Microseismic source location in tunnels: Effect of arrival-time picking

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Abstract. The microseismic (MS) monitoring technique is widely used in deep tunnels for rock mass stability monitoring and disaster warning. MS source location is the basis of the MS monitoring technique. This study investigates the effect of arrival-time picking on MS source location in a tunnel. A total of 1000 MS sources, 12,000 arrival-time pickings, and particle swarm optimization are used. Accordingly, 3796 source-locating operations are conducted for each MS source. The results show that the number of arrival-time pickings and their mode of combination significantly affect the accuracy and the stability of MS source location in a tunnel. The optimal location cannot be obtained when using the arrival-time pickings with the smallest errors. The optimal location accuracy decreases with the increase in the number of arrival-time pickings; however, the average location accuracy increases therewith. The source location accuracy significantly changes when the number of arrival-time pickings is small. The location result becomes more stable with the increasing number of arrival-time pickings. Accordingly, a suggestion involving the usage of all arrival-time pickings for MS source location in a tunnel is provided. The results will contribute to rock mass stability monitoring and disaster warning in tunnels using the MS monitoring technique.

1. Introduction

Many deep underground projects, such as deep petroleum caverns, deep drainage tunnels, deep mines, and deep powerhouses, have been built, are under construction, or are being planned. These deep underground projects are undertaken in a special environment subject to high stress. During the deep rock engineering operations in the recent years, high stress-induced geotechnical disasters have frequently occurred. These disasters include rock bursts, stress-induced collapses, stress-induced deformation, mining-induced earthquakes, water inrush accidents, fault slip, etc., which have seriously endangered the safety of underground geotechnical engineering personnel and the utilization of deep underground space.

Microseismic (MS) monitoring techniques are widely used in deep rock engineering projects for stress-induced disaster monitoring, accident warning, and risk mitigation, albeit with differing degrees of success [1–24]. As one of the important parts of any MS monitoring technique, MS source location has been studied for many years [2, 12, 17–19, 25–26]. Errors in MS source location are inevitable [2, 12, 17–19, 25], especially in deep tunnel engineering [12, 17–18]. These errors and the number of arrival-time pickings significantly affect the MS source location accuracy; however, the relationships between them are unclear in tunnel engineering scenarios. Meanwhile, using a large number of MS...
sensors in MS monitoring practice requires much manpower and material resource for gathering more information pertaining to arrival-time pickings. This study investigates the effect of arrival-time picking on MS source location in a tunnel to optimize the MS monitoring scheme in tunnel engineering work. The effects of the combination mode and the number of arrival-time pickings on the MS source location accuracy and stability are analyzed. An efficient global optimization algorithm, called particle swarm optimization (PSO), is used in MS source location for the present analysis. The results will contribute to the rock mass stability monitoring, disaster warning, and risk mitigation in tunnels using the MS monitoring technique.

2. Numerical experimentation: An overview
Numerical experimentation is used to test the MS source location accuracy and stability in a tunnel under different combination modes and given different numbers of arrival-time pickings. For these tests, we considered a location network consisting of six sensors, whose coordinates are listed in Table 1. The P and S-wave velocities were set to 6000 and 3500 m/s, respectively. The time origin of each MS source was set to 0. In tunnel engineering, MS sources always develop outside the array of MS sensors. Figure 2 depicts that the randomly simulated MS sources were all outside the network. A total of 100 MS sources were simulated. Random errors were assigned to the arrival times of P- and S-waves at each sensor for all 100 MS sources, and those in the trigger times of both waves were controlled to be within ±0.5 ms. Tables 2 and 3 present as an example the arrival times of the P- and S-waves for MS Source 1 and its coordinates, respectively.

Table 1 MS sensor coordinates.

| MS sensor no. | Coordinate x (m) | y (m) | z (m) |
|---------------|------------------|-------|-------|
| 1             | 1                | 8     | −4    |
| 2             | 0                | 2     | 8     |
| 3             | 2                | −9    | −5    |
| 4             | 38               | 9     | −2    |
| 5             | 43               | −3    | 7     |
| 6             | 42               | −7    | −4    |

![Figure 1](image1.png)

Figure 1 Layout of the simulated six MS sensors and 100 MS sources.

