Journal of Engineering Science and Technology Review 17 (5) (2024) 48-54

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Effects of Velocity Errors and Arrival Time Errors on the Location Accuracy of Microseismic Monitoring using Dual Waves

Zhigang Wang*, Xiaoqing Wang and Shunlin Yin

College of Energy Engineering, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China

Received 11 July 2024; Accepted 30 September 2024

Abstract

The dual-wave location technique in microseismic monitoring can improve the location accuracy in areas outside the monitoring network and near the sensors, increasing the monitoring range with high precision. However, the response of seismic source location accuracy to input parameter errors remains unclear. In this study, numerical simulation methods were employed to understand the impact of wave velocity errors and arrival time errors on location accuracy when the P–S-wave location technique was used. Three points inside and three points outside a typical monitoring network were selected. Then, P waves and dual waves were applied to the seismic source locations, and the variations in location errors in the horizontal and vertical directions were analyzed as the relative wave velocity error ranged from −10% to 10% and the arrival time error ranged from −0.05 to 0.05 s. The results demonstrate that, when P waves are used, the location error outside the monitoring network increases rapidly and rapidly reaches an unacceptable range. By contrast, when dual waves were used, the ability of the microseismic monitoring system to handle input parameter errors was improved; the location errors increased linearly with increasing input parameter errors. Furthermore, for the same wave velocity error or arrival time error, the location results with the dual waves are relatively close to the actual seismic source location and stable, especially outside the network, where the reduction in location error could exceed 90%. The findings provide a scientific basis for accurately assessing and understanding the location results of microseismic monitoring with the use of dual waves.

Keywords: Seismic source location, P wave and S wave, Wave velocity error, Arrival time error, Location accuracy

1. Introduction

Microseismic monitoring can monitor and capture unstable signals (i.e., rockbursts, coal and gas outbursts) in real time in underground engineering [1–5]. Moreover, this technique enables the analysis of the occurrence locations and characteristics of these events [6-7]. The accurate location of a seismic source is crucial for the precise assessment of underground engineering stability and the prevention of geological disasters [8]. The key factors affecting the accuracy of seismic source location include the accuracy of the stress wave velocity model adopted, the accuracy of the arrival time of the stress wave at the sensors, the geometric distribution and size of the monitoring network, the accuracy of the coordinates of each sensor in the monitoring network, and the relative location of the seismic source to the monitoring network [9–13]. However, under reasonable arrangements of the monitoring network, errors in the wave velocity model and arrival time are the primary sources of location error.

Scholars worldwide have proposed various models, including single-wave velocity models, non-average velocity models [14], layered wave-velocity models [15-16], and anisotropic wave-velocity models [17], to improve the location accuracy of microseismic monitoring. These models aim to improve location accuracy by reducing wave velocity errors. The arrival time error refers to the difference between the calculated arrival time parameters and the actual arrival time parameters. Factors such as the signal-to-noise ratio, onsite construction operations, and arrival time picking algorithms can affect the accuracy of arrival time picking. Currently, high-precision arrival time picking is achieved via methods such as improving the signal-to-noise ratio, optimizing algorithms, and automatically picking microseismic waveforms [18–20]. However, for microseismic events occurring at the edges and outside of the geometric distribution of sensors, the location error remains significant and may even be unlocatable.

On the basis of these findings, some researchers have utilized S waves, that is, the use of both P and S waves for seismic source location [21]. Microseismic events within and outside a certain area of the sensor array layout can also be located with high accuracy [22]. However, in real environments, whether it is a P wave or an S wave, a difference exists between the wave velocity used in calculations and the actual propagation velocity of stress waves in the rock mass. Additionally, discrepancies arise between the input arrival time parameters and the actual time at which the sensors receive the microseismic waves, resulting in a distance between the calculated location results and the actual locations of the microseismic events. Therefore, exploring the response of the location accuracy of microseismic monitoring using dual waves to the wave velocity errors and arrival time errors and comparing it with the results from single P wave responses has significant practical implications.

