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Effects of sonic speed on location accuracy of acoustic emission source in rocks

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Abstract: To quantitatively study the location errors induced by deviation of sonic speed, the line and plane location tests were carried out. A broken pencil was simulated as acoustic emission source in the rocks. The line and plane location tests were carried out in the granite rod using two sensors and the cube of marble using four sensors, respectively. To compare the position accuracy between line and plane positions, the line poison test was also carried out on the marble surface. The results show that for line positioning, the maximum error of absolute distance is about 0.8 cm. With the speed difference of 200 m/s, the average value of absolute difference from the position error is about 0.4 cm. For the plane positioning, in the case of the sensor array of 30 cm, the absolute positioning distance is up to 8.7 cm. It can be seen that the sonic speed seriously impacts on the plane positioning accuracy. The plane positioning error is lager than the line positioning error, which means that when the line position can satisfy the need in practical engineering, it is better to use the line position instead of the plane location. The plane positioning error with the diagonal speed is the minimum one.

Key words: acoustic emission source; sonic speed; line location; plane positioning; rock

1 Introduction

Geophysical methods, such as acoustic emission, microseismic monitoring, geotomography, and in-seam seismic techniques, have shown an increased significance in rock mechanics and mining engineering in recent decades [1, 2]. And the acoustic emission and microseismic monitoring have become the most important method to predict the rockburst hazards and microseismic evens in the deep level geotechnical engineering. Many countries, such as South Africa, Poland, Canada, the United States, Australia, China, India, Chile, Germany and Japan, have experienced different rockburst hazards at different time in some mines and tunnels [2−7]. The developments of seismic monitoring bring hope to predict the rockburst hazards.

As we all know, the prediction of time for rockburst is almost impossible, which likes the problem with the earthquake, but the prediction of space is entirely possible. The main objectives of the prediction of rockburst through routine seismic monitoring in mines are to indicate the locations of potential rockbursts associated with intermediate or large seismic events, and to detect spatio-temporal changes in seismic parameters and relate these changes to the stability of deformation within the volume of interest. This prediction would guide control measures and warnings to manage the exposure to potential rockbursts. Therefore, the seismological method of the prediction of the areal rockbursts is very important for rockburst control and warning in a mine, and the method to locate possible position of microseismic of pre-rockburst time effectively by a seismic monitoring system is the most important problem, which could ensure the safety of deep geotechnical engineering.

Many researchers have developed many acoustic emission or seismic source location techniques [8−13], and some of which were mature technologies and widely used in the positioning of acoustic emission or seismic source currently. However, all of them almost require a given sonic speed or practical measured sonic speed. The

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sonic speed is influenced by the materials, size and surface conditions of transmission media and other factors.

When the input sonic speed is different from the real sonic speed of the measured object, the error would occur in the system. On the one hand, the average sonic speed is different from various regions, and the actual location of the occurrence of rock burst is not necessary in the area pre-determined sonic speed. On the other hand, the measured velocity is affected significantly by the distance between probes. When the distance is large, the measured sonic speed of the general container is 2800−3100 m/s, while that is about 5000−6000 m/s when the distance is small. Therefore, both of these conditions result in some errors between the average sonic speed of entering the positioning system and the actual area, and this would result in a huge position error [14, 15].

Generally, the locating error, caused by the sonic speed measurement deviation, is generally 10−50 m, even more, which would seriously affect the accuracy of rockburst prediction. It can be seen that the sonic speed measurements have seriously affected the positioning accuracy in the actual engineering and tests. It is possible to study the location accuracy induced by sonic speed. Therefore, the quantitative study for sonic speed effect on location accuracy of acoustic emission source was discussed in this work.