Table 2 Arrival times for MS Source 1.

| MS sensor no. | Actual arrival time (s) | Arrival-time picking (s) | Errors in arrival-time picking (s) |
|---------------|-------------------------|--------------------------|-----------------------------------|
| 1*            | 0.01492908 0.02559271   | 0.01443033 0.02565629    | 0.00049875 0.00006359             |
| 2*            | 0.01537999 0.02636569   | 0.01507329 0.02667443    | 0.00030670 0.00030874             |
| 3*            | 0.01484595 0.02545019   | 0.01493096 0.02543007    | 0.0008501 0.00002013              |
| 4*            | 0.00890337 0.01526292   | 0.00875366 0.01565888    | 0.00014971 0.00039596             |
| 5*            | 0.00852013 0.01460593   | 0.00884297 0.01485254    | 0.00032284 0.00024660             |
| 6*            | 0.00827620 0.01418777   | 0.00795031 0.01454671    | 0.00032589 0.00035894             |
Table 3 MS Source 1 coordinates.

| MS source no. | Coordinate |
|---------------|------------|
|               | x (m)      | y (m)      | z (m)      |
| 1             | 90.025025  | 2.543413   | -12.267830 |

3. Location method
The function for locating the MS source is expressed as follows:

\[ f = \sum_{i=1}^{n} ((t^P_i - t_o - R_i/V^P)^m + (t^S_i - t_o - R_i/V^S)^m) \]  

(1)

where, \( f \) is the time residual. When the target function \( f \) attains its minimum value, the solutions obtained for \((x_o, y_o, z_o)\) are the optimum values for the MS source location. \( n \) represents the number of sensors. \( i \) is the label of a sensor. \( t^P_i \) and \( t^S_i \) are the arrival-times of the P- and S-waves at sensor \( i \), respectively. \( t_o \) is the seismogenic time of the MS source. \( V^P \) and \( V^S \) are the velocities of the P- and S-waves from the MS source to the sensor, respectively. \( m \) is the norm. \( R_i \) is the distance between the MS source and sensor \( i \) given as follows:

\[ R_i = \sqrt{(x_i - x_o)^2 + (y_i - y_o)^2 + (z_i - z_o)^2} \]  

(2)

where, \((x_i, y_i, z_i)\) depict the MS sensor \( i \) coordinates.

The PSO algorithm was used to seek the MS source location based on Eq. (1) because of its powerful global search capability. PSO is an emerging and intelligent optimization method [27], which is a powerful global optimization algorithm that has been successfully used in many problems. An introduction to PSO in MS source location can be found in the literature [12, 17].

4. Numerical analysis: Results
4.1. MS source location process
As an example, 12 arrival-time pickings were used to find the location of the simulated MS Source 1 based on the location function [Eq. (1)] with the PSO algorithm. The PSO parameters were set to the following values: learning rates: \( c_1 = c_2 = 2 \); inertia weight: \( c_0 = 0.8 \); number of particles: \( m = 500 \); flying time: \( N_t = 1000 \); and a fitness condition such that \( e = 1.0 \times 10^{-20} \). Figure 2 depicts the particle flying process that occurs during the search for MS Source 1. A location result was obtained after each step in the particle flying time. In the early stages of the solution process (flying times from 0 to 20), the search results significantly fluctuated and gradually became more stable as the flying time increased. Finally, all the search results converged and remained stable after a certain flying time. Thus, the best location result was (92.065115, 1.451013, -20.209529), and the location error was 8.27 m.
Different numbers and combination modes of arrival-time pickings were used in the tests to find the locations of the 100 simulated MS sources. The least number of arrival-time pickings was four, and 3797 location operations were conducted for each MS source (Table 4). Different location results were then obtained and used in a subsequent analysis.

**Table 4** Arrival times for MS Source 1

| Number of arrival-time pickings | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 |
|---------------------------------|----|----|----|---|---|---|---|---|---|
| Number of locations for each MS source | 1 | 12 | 66 | 220 | 495 | 792 | 924 | 792 | 495 |

### 4.2. Location accuracy and stability analysis

#### 4.2.1. Effect of the combination mode of arrival-time pickings

Figure 3 shows, as an example, the location errors for MS Source 1 based on different combinations of six arrival-time pickings, wherein the minimum location error was 1.71, while the maximum error was 58.9 m. Figure 4 depicts the location error distribution for MS Source 1 based on different combinations of the six arrival-time pickings. The location errors were mainly within 15 m, which accounted for 84% of all points. Most location errors were between 5 m and 10 m. The results showed that the combination mode of arrival-time pickings significantly affects the MS source location accuracy.