On the basis of these considerations presented above, a comparative analysis via extensive numerical simulations was conducted to examine the impact of different wave

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*E-mail address: zhigangwong@xust.edu.cn

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doi:10.25103/jestr.175.06

velocity errors and arrival time errors on the location results of a typical three-dimensional distribution monitoring network when dual waves and a single wave were utilized. The aim was to analyze the effects of wave velocity errors and arrival time errors on location accuracy, thereby offering insights that could guide a comprehensive evaluation of location results by using dual waves and promoting the advancement of dual-wave location techniques in microseismic monitoring.

2. State of the art

The wave velocity error is the primary factor affecting the accurate determination of seismic source locations, and many scholars have conducted extensive research on this topic. For example, Jia et al. [23] established an ideal theoretical velocity model and combined it with a particle swarm optimization algorithm to analyze the location errors of microseismic monitoring when the relative wave velocity error ranged from −15% to 15%. They reported that the location error of the seismic source point increases with increasing wave velocity error and that the location accuracy within the monitoring network is higher than that outside it. The external location error increases approximately exponentially with increasing wave velocity error; the lower the velocity is, the more significantly the location results are affected. Han et al. [24] used numerical simulations to analyze the seismic source location errors in the X, Y, and Z directions via the homologous wave–time difference method under different wave velocity models. The results indicate that as the error, referred to as the difference between the inverted velocity model and the accurate velocity model, increases, the accuracy of the seismic source location gradually decreases. When the velocity model error is within 200 m/s, the overall location error can be controlled within 20 m. Feng et al. [25] introduced velocity errors of ±5% and ±10% into the velocity model and conducted reverse double-difference time imaging. They reported that the location error increases with increasing wave velocity model error. When the velocity model is close to the accurate model, the error is almost zero. The location error caused by negative errors in the velocity model is greater than that caused by equivalent positive errors. Yin et al. [26] analyzed the changes in X-error, Y-error, Z-error, and absolute error with velocity model errors ranging from −10% to 8% via numerical simulation. They concluded that the X-error is the largest and that the location error caused by negative errors in the velocity model is greater than that caused by equivalent positive errors; however, all the errors generally increase with increasing wave velocity error. Feng et al. [27] analyzed the impact of the accuracy of the velocity used in location algorithms in tunnels on the accuracy of seismic source location and concluded that the location error increases with the absolute value of the wave velocity error. In the absence of wave velocity errors, the location error is zero, and the location accuracy within the sensor arrangement is higher than that outside of it. Li et al. [28] studied the changes in seismic location accuracy under internal velocity errors ranging from 0 to 30% and external velocity errors ranging from 0 to 50% in a monitoring network. They reported that the location error increases with increasing velocity error, and under the same velocity error, the location accuracy within the sensor is significantly higher than that outside it. Wave velocity errors remarkably affect precise seismic source locations. However, the abovementioned studies considered scenarios in which only a single P wave was used for location detection, and for microseismic events occurring outside the sensor array, the location error is particularly large, hindering accurate location detection. Furthermore, the response mechanism of location results to wave velocity errors when P–S waves are used for seismic source location has not yet been reported.