2 Measurement and analysis of sonic speeds for samples

The ultrasonic test of rock was widely applied to the field of rock mechanics. The dynamic elastic modulus, Poisson ratio and other parameters can be calculated by measuring the sonic speed. And the measurement of sonic speed is one of the most important parameters in the problems of acoustic emission source location. A site test result in a marble mine showed that longitudinal wave speed of 1390−6905 m/s with 80 ultrasound tests in various 8 locations, and the gap is enormous. Because there is damping in the probe, and regardless of how sharp electrical pulse launched, the probe vibration is always gradually increasing, therefore, the received waveform is gradually rising. The waveform and signal attenuation of the first time are influenced by the coupling ratio and the way of the probe. Therefore, the measurement accuracy of ultrasonic pulse method can only reach 1%−3% [16]. Several tests in no obvious defect on the rocks of naked eye were carried out by YOU [17], and it has found that compared with the average of several tests, the variability measured speeds is from 2.55% to 9.34%. It shows that the accurate measurement of longitudinal wave speed is very difficult to express by an average because of the anisotropy of the rocks.

To quantitatively study the location errors induced by deviation of sonic speed, the line and plane location tests were carried out. A broken pencil was simulated as acoustic emission source in the rocks. For line location problem, the test was carried out in the cross section of 35 mm×35 mm, 500 mm-length rod of granite rock using two sensors. For the plane problem, the test was carried out in the 400 mm×400 mm cube of marble using four sensors. The direction of sonic speed measurements is shown in Fig. 1. The sonic speed measurement direction of line position sample is *AB*, the sonic speed measurement directions of plane position sample are *DF*, *DE*, *CF*, *EF*, *CD*, and *CE* on the face of the sample. Measurement results are shown in Tables 1 and 2. To compare the variation of the measurements, the average deviation, coefficient of variation, and average speed (m/s) are also listed in Tables 1 and 2. From the several measured results of sonic speed, it shows that the coefficient of variation for line position is smaller than six direction speeds of plane position.

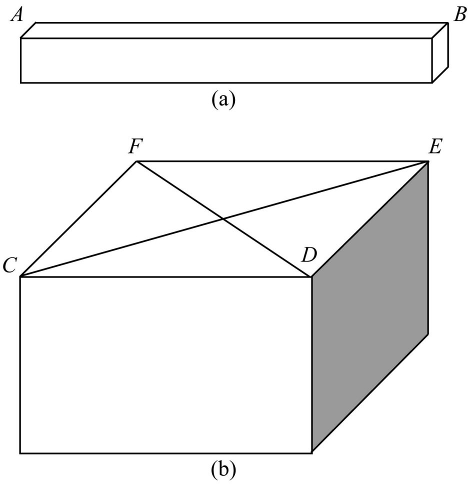

Fig. 1 Diagram of locating samples and measurement directions: (a) Line location sample; (b) Plane location sample

Table 1 Measurement results of sonic speed in line position

Measurement No.	Sonic speed/ ($m\cdot s^{-1}$)	Average deviation	Coefficient of variation	Average speed/ ($m\cdot s^{-1}$)
1	4687.5000			
2	4736.8421			
3	4761.9048			
4	4774.5358			
5	4851.7520			
6	4749.3404	44.0387	0.0119	4779.7563
7	4864.8649			
8	4761.9048			
9	4761.9048			
10	4864.8649			
11	4761.9048			

Table 2 Measurement results of sonic speed in plane position

Measurement No.	Sonic speed/(m·s^{-1})					
	DF	*DE*	*CF*	*EF*	*CD*	*CE*
1	2 186.928 2	2 218.114 6	2 790.697 7	1 933.985 3	2 259.887	2 097.721
2	2 170.148 7	2 366.863 9	3 141.361 3	2 271.362 6	2 575.107 3	2 092.547 8
3	2 175.713 2	2 400.000 0	3 361.344 5	2 084.832 9	2 259.887	2 069.580 8
4	2 178.506 1	2 285.714 3	3 409.090 9	2 011.152 3	2 112.676 1	2 113.395 1
5	2 170.148 7	2 259.887 0	3 157.894 7	2 039.726	2 238.806	2 102.919 8
6	2 186.928 2	2 242.990 7	3 191.489 4	2 097.202 8	2 268.431	2 100.317 2
7	2 178.506 1	2 285.714 3	3 208.556 2	2 058.620 7	2 298.850 6	2 077.180 3
8	2 184.113 6	2 277.039 8	3 217.158 2	2 752.293 6	2 264.150 9	2 525.381 4
9		2 247.191 0	3 225.806 5	1 816.166 5	2 247.191	2 072.107 8
10		2 251.407 1	3 208.556 2	2 115.584 7	2 264.150 9	2 095.131 2
11			3 370.786 5	1 970.297		
Average deviation	5.336 9	40.864 7	99.753 6	150.049 2	63.226 1	78.150 6
Coefficient of variation	0.003 1	0.025 0	0.051 4	0.115 7	0.050 6	0.064 7
Average speed	2 178.874 1	2 283.492 3	3 207.522 0	2 104.656 8	2 278.913 8	2 134.628 2

