Application of Multistep Source Localization Method with Narrowing Velocity Interval in Mines

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Abstract The heterogeneity of the rockmass and the premeasured P-wave velocity significantly affect the accuracy of the source localization. Based on the arrival time difference algorithm, a multistep localization method with narrowing velocity interval was proposed, in which the premeasured P-wave velocity is not needed. The minimum and maximum velocity values of the former results were used as the initial velocity interval of the next localization. The preliminarily optimized source coordinates and the re-narrowed P-wave velocity interval were calculated by loop computation. The optimized source coordinates and the best velocity interval were selected until the velocity differences of the latest three velocity interval were less than the threshold. The proposed multistep localization method was applied to locate the microseismic sources of Kaiyang phosphorus mine. The accuracy of localization results was compared with the results of one-step localization. Results show that the multistep localization method is obviously superior to the traditional localization method. The multistep localization method highlights two outstanding advantages: it can eliminate the errors caused by the premeasured velocity; it can improve the locating accuracy in the heterogeneous media. Therefore, the multistep localization method is an accurate and effective method for the microseismic source localization in mining engineering.

Keywords Microseismic monitoring · Multi-step localization · Wave velocity interval · Optimization

1 Introduction

It has been a new normalcy that deep mining projects are carried out in many countries, including South Africa, Canada, Australia, America, and China, due to the increasing demand for valuable resources and the development of mining

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technology [1–3]. However, the deep rockmass will be disturbed by increased geostress, as well as the dynamic and continuous mining in multilevel and multi-stope, which may cause the instability of the rockmass [4, 5]. As a result, the dangerous disasters including rockmass deformation, roof collapse, tailings dam failure, and even rockburst will be induced, which may pose destructive hazards to the safety of workers and equipment [6–10]. Currently, the microseismic monitoring system is the most effective method for geostress monitoring and controlling [11–13]. Based on the real-time monitoring and numerical simulation, Dong et al. established a pre-alarm model for tailing dam, in which the Internet of things and the cloud computing are considered [14]. Ma et al. applied the full waveform inversion and statistical methods to investigate the different microseismic source mechanisms in an underground mine [15–17]. It is feasible to achieve long-term monitoring and short-term forecasting for microseismicity in the complex under-ground structure, while its effectiveness depends on the accurate and efficient localization method, a fundamental and significant problem for the microseismic monitoring technology.

In general, the current localization methods can be classified into two groups, where one is the iterative localization method and another is the analytical localiza-tion method. Through the established nonlinear governing equations for a micro-seismic event, the source coordinates can be solved according to the derived explicit analytical formulas, which is exactly the main thought of the analytical localization method [18, 19]. Traditionally, the P-wave velocity is taken as a known parameter in many analytical localization methods including INGLADA and USBM methods [20]. For instance, through the spherical interpolation method and the least square method, Chan and Ho developed the 3D closed-form solutions using arrival time difference [21]. Nevertheless, the above localization methods fail to consider the temporal and spatial errors caused by predetermined P-wave velocity. Focusing on this important issue, Dong et al. proposed the 3D analytical solutions without predetermined P-wave velocity successively for cube, cuboid, and random monitor-ing networks contained six sensors [22–24]. To solve the problem that more than six sensors are deployed in the practical engineering, the source coordinates can also be calculated through the combination of the analytical solutions and probability density functions [25]. However, it is common that the abnormal arrivals are recorded in the deep mining process, which directly affect the accuracy of input data and then the analytical localization accuracy [26].

Compared to the analytical localization methods, the iterative localization methods are more applicable to the deep mining environment with dynamic distur-bances, since the optimal localization results can be investigated through multiple sensors and numerous iterations. Based on the thought of Geiger, numerous opti-mized iterative localization methods were proposed to locate the earthquake hypo-centers [27–30]. However, these methods are developed in the field of geophysics, where the wave velocity is taken as a premeasured parameter using large numbers of hypocenters and arrivals. In the dynamic mining environment, the stress adjustment and the change of rockmass structure will change the regional P-wave velocity, which results in that the velocity model using premeasured velocity is not suitable

and applicable. To eliminate the location error caused by premeasured P-wave velocity in complex and dynamic mining environment, Dong et al. [31, 32] presented an iterative localization method to locate the microseismic events and the blasting experiments, which takes the time difference (TD) as the dependent variable. Although the TD method is relatively accurate and efficient for sources localization, the velocity interval is not constrained, which means that the velocity value used in the computational process is only greater than 0. Thus, there will be a long computation time due to the great range of P-wave velocity. In addition, it is possible to obtain a local optimum, instead of the global optimum, using TD method. It is important to develop an accurate localization method for solving the global optimum with high computational efficiency, which can be applied to the complex and dynamic mining environment.

