity in the actual monitoring area, a great error will occur in the location results. Therefore, to eliminate the influence of wave velocity error on the MS source location and improve the location accuracy of the MS source, many scholars have studied the MS source location methods without pre-measuring wave velocity. Among them, Dong et al. [18, 19] eliminates the wave velocity through formula derivation and proposed the time difference (TD) method without pre-measuring velocity, which achieves a better location effect. Its objective function is given by,

\[
Q(x_0, y_0, z_0, v) = \sum_{i,j=1}^{n} (\Delta t_i^c - \Delta t_j^c)^2
\]

\[
\Delta t_i^c = t_i^c - t_j
\]

\[
\Delta t_j^c = t_j^c - t_j^c = \frac{l_i - l_j}{v}
\]

Where \( v \) is the velocity of the P-wave, which is unknown. \( l_j \) is the distance from the \( j \)-th sensor to the MS source. \( t_j \) is the observed arrival time of the \( j \)-th sensor, and \( t_j^c \) is the theoretical arrival time of the \( j \)-th sensor. \( \Delta t_{ij} \) is the observed arrival time difference between the \( i \)-th sensor and \( j \)-th sensor, and \( \Delta t_{ij}^c \) is the theoretical arrival time difference between the \( i \)-th sensor and \( j \)-th sensor.
The above methods need to solve the wave velocity. When the difference between the calculated wave velocity and wave velocity of the actual formation is large, the location results are bound to be inaccurate. Therefore, the objective function needs to be improved.

2.2. A new objective function without pre-measuring velocity

The arrival time of the $i$-th and $j$-th sensor can be expressed as

$$t_i = \frac{l_i}{v} + t_0 \quad (7)$$

$$t_j = \frac{l_j}{v} + t_0 \quad (8)$$

The wave velocity of $i$-th sensor and $j$-th sensor are equal

$$v = \frac{l_i}{t_i - t_0} = \frac{l_j}{t_j - t_0} \quad (9)$$

Then, we can get

$$l_i(t_j - t_0) - l_j(t_i - t_0) = 0 \quad (10)$$

Therefore, the objective function without pre-measuring velocity based on the joint solution of four source parameters $(x_0, y_0, z_0, t_0)$ is given by,

$$Q(x_0, y_0, z_0, t_0) = \sum_{i,j=1}^{n} (l_i(t_j - t_0) - l_j(t_i - t_0))^2 \quad (11)$$

$t_0$ should satisfy the following formula

$$t_{\text{min}} - \frac{d}{c} < t_0 < t_{\text{min}} \quad (12)$$

Where $t_{\text{min}}$ is the minimum arrival time of all triggering sensor, and $d$ is the maximum distance from the sensor to the MS event in the monitoring area.

Making $Q(x_0, y_0, z_0, t_0)$ in equation (11) reach the minimum, source coordinates $(x_0, y_0, z_0)$ and the seismogenic time $t_0$ can be obtained. The new objective function is named Time Method (TM). To realize the location process of the TM method, particle swarm optimization is introduced, forming finally the TM-PSO method. There are four parameters needed to be inverted in this method. But the propagation velocity of P-wave is eliminated by formula derivation, so the method requires at least five sensors to be triggered. According to the boundary conditions of the monitoring area, the seismogenic time of the MS source can be controlled in a reasonable range by equation (12).

2.3. particle swarm optimization

Particle Swarm Optimization (PSO) is a random search algorithm, which is generally used in MS source location in recent years. This algorithm initializes a group of random particles (random solutions), and then the particles follow the current optimal particles to search the optimal solution in the solution space. There are two optimal solutions in each iteration, the first of which is the optimal solution searched by the particle itself and the second of which is the optimal solution searched by all particles. When these two optimal solutions are searched, the velocity and value of the particle are updated by the following formula \([20, 21]\)

$$V_{id}(j + 1) = wV_{id}(j) + c_1 r_1 (P_{id} - X_{id}(j)) + c_2 r_2 (P_{gd} - X_{id}(j)) \quad (13)$$