3 Sonic speed effects on location accuracy of acoustic emission source

3.1 Location principle of acoustic emission

3.1.1 Line location problem

A problem of line location needs two sensors to record the trigger time from acoustic emission source, the diagram of a line location is shown in Fig. 2. The coordinates of sensors No. 1 and No.2 were expressed x_1 and x_2, respectively. The sonic speed was denoted as v; the coordinate of acoustic emission source was expressed as x_0; the occurred time of acoustic emission source was expressed as t_0; the trigger times of sensors No. 1 and No. 2 from acoustic emission were expressed as t_1, t_2, respectively. According to the distance equation, it can be expressed by

$$\sqrt{(x_1-x_0)^2}=(t_1-t_0)v \tag{1}$$

$$\sqrt{(x_2-x_0)^2}=(t_2-t_0)v \tag{2}$$

From Fig. 2, $x_2>x_1$, Eq. (1) minus Eq. (2), the coordinate of acoustic emission source can be calculated by

$$x_0=\frac{(t_1-t_2)v+x_1+x_2}{2} \tag{3}$$

where t_1, t_2, x_1, x_2, and v are known parameters; x_0 is the unknown parameter, and x_0 can be solved by Eq. (3).

Fig. 2 Diagram of line locating problem

3.1.2 Plane location problem

The function of the acoustic emission related with time can be expressed as

$$\sqrt{(x_i-x)^2+(y_i-y)^2}=(t_i-t)v \tag{4}$$

where x_i, y_i and t_i respectively express the 2D coordinate axis and the time of the ith sensor; x and y are the source locations of acoustic emission in 2D coordinate; t is the happened time of acoustic emission; v is the sonic speed (v>0). There are three undetermined coefficients including x, y, and t. Therefore, more than three sensors are needed to locate the source of acoustic emission. To eliminate the location errors, four sensors were used, as shown in Fig. 3. The theory of source location in acoustic emission is simple; however, it can lead to the mistaking location due to the asymmetry sonic speed and environmental noise. In order to eliminate the effects of asymmetry sonic speed, the influences of sonic speed on location results were studied in this work.

The time difference between the ith and jth sensors and their corresponding 2D coordinates can be written as

$$\left[\sqrt{(x_i-x)^2+(y_i-y)^2}-\sqrt{(x_j-x)^2+(y_j-y)^2}\right]\Big/v=t_i-t_j \tag{5}$$

where x and y are unknown parameters, and the others

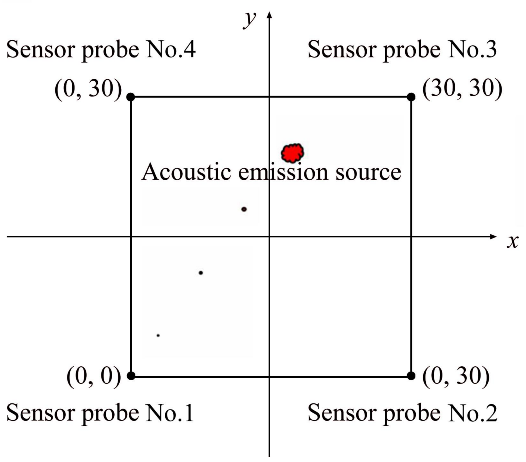

Fig. 3 Diagram of plan location

are known. The nonlinear fitting equation is can be resolved using Marquardt method.