In our previous studies, through the narrowing and optimization of the velocity interval, a multistep localization method without premeasured velocity is proposed, to improve the location accuracy and computational efficiency in buildings [33]. The multistep localization method is expected to provide useful information for the accurate localization of invisible rock cracks and the determination of potential hazard areas. In this paper, the multistep localization method is applied to locating the microseismic sources of Kaiyang phosphorus mine.

2 Overview of the Multistep Localization Method

The calculation process of the multistep localization method is shown in Fig. 1. All of the data needed were obtained by the microseismic system, supposing that the coordinates of a microseismic source are $P(x, y, z)$ and the coordinates of the triggered sensors are $S_i = (x_i, y_i, z_i)$. The average P-wave velocity is v.

The first step localization for the microseismic sources was carried out using the TD algorithm with the initial velocity interval of [0, 10000] m/s. Among the locating results, the maximum velocity v_{max}^l and the minimum velocity v_{min}^l were obtained. The calculated source coordinates and the narrowed velocity interval $\left[v_{min}^l, v_{max}^l\right]$ were used as the initial values for the second step localization. Similarly, the preliminarily optimized source coordinates $\left(x_0^i, y_0^i, z_0^i\right)$ and the re-narrowed P-wave velocity interval $\left[v_{min}^l, v_{max}^l\right]$ were calculated by loop computation. The optimized source coordinates and the best velocity interval were selected until the latest velocity interval and the two narrowed velocity interval before satisfied the conditions of Eq. (1).

$$\begin{aligned}
\left|v_{max}^i - v_{max}^{i-1}\right| < n, \left|v_{min}^i - v_{min}^{i-1}\right| < n \\
\left|v_{max}^{i-1} - v_{max}^{i-2}\right| < n, \left|v_{min}^{i-1} - v_{min}^{i-2}\right| < n
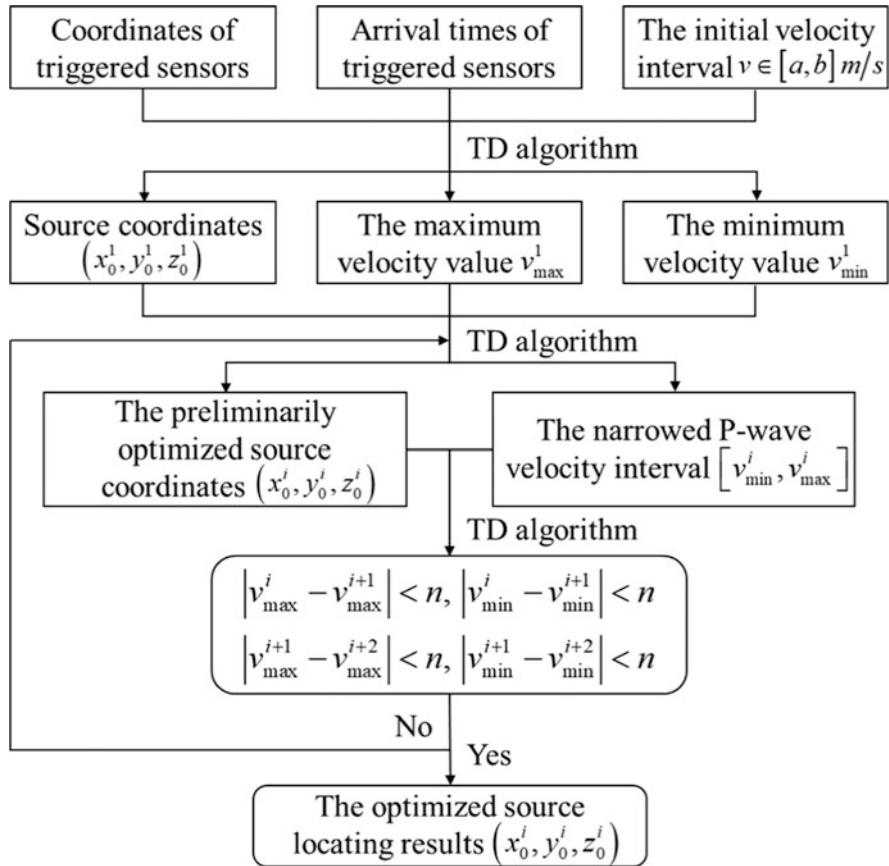\end{aligned} \tag{1}$$