$$X_{id}(j + 1) = X_{id}(j) + V_{id}(j + 1) \quad (14)$$

Where $w$ is the inertia weight, which is used to control the convergence velocity; $c_1$ and $c_2$ are non-negative constant learning rates; $r_1$ and $r_2$ are uniformly distributed random numbers between 0 and 1; $d=1,2,...,D$, which is the dimension; $V_{id}(j)$ is the velocity of the $i$-th particle in the $j$-th iteration, and $V_{id}(j + 1)$ is the velocity of the $i$-th particle in the $(j+1)$-th iteration; $X_{id}(j)$ is the value of the $i$-th particle in the $j$-th iteration, and $X_{id}(j + 1)$ is the value of the $i$-th particle in the $(j+1)$-th iteration; $P_{id}$
is optimal value searched so far by the \(i\)-th particle, and \(P_{gd}\) is the optimal value searched so far by all particles.

### 3. The convergence and correlation analysis of the TM-PSO method

When the TM-PSO method is used for locating the MS events, with the increase of particle flight times, the source parameters gradually stabilize until the end of the search, and it is considered that the TM-PSO method is convergent. When there are multiple source parameters that satisfy simultaneously the objective function of the TM-PSO method, there is correlation between source parameters. Therefore, the convergence and correlation of the TM-PSO method need to be analyzed theoretically to judge the influence of the location relationship between the MS source and sensor array on the localization.

Li et al. [22] studied the problem of type I multiple solutions in three-dimension, and drew conclusion that type I multiple solutions could be subdivided into the following two situations. Firstly, when all sensors are in a plane and not in a straight line, multiple solutions consist of two solutions and they are symmetrical about this plane passing through these sensors. Secondly, when all sensors are on a straight line, the number of solutions is infinite and they form a circle which is perpendicular to the straight line with the center on it. Therefore, the following discussion does not involve the case where the sensor is arranged on the same straight line and plane. The general formula of the TM-PSO method under ideal circumstances is shown in equation (10). The convergence and correlation of the TM-PSO method are discussed in the following five cases.

1. When the arrival time \(t_1\) of all the sensors only have one value, \(t_1\) is set to \(t_1\). At this time, the sensors are located on the same spherical surface and the MS source is located at the center of the sphere, shown in figure 1(a). The distance \(l_1\) between sensor and the MS source and the MS source coordinate \((x_0,y_0,z_0)\) can be obtained based on the sensor coordinates. Therefore, the MS source coordinate is unique, and the seismogenic time \(t_0\) can be any value that satisfies formula \(t_1 - t_0 > 0\).

2. When the arrival time \(t_0\) of all the sensors only have two different values and the sensors are on two spherical surfaces that have same center of sphere, \(t_1\) is set to \(t_1\) and \(t_2\), shown in figure 1(b). At this time, the MS source is located on the center of the two spherical surfaces, and there is only one MS source \(S\). The distance \(l_1\) and \(l_2\) between sensor and the MS source can be obtained based on the source coordinates, and the solution formula is as follows:

\[
l_1(t_2 - t_0) = l_2(t_1 - t_0) \tag{15}
\]

There is only one equation with one unknown parameter, so the solution is unique.

3. When the arrival time \(t_1\) of all the sensors only have two different values and all sensors divided into two groups of sensors on the same spherical surface, and two groups of sensors located on the cross-section circle parallel to each other, shown in figure 1(c). At this time, there are numerous MS sources located on the perpendicular bisector of the cross-section circle except for the center of the sphere, and equation (15) is satisfied for each MS source. Therefore, the solution of the MS source is not unique and the seismogenic time \(t_0\) varies with the MS source coordinates.

4. When the arrival time \(t_1\) of all the sensors only have three different values, \(t_1\) is set to \(t_1\), \(t_2\) and \(t_3\) and the arrangement of the sensor array is shown in figure 1(d). Theoretical analysis shows that the MS source is on the horizontal symmetry axis of the two sensors with the same arrival time. The distance between sensor coordinates and MS source is set to \(l_1, l_2\) and \(l_3\), and the formula is given by,

\[
\begin{align*}
&l_1(t_2 - t_0) = l_2(t_1 - t_0) \\
&l_1(t_3 - t_0) = l_3(t_1 - t_0) 
\end{align*}
\tag{16}
\]

Due to the MS source is on the horizontal symmetry axis of the two sensors with the same arrival time, there is a linear relationship between \(l_1, l_2\) and \(l_3\), and \(l_1, l_2, l_3\) can be expressed by \(l_1\). Therefore, there are two equations with two unknown parameters, such as \(l_1\) and the seismogenic time \(t_0\), so the solution of the MS source is unique.