3.2 Tests of line and plane position

For the line location problem, a broken pencil was simulated as acoustic emission source in the rocks, and the test was carried out in the cross section of 35 mm× 35 mm, 500 mm-length rod of granite rock using two sensors. Seven acoustic emission events and trigger times of two sensors are listed in Table 3. For the plane problem, a broken pencil was also simulated as acoustic emission source in the rocks, the test was carried out in the 400 mm×400 mm cube of marble using four sensors. To compare the position accuracy between line and plane positions, the line poison test was also carried out in the marble surface. Nine acoustic emission events and trigger times of four sensors are listed in Table 4. Figures 4 and 5 show the typical waves of the line and plane locations.

Table 3 Line location events and sensor trigger time

Acoustic emission event	Coordinate/cm	Sensor trigger time/s	
		No.1	No.2
1	40	3.889 704	3.889 778
2	35	8.369 15	8.3691 97
3	30	13.281 004	13.281 04
4	20	17.745 28	17.745 27
5	15	21.829 815 25	21.829 780 00
6	10	26.079 266 25	26.079 210 00
7	5	30.356 841 5	30.356 770 0

Table 4 Plane location events and sensor trigger time

Acoustic emission event	Sensor trigger time/s			
	No.1	No.2	No.3	No.4
1	17.343 636 50	17.343 657 3	17.343 609 50	17.343 719 70
2	26.729 490 25	26.729 441 8	26.729 426 75	26.729 495 00
3	33.815 843 50	33.815 745 8	33.815 809 50	33.815 822 75
4	41.477 020 25	41.477 064 5	41.476 998 50	41.477 068 25
5	46.204 368 75	46.204 370 8	46.204 368 00	46.204 375 25
6	52.649 379 75	52.649 323 5	52.649 361 75	52.649 328 00
7	57.804 284 50	57.804 391 3	57.804 333 50	57.804 360 75
8	62.582 124 50	62.582 199 0	62.582 184 00	62.582 151 50
9	67.399 186 00	67.399 171 3	67.399 217 50	67.399 120 50

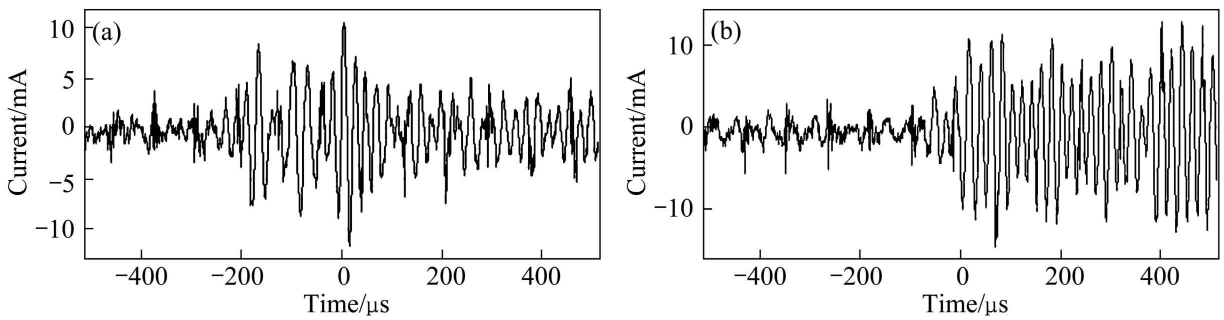

Fig. 4 Typical waves of line location: (a) Sensor No. 1; (b) Sensor No. 2

3.3 Position accuracy analysis under different levels of sonic speeds

According to measured speed results in Section 2, the location method described in Section 3.1, and the sensors triggered time of the acoustic emission source in Section 3.2, the coordinates of acoustic emission source were calculated. With different speed levels, the results of line and plane positions are shown in Tables 5 and 6.

To further analyze the impact of speed on the positioning accuracy, Fig. 6 shows errors of the absolute distance diagram under the different speed levels of line positioning, and Fig. 7 shows the positioning errors diagram of the absolute distance under different speeds of plane positioning.

From Fig. 6, it can be seen, for line positioning, the maximum error of absolute distance is about 0.8 cm. When the sonic speed is 4587.15 m/s, the error of absolute distance is up to the maximum; when the sonic speeds are 4736.8421, 4749.3404, 4774.5358, 4761.9048 m/s, the errors of absolute distances are relative small.