Fig. 1 The flowchart for locating the microseismic sources using the multistep localization method

where $v_{min}^1, v_{max}^i, v_{min}^{i-1}, v_{max}^{i-1}, v_{min}^{i-2}$, and v_{max}^{i-2} indicate the minimum and the maximum velocity of the latest three calculated results, respectively. n is the threshold of the velocity difference.

Considering that the traditional localization method is still widely used, the effectiveness and the accuracy of the multistep localization method are compared with the results of the traditional localization method. As a result, the number of the effective localization results is more than the number of the traditional localization method, which indicates that the locating accuracy with the narrowed and optimized velocity interval is improved.

3   Results and Discussions

The surface elevation and current mining depth of Kaiyang phosphorous mine are about +1500 m and more than 700 m, respectively. The relative mining depth is approximately 800 m, which belongs to the deep mining. In the early mining stage,

the open stope mining method is large-scale used, which resulted in numerous underground goafs in the underground mining area and the phenomenon of local stress concentration [34]. The large-area rockmass instability or the rockburst may be induced at a time. Thus, a 32-channel microseismic monitoring system was established in the Yongshaba mine, the main mining area of Kaiyang phosphorous mine, to avoid the destructive disasters. A total of 26 single-component sensors and two 3-component sensors are distributed on the transport tunnels in 930, 1080, and 1120 levels. The natural frequency of the used sensors is 14 ± 1 Hz, and the response frequency is from 50 Hz to 5 KHz [26]. The location of Kaiyang phosphorous mine and the layout of the microseismic sensors are shown in Fig. 2. The coordinates of each sensor are listed in Table 1.
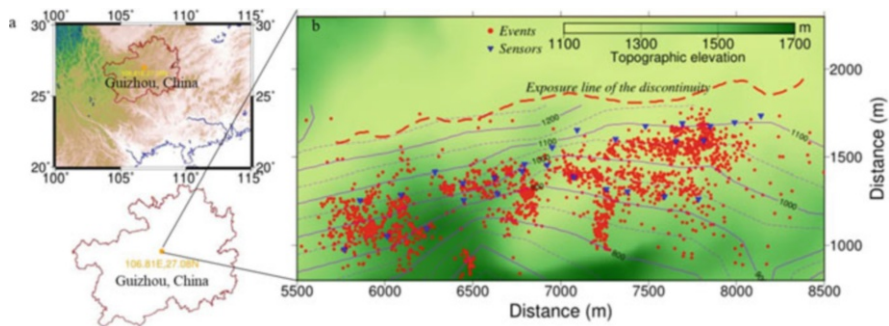

Fig. 2 (**a**) The location of Kaiyang phosphorous mine; (**b**) map view of the monitoring area: the blue triangles show the microseismic sensors, and the red points show the events in this area

