Acoustic Emission Location Method for Quasi-Cylindrical Structure With Complex Hole

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ABSTRACT

As an effective structure health monitoring technology, acoustic emission (AE) has been developed rapidly in various fields over recent years. AE source localization is the core element of AE technology. In this paper, a Node Block Location Method (NBLM) based on the collaborative model of node and block matrix was proposed to meet the high-precision requirement of source localization in the quasi-cylindrical structure with complex hole. NBLM can not only bypass the empty area, but also fit the actual propagation of elastic waves better in the complex boundaries. In order to evaluate the effectiveness of NBLM, lead-breaking tests were carried out on two cylindrical structure: one with square hole and the other with circular hole. The lead-breaking points were used as AE source in the test. The source coordinates were inverted by three separate location methods according to arrivals. Test results verify the superiority of NBLM and show that the location accuracy of the NBLM has been greatly improved compared to the existing methods.

INDEX TERMS

Acoustic emission (AE), lead-breaking test, node block location method (NBLM), source localization.

I. INTRODUCTION

Acoustic emission (AE) monitoring technology has been paid attention to aviation, metallurgy, transportation, construction and other fields in recent years because it can effectively perform the non-destructive dynamic health test for materials and structures [1]–[8]. AE is a physical phenomenon that generates transient elastic waves due to the rapid release of local energy. It usually accompanies with material deformation, crack cracking and propagation. AE monitoring technology assesses the structure by recording and analyzing the spatial-temporal characteristics of AE events. In the 1950s, some scholars began to research on AE and made extensive pioneering work [9]. With the continuous improvement of modern instruments and algorithms, AE monitoring technology has been able to effectively assess the location, property and severity of structural damage [10], [11]. Among them, AE source localization is the core element of AE monitoring technology. The location accuracy directly affects the application of AE monitoring technology, since the location and occurrence time of AE event in the solid can be only determined by AE source localization.

AE event has similar source mechanism and signal parameters with natural seismic event. Then the source location method in natural seismology can be referred in the study of AE source location. However, the AE signal is monitored at close range from the AE source on the surface of structure. The S-wave signal monitored by AE sensor is not obvious due to the interference of the coda P-wave. Therefore, P-wave arrival time is generally used in AE source localization. Many classical source location methods have been proposed and applied since Geiger first proposed the source location method...
algorithm in 1912 [12], such as Thurber’s location method [13], the USBM [14], [15] and the location method based on simplex stepping [16]. These methods [12]–[16] are based on two main assumptions: (1) the traveling path of the elastic wave between the source and the AE sensor is assumed to be a straight path; (2) the elastic wave velocity is set as a fixed value without considering the velocity error of the elastic wave between the measured path and the actual path. However, in the complex structure with irregular shape (such as fracture zone, bearing crack and hole), the wave path is usually not a straight line. Moreover, the wave velocity changes with time, temperature and pressure in the process of continuous AE monitoring, especially during the cracking process [17], [18]. Hence, these assumptions are not satisfied. Dong et al. [19] proposed an iterative localization method TD, which can reduce the location error caused by the variation of wave velocity in the monitoring process. But this method still does not consider the effect of the irregularity of the structure shape in the localization. Baxter et al. [20] utilized artificial sources and arrival to train the data map of ($\Delta T$) to determine source position, which was applicable to the source location in the structures with complex geometry. Eaton and Hensman [21], [22] improved this method and evaluated the robustness of the method. However, these methods [20]–[22] are only available for two-dimensional component in the current literature, which also need a considerable amount of time for repeated training to cover the component. Considering these factors, Longjun Dong and Qingchun Hu proposed A* Location Method (ALM) [23], which is based on A* search algorithm [24], [25] and a grid node model. The node model is used to build a node matrix with the digits 0 or 1 to represent the specimen shape. The results of the lead-breaking tests show that the ALM can be used in the structure with square hole to reduce the location error effectively. However, when the shape of the hole becomes more complicated (such as arc-shaped cavity, etc.), the specimen cannot be described well only by the node model. The deviation between the model constructed by ALM and the actual situation cannot be ignored.

In this paper, a Node Block Location Method (NBLM) was proposed for the quasi-cylindrical structure with complex hole, such as tunnels and deep wells. This location method joints node matrix and block matrix to construct the location model, which is improved based on ALM. To evaluate the effectiveness of the NBLM, lead-breaking tests were carried out on two cylindrical structure: one with square hole and the other with circular hole. The location results show that the NBLM can effectively adapt to the quasi-cylindrical structure with complex hole, and significantly improve the location accuracy of AE sources, especially on arc edges.

II. METHODS
A. INTRODUCTION TO ALM
The ALM [23] has four main steps (as shown in Fig. 1), and the following is a brief overview of these steps:

1) MESHING THE LOCATION REGION AND MARKING IT WITH THE DIGITS 0 OR 1
The geometry of the location region and the size of the unit square grid are determined according to the condition of the empty region and the accuracy requirement of the source location. A zero matrix $M$ with the same size as the grid node is established, and the index position ($i, j, k$) of the matrix $M$ is in one-to-one correspondence with the grid node. If the node falls into the empty region, the value of $M(i, j, k)$ corresponding to the empty area is changed to 1, which means that the node is invalid. And the coordinate of the AE sensors can also be determined in the matrix $M$.