The input time error of the microseismic waves reaching the sensor significantly affects the location accuracy. Han et al. [24] studied the effect of initial arrival time picking errors of 10, 20, and 40 ms on the accuracy of microseismic source location when the homologous wave–time difference method was used in mining. They reported that the seismic source location error increases with increasing initial arrival time picking error. When the picking error is controlled within 10 ms, the overall seismic source location error can be kept within 20 m. Luo et al. [29] analyzed the seismic source location errors via three location methods: P- and S-wave arrival time combined Bayesian location (P_SBL), P-wave arrival time Bayesian location (P_BL), and S-wave arrival time Bayesian location (S_BL), with different arrival time errors. The results show that in the absence of Gaussian noise, the location error is close to 0; as the Gaussian noise added to the P wave and S wave travel time data increases, the location error also increases. Compared with the P_BL method and the S_BL method, the P_SBL method improves the location accuracy by 25.40% and 60.78%, respectively, highlighting the importance of including S-wave arrival time data. Chen et al. [30] increased the arrival time error by 1% to 9% and analyzed the impact of arrival time picking errors on the seismic source location, concluding that for every 2% increase in the arrival time picking error, the location error increases by approximately 5 m. When the arrival time error increases to 9%, the location error reaches 50 m, demonstrating the importance of a 2% to 3% increase in the accuracy of arrival time picking. Jiang et al. [31] studied location errors under different numbers of triggering sensors with Gaussian noise levels of 1 and 2 ms and reported that the greater the Gaussian noise is, the larger the location error; moreover, the greater the number of triggering sensors is, the higher the location accuracy. Li Nan [32] conducted theoretical analysis and numerical simulations and concluded that the impact of the arrival time on the microseismic location is determined mainly by the accuracy of the arrival time picking and the correct picking of the arrival waves. When the types of arrival waves are analyzed and identified, the abnormal signals are eliminated, and sensors employ the S wave velocity to determine whether the S wave would arrive. This technique can significantly improve location accuracy. Therefore, the arrival time error received by sensors evidently plays an important role in the accuracy of seismic source location, and incorporating S-wave arrival time picking can increase location accuracy. However, the abovementioned scholars did not comprehensively and systematically analyze the impact of the difference between the arrival time parameters used and the actual arrival time parameters on the accuracy of the seismic source location within and outside the monitoring network, nor did they discuss the response of the microseismic monitoring system to arrival time errors by using dual-wave location techniques.

The abovementioned research findings focus mainly on the relationships between wave velocity errors, arrival time picking errors, and location errors. On the one hand, most of the aforementioned studies consider only the scenario of applying a single P wave, with little discussion on the impact of input parameter errors on location accuracy when dual waves are used. On the other hand, the research is limited in terms of how the location accuracy in external areas of the monitoring network responds to input parameter errors. Furthermore, the effects of different input parameter errors on the location accuracy of the monitoring system when dual waves and single P waves are used in microseismic monitoring systems have not yet undergone systematic comparative analysis. In this study, a numerical simulation program was developed. A monitoring network with three sensors arranged underground, with other sensors placed on the ground in a centrally circular distribution, was employed. The program employed dual waves and a single P wave for seismic source location. Three monitoring points were selected both inside and outside the network to analyze the changes in location accuracy as the relative wave velocity error varied from −10% to 10%, and the arrival time picking error ranged from −0.05 to 0.05 s. After applying P–S waves, the ability of the microseismic monitoring system to handle input parameter errors improved, and the location error increased linearly with increasing input parameter errors. For the same wave velocity error or arrival time error, the location results are closer to the actual seismic source location and are more stable, especially in the external areas of the monitoring network. The research results provide a scientific basis for a comprehensive and accurate assessment of the location results when dual waves are used in microseismic monitoring.

The remainder of this article is organized as follows. The third part discusses the methods and schemes for numerical simulation. The fourth part presents a comparative analysis of the effects of wave velocity errors and arrival time errors on the location accuracy inside and outside the network distribution in typical monitoring networks when dual waves and a P wave are utilized, respectively. The final section summarizes the findings and presents relevant conclusions.

3. Methodology

3.1 Simulation method

MATLAB computational software was utilized to develop a numerical simulation program. This program was used to analyze the location results under different wave velocity errors and arrival time errors when dual waves and a single wave were utilized.