5. When the arrival time \(t_1\) of all the sensors have four or more different values, the solution of the MS source is unique.
Overall, when all sensors are located on the cross-section circle parallel to each other of the same spherical surface, there will be multiple solutions using the TM-PSO method. Therefore, the location relationship between the sensor array and the MS source should be taken into consideration in the scheme design of the MS monitoring sensor layout, to avoid the situation of multiple solutions due to the inappropriate sensor array.

![Figure 1. Plane sketch diagram of the location relationship between the MS source and sensor array (T_i is the i-th sensor, and S is the MS source, and t_i is the arrival time of the i-th sensor).](image)

4. Engineering verification

4.1. Beiminghe Iron Mine

The Beiminghe Iron Mine in Hebei Province covering an area of 209500 m² began production in 2002 and had a designed annual production of 1.8 billion kg of iron ore. The height of the level is 60 m and the height of each sublevel is 15 m. Miners have repeatedly encountered abnormal situations since 2017, such as, the staff at the substation on the -122 m level and the excavation roadway on the -185 m level frequently hear the sound of abnormal blasting. For the safety of the mining area, a 16-channel SSS MS monitoring system jointly developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, and Hubei Seaquake Technology Co., Ltd., is deployed. The MS monitoring system consists of a 32-bit A/D acquisition apparatus, moving coil sensors with a sensitivity of 100 V/ms⁻¹, a PTP high-precision time synchronization server. Since the roadways above and below the -230 m level of the mine are the main mining roadway, the arrangement of sensors along these roadways will affect normal construction. Therefore, a total of 10 mono-component sensors and 2 three-component sensors are arranged mainly at the -230 m level and the sensor coordinates are shown in Table 1.

| No.  | Coordinate(m) | Sensor type  |
|------|---------------|-------------|
|      | x             | y           | z           |               |
| 101  | 1599.54       | 8771.51     | -245.77     | Mono-component|
| 102  | 1688.85       | 8749.96     | -226.38     | Mono-component|
| 103  | 1775.20       | 8690.28     | -230.48     | Mono-component|
| 104  | 1818.63       | 8743.12     | -227.06     | Three-component|
| 105  | 1912.76       | 8750.27     | -244.76     | Mono-component|
| 106  | 1892.18       | 8699.04     | -230.23     | Mono-component|
| 201  | 1956.15       | 8646.69     | -235.43     | Mono-component|
| 202  | 1965.26       | 8737.80     | -218.34     | Mono-component|
| 203  | 2075.01       | 8675.53     | -229.89     | Mono-component|
| 204  | 2020.12       | 8567.80     | -221.69     | Mono-component|
| 205  | 2057.23       | 8526.09     | -231.02     | Mono-component|
| 206  | 2138.42       | 8693.26     | -230.23     | Three-component|

Table 1. Sensor coordinates.
To verify the location effect of the TM-PSO method, 12 blasting events were carried out in the Beiminghe Iron Mine from September 17 to October 7, 2018, and the locations of these blasting events were shown in Table 2. The blasting tests are single-hole blasting with a small charge and the location of the blasting, time, waveform and other data are recorded. 12 blasting events are located by the TM-PSO method, the TMSL method with a uniform velocity model set to 5222 m/s and the TD method. The PSO parameters are set to $[23, 24]$: the learning rates $c_1 = c_2 = 2$, inertial weight $w=0.8$, population number $N_{\text{pop}}=4000$, the flying times $N_g=5000$, and fitness conditions $e = 1.0 \times 10^{-10}$. The range of coordinates $x \in (1500, 2200)$, $y \in (8400, 8800)$, $z \in (-250, -150)$, and the unit is m. The range of velocity $v \in (4000, 7000)$, and the unit of wave velocity is m/s. The range of the seismogenic time $t_0 \in (t_{\text{min}} - 0.14, t_{\text{min}})$, where is the minimum arrival time of all triggering sensors, and the unit is s. The location results of the TM-PSO method, the TMSL method, and the TD method are shown in figure 2. The average location errors of the TM-PSO method, TMSL method, and TD method are 11.38 m, 22.41 m, and 18.19 m, respectively. Overall, the location accuracy of the TM-PSO method is 49.22% greater than that of the TMSL method and 37.44% greater than that of the TD method. For some blasting events, such as blasting event No.10, 11 and 12, the location effect of the TM-PSO method is worse than that of the TD method. In general, the TM-PSO method achieves higher accuracy and better stability than the TMSL method and the TD method.