**Figure 3** Location errors for MS Source 1 based on different combinations of six arrival-time pickings.

**Figure 4** Distribution of the location errors for MS Source 1 based on different combinations of six arrival-time pickings.

The combinations of the arrival-time pickings for the optimal location with different numbers of arrival-time pickings were investigated herein. Figure 5 shows the result for MS Source 1. The optimal
location for four arrival-time pickings was obtained when using the arrival-time pickings, whose errors were ranked as 6, 7, 8, and 11 (i.e., the smaller the rank, the lower the error in arrival-time picking). However, the optimal location cannot be obtained using the arrival-time pickings with the smallest errors (i.e., ranked 1, 2, 3, and 4 in Figure 5), wherein the same results from the other numbers of arrival-time pickings can be found (i.e., the optimal location cannot be obtained using the arrival-time pickings with the smallest errors in the test). Therefore, no direct relationship was found between the optimal location accuracy and the errors in the arrival-time pickings.

Figure 5 Combinations of the arrival-time pickings for the optimal location of MS Source 1 with different numbers of arrival-time pickings. On the horizontal axis, 1 denotes the arrival-time picking with the smallest error, and 12 denotes that with the largest.

4.2.2. Effect of the number of arrival-time pickings
Figure 6 exhibits the optimal location errors for the first 10 MS sources based on different numbers of arrival-time pickings and the evolution of the optimal location error with the increasing number of arrival-time pickings. The results showed that the optimal location error tends to decrease with the decreasing number of arrival-time pickings.

Figure 6 Evolution of the optimal location error with the increasing number of arrival-time pickings.
Figure 7 illustrates the evolution of the average and optimal location errors for the 100 MS sources with the increasing number of arrival-time pickings. The optimal location accuracy decreased (i.e., the optimal location error increased) with the increasing number of arrival-time pickings; however, the average location accuracy increased (i.e., the optimal location error decreased) therewith. The optimal location cannot be obtained using the arrival-time pickings with the smallest errors in the test; hence,
finding the optimal location result is difficult in practice. In other words, using all the arrival-time pickings for MS source location in a tunnel would be better.

**Figure 7** Evolution of the average and optimal location errors with the increasing number of arrival-time pickings.

### 4.2.3. Solution stability analysis
MS Source 1 was used herein as an example to study the solution stability. Figure 8 shows the variance evolution and the difference between the maximum and minimum values with the increasing number of arrival-time pickings for MS Source 1. The difference between the maximum and minimum values changed with the number of arrival-time pickings (i.e., the greater the number of arrival-time pickings, the smaller the absolute value between the maximum and minimum values). In other words, the source location significantly changed when the number of arrival-time pickings was small. This result can be analyzed in a more quantitative manner using the variance. The variance in the source location of MS Source 1 for different numbers of arrival-time pickings is given as follows:

\[
\sigma^2 = \frac{\sum_{j=1}^{N} (X_j - \bar{X})^2}{N} \tag{3}
\]

where, \(\sigma^2\) is the variance of the data; \(N\) is the number of MS source locations; \(X_j\) is the \(j\)th source location; and \(\bar{X}\) is the mean value of all source locations.

Eq. (3) was used to calculate the variance in the MS source locations (Figure 8).

**Figure 8** Evolution of the difference between the maximum and minimum values and the variances with the number of arrival-time pickings for MS Source 1.

The greater the number of arrival-time pickings, the smaller the variance. In conclusion, the location accuracy became more stable with the increasing number of arrival-time pickings used. The variance
significantly increased with the decrease in the number of arrival-time pickings when the number of arrival-time pickings was less than seven. Therefore, using all arrival-time pickings for MS source location in a tunnel is deemed better.

5. Conclusion
This study investigated the effect of arrival-time picking on MS source location in a tunnel. The effects of the combination modes and the number of arrival-time pickings on the MS source location accuracy and stability were analyzed. The results will contribute to rock mass stability monitoring, disaster warning, and risk mitigation in tunnels using the MS monitoring technique. The following results were obtained from this study:
(1) The number of arrival-time pickings and their combination modes significantly affect the MS source location accuracy in a tunnel. The optimal location cannot be obtained when using the arrival-time pickings with the smallest errors in the test.
(2) The optimal location accuracy decreases with the increasing number of arrival-time pickings; however, the average location accuracy increases therewith.
(3) The source location accuracy significantly changes when the number of arrival-time pickings is small. The location accuracy becomes more stable with the increasing number of arrival-time pickings. All arrival-time pickings are suggested for use in MS source location in a tunnel.

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