Using computers for numerical simulation, numerous calculations were performed for each point within the monitored area, which further implies that a significant number of computer simulation experiments were conducted for each point. During the simulation process, two types of errors were introduced: wave velocity error and arrival time error. The propagation velocities of the P wave and S wave are assumed to follow normal distributions $V_p \sim N(\widehat{V}_p, \sigma_{V_p})$ and $V_s \sim N(\widehat{V}_s, \sigma_{V_s})$, respectively. Similarly, the time errors of the stress wave arriving at each sensor follow a normal distribution, $\xi \sim N(0, \sigma_t)$. Therefore, the required time for the P wave to travel from the source point $P_j(x_j, y_j, z_j)$ to the sensor T_i is solved as:

$$t_{i,j} = \frac{d_{i,j}}{\langle V_p \rangle} + \langle \xi \rangle \tag{1}$$

and for the S wave:

$$t_{i,j} = \frac{d_{i,j}}{\langle V_s \rangle} + \langle \xi \rangle \tag{2}$$

where $d_{i,j}$ represents the distance between sensor T_i and point P_j. $\langle V_p \rangle$ and $\langle V_s \rangle$ represent the randomly generated velocities of the P wave and S wave, respectively. $\langle \xi \rangle$ represents the randomly generated arrival time error.

Then, the seismic source location was determined via the randomly generated velocity samples and the contaminated arrival times. After a large number of repeated experiments, the average distance between the calculated seismic source location $P_j^{'}$ and the actual seismic source location P_j was defined as the seismic source error of this point as follows:

$$\sigma(P_j) = \frac{\sum_{k=1}^{N} \sqrt{[(x'_j)^k - x_j]^2 + [(y'_j)^k - y_j]^2 + [(z'_j)^k - z_j]^2}}{N} \tag{3}$$

where N represents the number of repetitions and (x'_j, y'_j, z'_j) denotes the coordinates of the point $P_j^{'}$.

Numerical simulations were employed to analyze the accuracy of the seismic source location. The number of repetitions N was set to 1000. Assuming that the mean value of the P wave velocity $\widehat{V}_p$ was 3000 m/s, the standard deviation of the P wave velocity σ_{V_p} was 10% of the mean value, i.e., 300 m/s. Assuming that the S wave propagation velocity was 60% of the P wave velocity, the mean S wave velocity $\widehat{V}_s$ was 1800 m/s. Similarly, the standard deviation of the S wave velocity σ_{V_S} was set to 10% of its mean value, resulting in a standard deviation of 180 m/s. The arrival time error σ_t was set to 0.005 s. The Simplex seismic source location algorithm based on the least square method was employed to search for the seismic source location.

3.2 Simulation scheme

Numerical analysis was employed to investigate the impact of wave velocity errors and arrival time errors on location accuracy, and a monitoring network with three sensors placed underground and four sensors arranged in a central ring configuration on the surface was designed (Table 1). Three points inside the network and three points outside the network were selected for investigation. The coordinates of the six monitoring points are listed in Table 2. The monitoring network and arrangement of monitoring points are shown in Fig. 1. The red rectangles indicate the sensor locations, and the blue circles denote the locations of the monitoring points. In particular, points 1, 2, and 3 are located within the monitoring network, whereas points 4, 5, and 6 are situated outside the geometric configuration formed by the sensors.

Table 1. Sensor deployment coordinates of the monitoring network

Sensors	x/m	y/m	z/m
1	433	−250	0
2	0	500	0
3	−433	−250	0
4	0	0	0

5	433	−250	−100
6	0	500	−100
7	−433	−250	−100

Table 2. Coordinates of the monitoring points

Monitoring points	x/m	y/m	z/m
1	100	100	−40
2	0	0	−50
3	−200	−200	−60
4	−650	−650	−180
5	700	700	−200
6	−750	750	−220