Table 1 The coordinates of each sensor of the microseismic monitoring system

| Sensor ID	x/m	y/m	z/m	Sensor ID	x/m	y/m	z/m
1	2,995,768.32	380,976.56	946.52	15	2,997,093.09	381,653.87	1076.37
2	2,996,238.50	381,095.98	952.94	16	2,996,951.03	381,554.87	1083.12
3	2,996,639.11	381,293.46	950.01	17	2,996,793.58	381,459.11	1078.15
4	2,996,780.77	381,419.76	946.06	18	2,996,623.81	381,385.38	1083.40
5	2,996,922.06	381,454.80	943.68	19	2,996,443.46	381,353.89	1083.13
6	2,997,074.43	381,387.86	950.66	20	2,996,284.23	381,416.19	1083.29
7	2,997,259.34	381,320.15	946.63	21	2,996,092.02	381,287.14	1084.81
8	2,997,379.52	381,306.67	951.39	22	2,995,857.80	381,256.53	1085.14
9	2,997,590.28	381,279.15	951.88	23	2,998,138.86	381,735.92	1136.97
10	2,997,783.62	381,263.74	944.27	24	2,997,989.02	381,697.15	1138.04
11	2,997,812.94	381,594.24	1083.76	25	2,997,850.48	381,677.02	1135.28
12	2,997,655.59	381,591.01	1084.26	26	2,997,691.70	381,692.57	1132.39
13	2,997,481.75	381,676.23	1080.45	27	2,996,013.86	381,052.56	953.88
14	2,997,311.53	381,602.69	1081.49	28	2,996,447.16	381,258.30	943.29
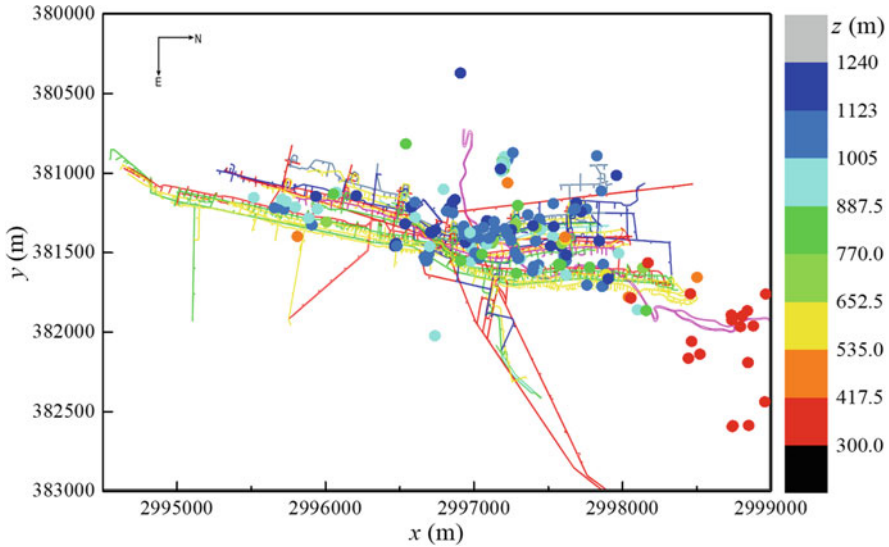
Fig. 3 The locating results of the traditional localization method, with the color scale that shows the altitude of the events

From January to April 2014, 1891 microseismic events were recorded by the IMS microseismic monitoring system of Kaiyang phosphorous mine. Two hundred of the 1891 microseismic events are randomly selected to verify the accuracy and effectiveness by locating the source coordinates. A microseismic event whose coordinates of x and y are out of the monitoring area is defined as an ineffective one. The traditional localization method with the premeasured wave velocity of 4500 m/s was first used. For the 200 microseismic events, the number of effective events is 173. The locating results are shown in Fig. 3, with a color scale indicates the altitude of the events. From Fig. 3 we can clearly find that the locating results are of big discreteness. Some of the points are located in the edge of the monitoring area, where no mining work is conducted.

The multistep localization method is used to locate the source coordinates. Considering the heterogeneity of the rockmass, the initial velocity interval and the threshold n are set as [0, 10000] m/s and 100 m/s. The number of the effective events is 178. The results of the localization are shown in Fig. 4a. Figure 4a clearly indicates that most of the effective events are located in the area of the tunnels, where a great deal of mining work is being conducted.