There are six events in the positioning error of about 0.2 cm. It can be got the granite bar quasi-real speed of 4 700 m/s or so. With the speed difference of 200 m/s,

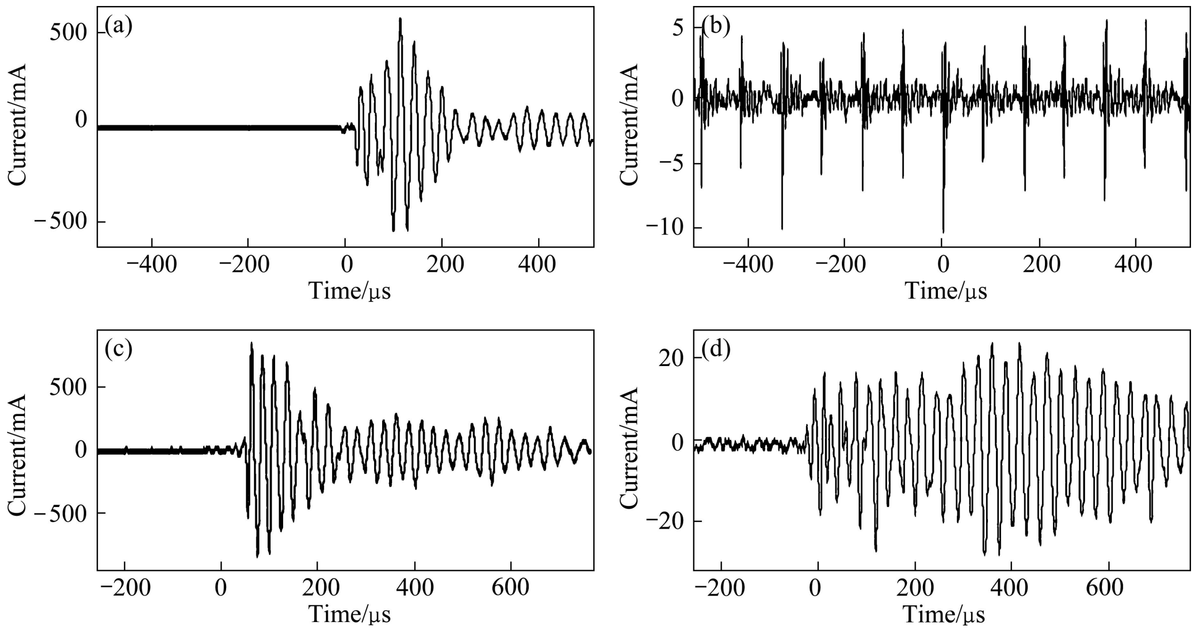

Fig. 5 Typical waves of plane location: (a) Sensor No. 1; (b) Sensor No. 2; (c) Sensor No. 3; (d) Sensor No. 4

Table 5 Real and calculated coordinates under various levels of sonic speeds for line position

Sonic speed/($m \cdot s^{-1}$)	Positioning coordinate/cm						
	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7
	40 cm	35 cm	30 cm	20 cm	15 cm	10 cm	5 cm
4 587.150 0	39.47	34.25	29.61	20.15	15.33	10.57	5.64
4 736.842 1	40.03	34.64	29.84	20.07	15.10	10.18	5.09
4 761.904 8	40.12	34.70	29.88	20.06	15.06	10.12	5.00
4 774.535 8	40.17	34.73	29.90	20.05	15.04	10.09	4.95
4 851.752 0	40.45	34.93	30.02	20.01	14.92	9.89	4.67
4 749.340 4	40.07	34.67	29.86	20.07	15.08	10.15	5.05
4 864.864 9	40.50	34.97	30.04	20.01	14.90	9.85	4.62
4 761.904 8	40.12	34.70	29.88	20.06	15.06	10.12	5.00
4 761.904 8	40.12	34.70	29.88	20.06	15.06	10.12	5.00
4 864.864 9	40.50	34.97	30.04	20.01	14.90	9.85	4.62
4 761.904 8	40.12	34.70	29.88	20.06	15.06	10.12	5.00