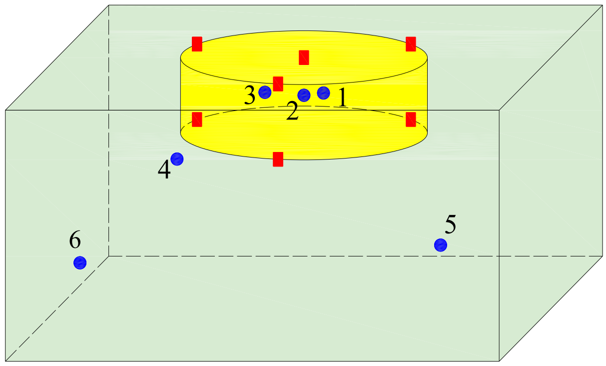


Fig. 1. The monitoring network and the arrangement of monitoring points

In investigating the impact of wave velocity errors on location accuracy, other parameters (i.e., sensor coordinates and arrival times) were assumed to be error-free, and only wave velocity errors were considered. The wave velocity errors were expressed as relative values, defined as the ratio of the absolute value of the error to the actual velocity. A negative relative error indicates that the velocity used in the calculations is less than the actual velocity, whereas a positive relative error indicates that the input velocity for the seismic source location is greater than the actual velocity. The analysis examined how location errors at each monitoring point change as the relative error ranges from −10% to 10%.

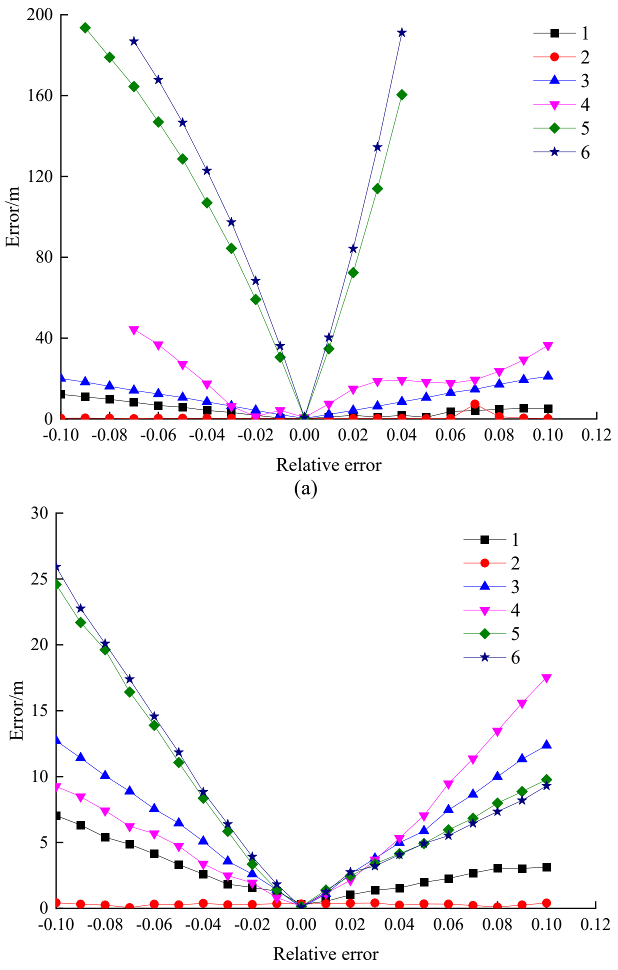
In analyzing the impact of arrival time errors on location accuracy, other parameters (i.e., sensor coordinates and stress wave propagation velocity) were assumed to be correct, with only the arrival time parameter of the stress wave being subject to error. The arrival time errors ranged from −0.05 to 0.05 s, where negative errors indicate that the input arrival time parameter for the seismic source location is less than the actual value of the arrival time, and positive errors indicate that the used arrival time parameter is greater than the actual arrival time parameter when searching for the seismic source location. The analysis examined the evolution of location errors at each observation point as the arrival time errors varied.

4. Experimental results and analysis

4.1 Effects of the velocity error on the location accuracy

4.1.1 Effect of the velocity error on the horizontal error

The variation in the horizontal location error with the wave velocity error in the location results of microseismic monitoring is shown in Fig. 2. When only P waves were used, the location accuracy for the three points inside the monitoring network (points 1, 2, and 3) was notably high, with errors within 25 m. However, for the three external points (points 4, 5, and 6), the location error increased rapidly with increasing relative wave velocity error. When the relative error exceeded 5%, the location error surpassed 200 m. By contrast, after applying dual waves, the location error for all six monitoring points gradually increased with increasing wave velocity error. The location error inside the network remained within 15 m, and the external location effect improved significantly, with the maximum error reduced to within 30 m, representing a reduction of over 90%. These results indicate that the microseismic monitoring system that uses P–S waves is more robust against wave velocity error, particularly in external areas of the monitoring network.