The minimum and the maximum values of the calculated wave velocity in the first step localization are 1946.88 and 9447.76 m/s. Therefore, the velocity interval of the second localization is set as [1946, 9447]m/s. One Hundred seventy-seven out of 200 events are located in the mining area. The lower limit and the upper limit of the calculated wave velocity are 3107.69 and 9065.38 m/s. According to the results, the third step localization was conducted. The number of the effective events is 179. The minimum and the maximum values of the wave velocity are 3114.06 and 9009.58 m/s.
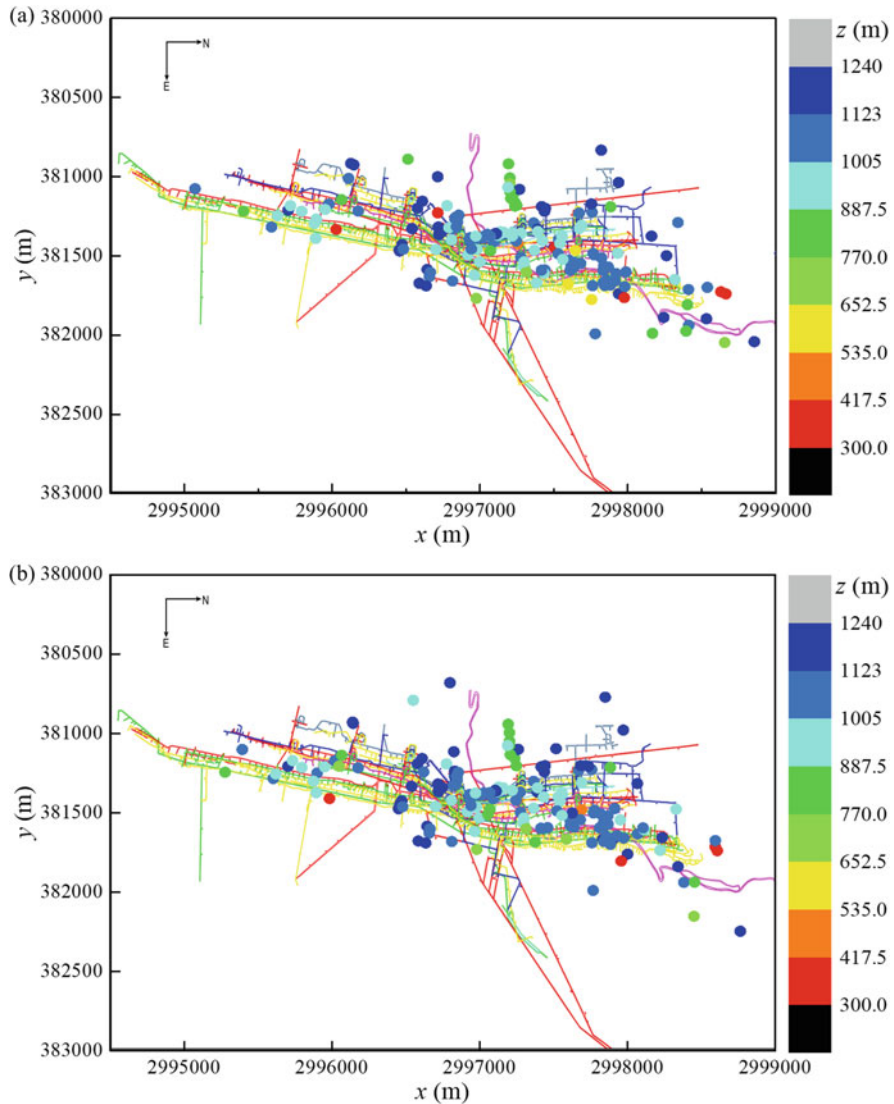
Fig. 4 The locating results of the multistep localization method: (**a**) the velocity interval is [0, 10000]m/s; (**b**) the velocity interval is [3114, 9009]m/s

Here, the velocity difference of the lower limit and the upper limit is both less than the threshold 100 m/s. It can be considered that the wave velocity is tending toward stability. Thus, the last velocity interval is set as [3114, 9009]m/s. The locating results are shown in Fig. 4b. There also have 179 effective events located in the mining area.

For the 200 microseismic events, the numbers of effective events for the traditional localization method and the multistep localization method are 173 and

179, which indicate that the multistep localization method is more effective than the traditional localization method. From Figs. 3 and 4, we can find that almost all the locating results of the multistep localization method are located in the mining area, while some results of the traditional localization method are located in the edge of the mining area, which indicates that the accuracy of the multistep localization method is higher than the result of the traditional localization method.

4 Conclusions

The frequent microseismic events significantly affect the stability of the mining stope; thus the accurate source localization is of critical importance. However, the heterogeneity of the rockmass and the premeasured P-wave velocity seriously affect the accuracy of the source localization. To eliminate the errors caused by the premeasured velocity and improve the locating accuracy, a multistep localization method was proposed in our previous study. In this paper, the multistep localization method was applied to locating the microseismic sources of Kaiyang phosphorous mine. The localization results of 200 randomly selected microseismic events were compared with the results of the traditional localization method. Results show that the effective events located by the two methods are 179 and 173, which indicates that the multistep localization method is more effective than the traditional localization method. The comparison also indicates that the results of the traditional localization method are more discrete than the results of the multistep localization method. Almost all the located events of the multistep localization method concentrated on the area of the mining tunnels. For the traditional localization method, many of the located events located in the edge of the mining area, where no mining work is conducted. According to the practical mining project, the microseismic events are mainly induced by the mining work. Hence we can conclude that the multistep localization method is more accurate than the traditional localization method.

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