Table 6 Real and calculated coordinates under various levels of sonic speeds for plane position

Acoustic emission event	Real coordinate		Positioning coordinate/cm													
			2364.68 m/s		2178.87 m/s		2283.49 m/s		3207.52 m/s		2104.66 m/s		2278.91 m/s		2134.62 m/s	
	X	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
1	8	6	9.176	4.365	9.509	5.253	9.319	4.758	7.706	−0.89	9.646	5.599	9.328	4.78	9.591	4.574
2	5	14	4.61	13.31	5.527	13.44	5.015	13.36	−0.15	12.71	5.884	13.49	5.038	13.37	5.741	13.47
3	6	23	5.232	22.34	6.016	21.79	5.575	22.1	1.592	24.81	6.329	21.57	5.595	22.09	6.203	21.66
4	13	6	12.71	4.866	12.88	5.751	12.78	5.256	11.87	0.337	12.95	6.098	12.79	5.278	12.93	5.958
5	14.5	14.5	14.57	14.23	14.6	14.29	14.6	14.29	14.42	13.96	14.62	14.32	14.58	14.26	14.61	14.31
6	15	23	13.51	22.7	13.6	22.06	13.55	22.42	13.18	25.79	13.63	21.81	13.55	22.41	13.77	21.91
7	22	6	21.26	3.283	20.82	4.291	21.07	3.729	23.6	−2.52	20.65	4.684	21.36	4.084	20.72	6.062
8	23	12	24.33	11.58	23.55	11.83	23.99	11.69	28.24	10.49	23.23	11.93	23.97	11.7	23.36	11.89
9	23	23	21.66	24.5	21.18	23.74	21.45	24.17	23.74	28.1	20.99	23.44	21.44	24.15	21.07	23.56

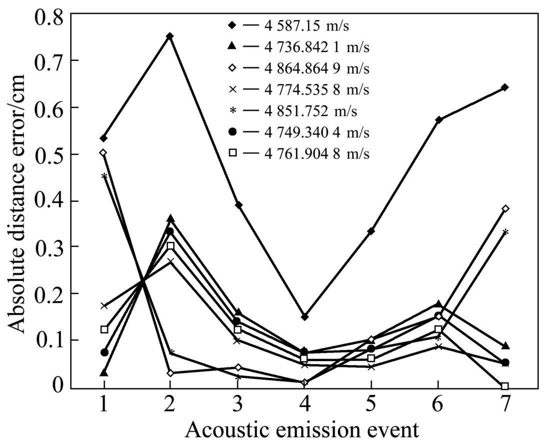

Fig. 6 Errors of absolute distance under different speed levels of line positioning

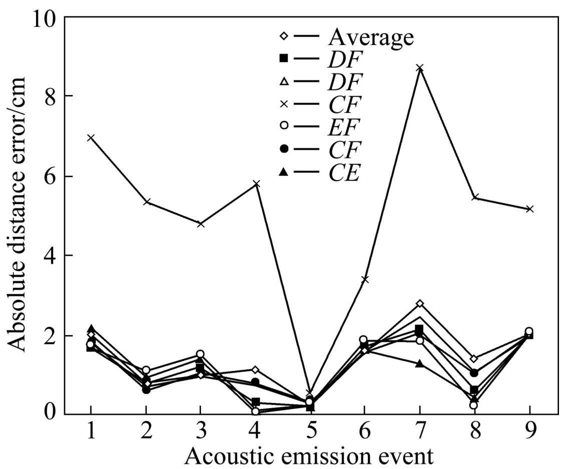

Fig. 7 Positioning errors of absolute distance under different speed levels of plane positioning

and the average value of absolute difference from the position error is about 0.4 cm.