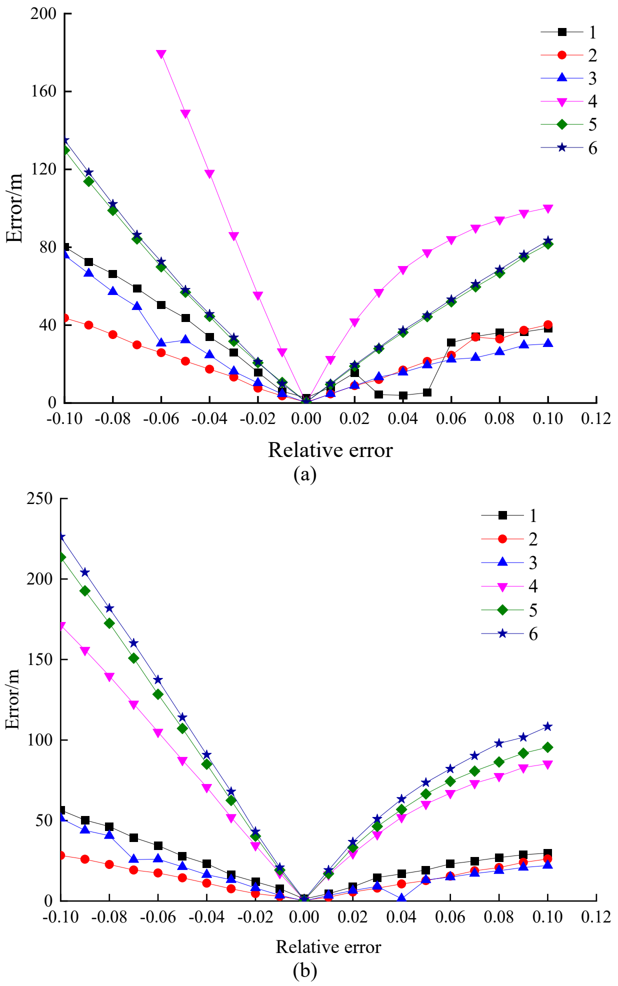
(a)

(b)

Fig. 2. Relationships between horizontal error and wave velocity error. (a) Utilization of P waves. (b) Utilization of P–S waves

4.1.2 Effect of the velocity error on the vertical error

The variation in the vertical error with the wave velocity error in the location results of microseismic monitoring is shown in Fig. 3. When only the P wave was used, the location accuracy for three points inside the monitoring network (points 1, 2, and 3) was relatively high, with errors within 80 m. Beyond the monitoring network, the location errors for points 5 and 6 increased linearly, reaching a maximum of 140 m. The location error for point 4 increased more rapidly, and when the negative wave velocity error exceeded 6%, the location results became unacceptable for engineering purposes. With the application of dual waves, the location errors for the three points within the network increased slowly with wave velocity error, with a maximum error of no more than 60 m, indicating a slight improvement in location accuracy compared with the use of only the P wave. For the three points outside of the network, the location error increased rapidly, reaching approximately 200 m, but the stability of the location results improved compared with that when only the P wave was used, simplifying the evaluation. These findings indicate that the microseismic monitoring system that uses dual waves has an enhanced ability to handle wave velocity errors in the vertical direction, particularly in areas outside the sensor network.