Table 2. Locations of the blasting events.

| No. | Site            | Coordinate (m) |   |   |   |
|-----|-----------------|----------------|---|---|---|
| 1   | 6-28drift       | 2087.38        | 8566.32 | -198 |
| 2   | 7# crossheading | 2034.44        | 8572.42 | -198 |
| 3   | 7# crossheading | 2032.51        | 8573.11 | -198 |
| 4   | 4-2drift        | 1993.25        | 8596.92 | -198 |
| 5   | 5# crossheading | 2020.55        | 8576.69 | -213 |
| 6   | 5# crossheading | 2016.90        | 8578.44 | -213 |
| 7   | 5# crossheading | 2018.63        | 8577.67 | -213 |
| 8   | 5# crossheading | 2024.27        | 8575.35 | -213 |
| 9   | 4-2drift        | 1994.13        | 8599.20 | -213 |
| 10  | 3-17drift       | 1927.97        | 8700.44 | -198 |
| 11  | 3-16drift       | 1906.93        | 8696.39 | -198 |
| 12  | 3-16drift       | 1907.93        | 8698.90 | -198 |
4.2. Headrace tunnel in the Neelum-Jhelum hydroelectric station

The headrace tunnel in the Neelum-Jhelum hydroelectric station in Pakistan has the characteristics of long tunnel, large buried depth and high in-situ stress, and the maximum in-situ measured principal stress is over 100MPa. Due to the frequent occurrence of geological disasters such as rockburst in the construction process of TBM, SSS monitoring system is introduced to continuously monitor the tunnel under construction for 24 hours, and the sensor coordinates move forward with the tunnel face. From June to September, 2016, 6 blasting events were carried out in the tunnel face, and the locations of these blasting events were shown in Table 3. 6 blasting events are located by the TM-PSO method, the TMSL method with a uniform velocity model set to 5500 m/s and the TD method. The PSO parameters are same to above parameters, and the range of three-dimensional coordinates vary with the tunnel face. The location results of the TM-PSO method, TMSL method, and TD method are shown in figure 3. The average location errors of the TM-PSO method, TMSL method, and TD method are 13.28 m, 34.05 m, and 32.15 m, respectively. Overall, the location accuracy of the TM-PSO method is 61% greater than that of the TMSL method and 58.69% greater than that of the TD method. For some blasting events, such as blasting event No.2 and 4, the location effect of the TM-PSO method is worse than that of the TD method. In general, the TM-PSO method achieves higher accuracy and better stability than the TMSL method and the TD method.

Table 3. Locations of the blasting events.

| No. | Coordinate (m) |          |          |
|-----|----------------|----------|----------|
|     | x              | y        | z        |
| 1   | 7904.30        | -6.10    | -64.20   |
| 2   | 8000.24        | 6.07     | -64.96   |
| 3   | 8018.24        | -6.07    | -65.11   |
| 4   | 8036.24        | -6.07    | -65.25   |
| 5   | 8636           | 0        | -58      |
| 6   | 8722           | 0        | -58      |
5. Conclusion

Based on particle swarm optimization, a new objective function without pre-measuring wave velocity, named TM-PSO method, is proposed. Based on the number of the arrival time of MS events, combining the sensor array and the expression of the TM-PSO method, the convergence and correlation of objective functions of the TM-PSO method are analyzed theoretically. It is concluded that when all sensors are located on the cross-section circle parallel to each other of the same spherical surface, there will be multiple solutions using the TM-PSO method. The field test of the Beiminghe iron mine in Hebei province and the headrace tunnel in the Neelum-Jhelum hydroelectric station in Pakistan show that the stability and location accuracy of the TM-PSO method is superior to the TMSL method and TD method, which has important practical application value.

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6. References

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