For the plane positioning shown in Fig. 7, in the case of the sensor array of 30 cm, the absolute positioning distance is up to 5 cm, or 8.7 cm. It can be seen that the sonic speed seriously impacts on the plane positioning accuracy. Positioning average errors of absolute distance by six directions of *DF*, *DE*, *CF*, *EF*, *CD*, *CE* and the average speeds of six directions are 1.163924, 1.27231, 5.099751, 1.167377, 1.21937, 1.112782, and 1.445625 cm. It is found that the *CF* direction speed generated the maximum average location error of absolute distance, which is up to 5.099751 cm. *CE* and *DF* directions speed generated the relative minimum average location errors of absolute distance, which are 1.112782, and 1.163924 cm, respectively. It is also found a strange phenomenon that the results of positioning error by the average speed of six directions are not the minimum. On the contrary, the average error is second only to the largest *CF*, and this is not the same as the conventional understanding. It tells us the traditional position method based on pre-measurement average speed could bring big errors in practice engineering. And the average speed should be careful to strike.

The experimental study was based on samples of small size, and the degree of precision positioning certainly was higher than the work of the site microseisms project. Though, in the case of the sensor array of 30 cm, the absolute distance error is up to 5 cm, or 8.7 cm. Under the positioning of this fine work under the proportional calculation, in the practical engineering of the sensor array of 300 m, the average speed measured by pre-positioning, the positioning error may be up to 50−80 m. It is usually greater than this range, because the microseismic location in field work was seriously influenced by the existing roadway engineering, blasting, groundwater and various human factors, in which case, the results of microseismic monitoring is difficult to be convincing. Therefore, it is very necessary to study the new location method without using the average sonic speed, and the specific contents may see the literature.

To compare the position accuracy between line and plane location, line location test was also carried out in *CE* direction on cube marble surface, and the calculated result is consistent with the results of line location by granite rock sample. It shows that the plane positioning error is lager than the line position, which means that when the line position can satisfy the need in practical engineering, it is better to use the line position instead of the plane location. The above important conclusions can apply useful guidance to acoustic emission or microseismic source locations in practice engineering.

4 Conclusions

1) From the several measured results of sonic speed, it shows that the coefficient of variation for line position is smaller than six direction speeds of plane position.

2) For line positioning, the maximum error of absolute distance is about 0.8 cm. When the sonic speed is 4587.15 m/s, the error of absolute distance is up to the maximum. There are six events in the positioning error of about 0.2 cm. With the speed difference of 200 m/s, the average value of absolute difference from the position error is about 0.4 cm. For the plane positioning, in the case of the sensor array of 30 cm, the absolute positioning distance is up to 5 cm or 8.7 cm. It shows that the results of positioning error by the average speed of six directions is not the minimum, on the contrary the average error is second only to the largest *CF*. This is not the same as the conventional understanding. It tells us the traditional position method based on pre-measurement average speed could bring big errors in practice engineering. And the average speed should be careful to strike.

3) The plane positioning error is lager than the line positioning error, which means that when the line position can satisfy the need in practical engineering, it is better to use the line position instead of the plane location. The experimental study is based on samples of small size, and the degree of precision positioning certainly is higher than the work of the project site microseisms. In the practical engineering of a 300 m sensor array, the positioning error may be up to 50−80 m. It is usually greater than this range.

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岩石中速度对声发射源定位精度的影响

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摘　要：为定量研究岩石中速度误差或偏差对声发射源定位精度的影响，分别就一维线和二维平面情况下岩石中声发射源定位情况进行试验。对于线定位，采用花岗岩岩杆，对于平面问题，采用正方体大理岩，用铅笔芯折断的声音模拟声发射源。为比较线定位与平面定位的精度，在大理岩上表面的中线上进行线定位。从速度的多次测量结果来看，线定位的速度变异系数较平面定位各个方向要小。研究发现，对于线定位，绝对距离最大误差在 0.8 cm 左右，当速度相差 200 m/s 时，绝对距离定位误差相差 0.4 cm 左右；对于平面定位，在传感器 30 cm 的阵列情况下，绝对距离定位高达 5 cm，甚至 8.7 cm，可见，平面定位速度严重影响定位精度；平面定位误差较线定位误差大，说明在工程实际中，能用线定位解决的问题尽量不用面定位；与常规认识不一致的是，平面定位中 6 个方向速度的平均值的定位精度不是最小的，而对角线上速度的均值的定位精度最小。

关键词：　声发射源；声速；线定位；平面定位；岩石

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