(a)

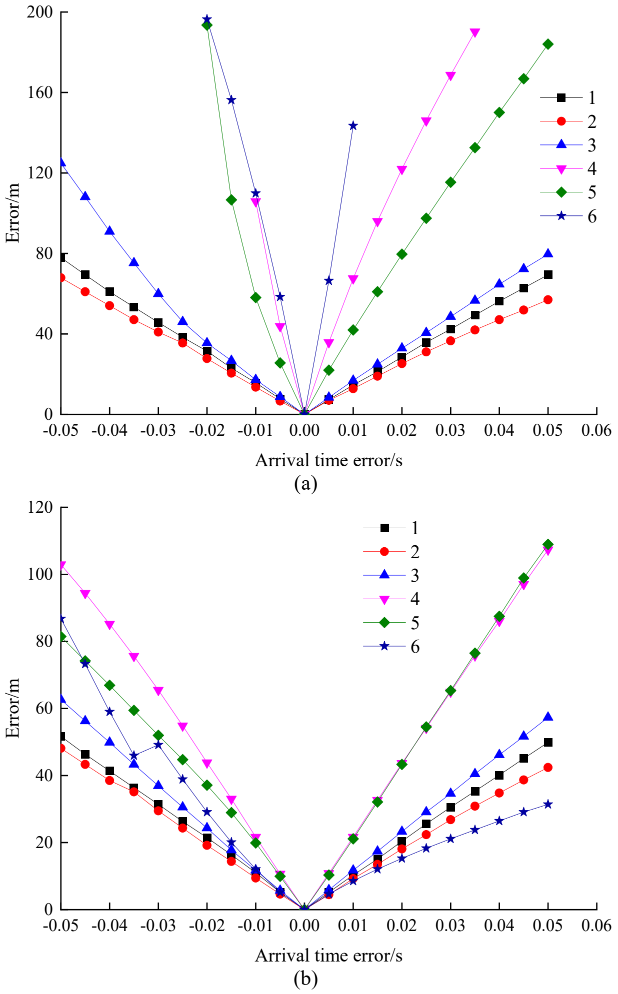
(b)

Fig. 3. Relationships between the vertical error and wave velocity error. (a) Utilization of P waves. (b) Utilization of P–S waves

4.2 Effects of the arrival time error on the location accuracy

4.2.1 Effect of the arrival time error on the horizontal error

The variation in the horizontal error with the arrival time error in the location results of microseismic monitoring is shown in Fig. 4. When only the P wave was used, the location accuracy for the internal monitoring network (points 1, 2, and 3) was relatively high, with errors within 130 m. For the external points (points 4, 5, and 6), the location errors increased rapidly, reaching over 200 m when the arrival time error exceeded 0.01 s. When P–S waves were used, the error for the internal monitoring network was reduced to no more than 65 m, indicating a significant decrease. For the three points outside the monitoring network (points 4, 5, and 6), the maximum location error was only 120 m, a substantial decrease compared with that when only the P wave was used. These data validate that the microseismic monitoring system that uses P–S waves has an enhanced ability to handle arrival time errors, especially for microseismic events occurring outside the monitoring network.



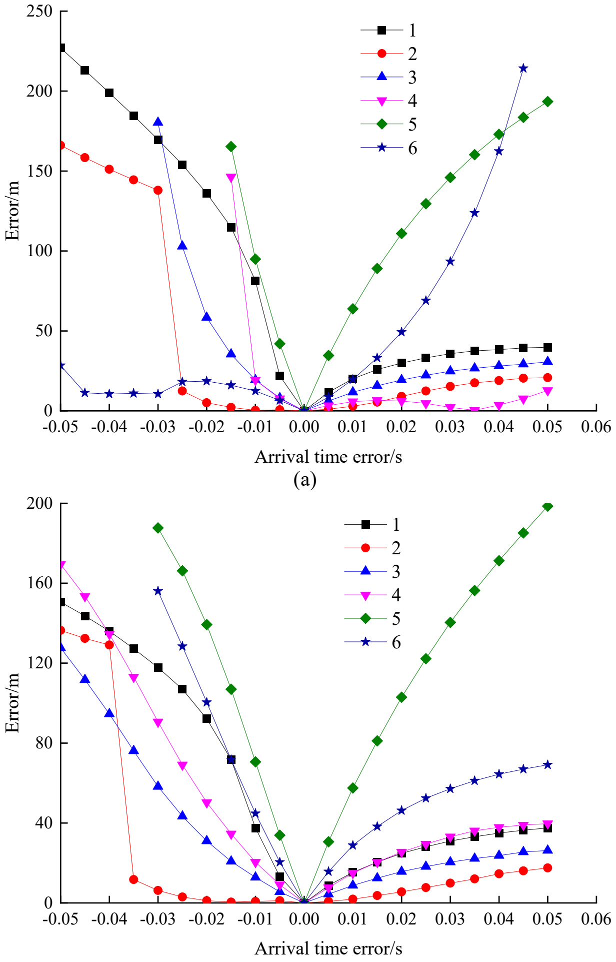
(a)

(b)

Fig. 4. Relationships between the horizontal error and arrival time error. (a) Utilization of P waves. (b) Utilization of P–S waves

4.2.2 Effect of the arrival time error on the vertical error

The variation in the vertical error with the arrival time error in the location results of microseismic monitoring is shown in Fig. 5. Using only the P wave, for the three points within the monitoring network (points 1, 2, and 3), the location error increased linearly and slowly with positive arrival time error, reaching a maximum of less than 50 m. With negative arrival time errors, points 1 and 3 exhibited a rapid increase in error, and the location results became unstable. In the external region, as the arrival time error increased, the location errors for points 4, 5, and 6 rapidly increased, with points 4 and 5 exceeding 200 m when the error reached −0.015 s. When dual waves were used, the location errors for points 1, 2, and 3 within the monitoring network remained below 150 m when the arrival time errors were negative, indicating a significant reduction. For external points 4, 5, and 6, the location errors decreased, and the rate of increase slowed. These results further confirm that the use of P–S waves for seismic source location results in smaller location errors for equivalent arrival time errors, enhancing the ability of the monitoring system to handle arrival time errors, especially in regions outside the monitoring network.



(a)

(b)

Fig. 5. Relationships between the vertical error and arrival time error. (a) Utilization of P waves. (b) Utilization of P–S waves

5. Conclusions

To understand the impact of wave velocity errors and arrival time errors using dual waves on the accuracy of location results, this study employed numerical simulation methods. Three points were respectively selected both inside and outside a typical three-dimensional monitoring network, and artificial wave velocity errors and arrival time errors were introduced. A comparative analysis was conducted on the effects of the above two types of input parameter errors on the horizontal and vertical location accuracies both inside and outside the monitoring network when dual waves and a single wave were utilized, respectively. The main conclusions are as follows:

(1) As the wave velocity errors increase, the location errors inside the monitoring network grow slowly, whereas those outside increase more rapidly. The addition of S waves significantly reduces horizontal errors outside the monitoring network and stabilizes the vertical location results. The use of dual waves also leads to a slight improvement in location accuracy within the monitoring network.

(2) As the arrival time errors increase, the location accuracy inside the monitoring network gradually decreases, whereas outside the network, it rapidly decreases. With the inclusion of S waves, the horizontal location accuracy significantly improves both inside and outside the sensor distribution, and the stability of the vertical location results is enhanced.

(3) Compared with the use of only P waves, the use of both P and S waves enhances the ability of a microseismic monitoring system to handle input parameter errors. In particular, for the same wave velocity error or arrival time error, the location results are closer to the actual seismic source location and more stable, particularly in regions outside the monitoring network.

In summary, this study systematically analyzed the impacts of wave velocity errors and arrival time errors on location accuracy when P waves and dual waves, respectively, were used in a typical monitoring network. These findings affirm that the dual-wave location technique results in greater error tolerance than does the use of a single P wave. However, as the research conducted was based solely on numerical analysis, future research should include indoor physical experiments and engineering field validations. These efforts will substantiate the advantages of the dual-wave location technique in effectively managing input parameter errors and allow for the precise assessment of location results.

Acknowledgements
This work was supported by the National Natural Science Foundation of China under Grant No. 52204155.

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