2) SEARCHING THE FASTEST WAVE PATH BETWEEN EACH SENSOR AND EACH GRID NODE
Each grid node is used as a potential AE source, which was marked as $P_{xyz}$. The improved A* search algorithm is used to obtain the theoretical fastest path $L_{xyz}^s$ from each grid node to each sensor. If the grid node $P_{xyz}$ is in the empty region, $L_{xyz}^s$ is considered as $\infty$.

3) COLLECTING THE ARRIVAL OF THE AE EVENT RECEIVED BY THE SENSOR
For the kth sensor $S_k$ that receives the signal, the coordinates are recorded as $(x_k, y_k, z_k)$. The first arrival time of the AE event is set as $t_0^k$. Calculate the actual time difference of the two different sensors $S_i$ and $S_m$, denoted by $\Delta t_{im}^lm$.

4) DETERMINING THE AE SOURCE LOCATION
As for the AE source excited in point $P_{xyz}$, the theoretical travel time $t_{xyz}^k$ is equal to the shortest propagation path $L_{xyz}^s$ between the AE source and the kth sensor divided by wave velocity $C$. The $C$ is set as a variable to adapt to the change of wave velocity in AE monitoring. The theoretical difference of arrival time between two different sensors $S_l$ and $S_m$, is equal to the difference of travel time $\Delta t_{lm}^lm$. According to the principle of least square method, the $D_{ijk}$ is introduced to describe the degree of deviation of the point $P_{xyz}$ from the unknown AE source by using $\Delta t_{ij}^lm$ and $\Delta t_{ij}^lm$. Therefore, the XYZ coordinate corresponding to the minimum $D_{xyz}$ value can be considered as the coordinate of the AE source.

B. METHOD OPTIMIZATION
In ALM, the digit corresponding to matrix $M$ is used to determine whether the path can pass through the current node. Any small segment path obtained by the A* search algorithm is surrounded by the nodes with the digit 0. When the shape of the hole is square, the fastest wave path between the sensor and the grid nodes is in line with the actual situation. However, when the shape of the hole is more complicated, the fastest path obtained by ALM will have a large deviation from the actual traveling path of the wave. Because the structure with the complex shape cannot be accurately described only by using a node matrix $M$. Fig. 2 shows that the same size grid planes (the side length of grid cells is $l$) contains
arc-shaped holes with different curvature radius $R$. The paths $L_{ALM}$ obtained by ALM in the grid planes are obviously not consistent with the actual wave path at the edge of arc-shaped holes.

The cylindrical structure with complex irregularity shape is common in the actual engineering, which usually cannot be described only by using a node matrix. The NBLM is proposed in this paper, which can build the location region better than ALM. The NBLM needs to establish two environment matrices: node matrix $M$ and block matrix $m$. The construction of the node matrix $M$ inherits the practice of ALM. The block matrix $m$ is established to judge whether the path can pass through. When the tiny cube block is completely in the entity region, the corresponding digit in the matrix $m$ is marked as 0.

When the tiny cube block is completely in the empty region, the corresponding digit in the matrix $m$ is marked as 1.

When the small cube block is at the edge of the empty region and contains part of the entity, the corresponding digit in the block matrix $m$ is marked as 0, which means that the wave can pass through. When the tiny cube block is completely in the entity region, the corresponding digit in the matrix $m$ is marked as 0.

The specific difference between NBLM and the original ALM is mainly reflected in the requirement whether the path can pass through. The main procedure of NBLM and the difference between NBLM and ALM and are shown in Fig. 1. The NBLM is used to re-search the path $L_{NBLM}$ at the edge of arc-shaped holes with different curvature radius $R$ in Fig. 2. Compared with the path $L_{ALM}$, the results show that the path $L_{NBLM}$ is more accordant with the arc-edge. The actual distance $D_R$ stands for the distance of the real fastest path of wave from source to sensor. The distance of search path $D_S$ (including $D_{ALM}$ and $D_{NBLM}$) is calculated by ALM and NBLM. $D_R$ and $D_S$ are recorded in Table 1. The relative error $E$ between the $D_S$ and $D_R$ can be expressed as:

$$E_i = \left| \frac{D_S}{D_R} - 1 \right| \times 100\%$$

The relative error $E$ of the obtained path is calculated and plotted in Fig. 3. Obviously, the $E$ of NBLM is much smaller
than that of ALM. It means that the path searched by NBLM is more suitable at the curved edge. As for the quasi-cylindrical structure with arbitrarily complex hole, it can be formed by multiple planes and curved surfaces. Therefore, the NBLM is more suitable for source location in the quasi-cylindrical structure with complex hole.

### III. RESULTS AND DISCUSSIONS

In order to evaluate the effectiveness of NBLM, lead-breaking tests were carried out as AE source on a cylindrical structure with square hole and a cylindrical structure with circular hole. The lead-breaking points were used as the AE source in the test.

#### A. CYLINDRICAL STRUCTURE WITH SQUARE HOLE

The first specimen is a cylindrical structure with square hole, which was made of polymer concrete. The diameter and height of the specimen are 170 mm and 60 mm. The square hole is located at the center of the cylindrical specimen. The size of the square hole is 55 mm × 55 mm × 60 mm, which is as high as the cylinder. Fig. 4 shows the site condition of the experimental device. The specimen, sensor, preamplifier, AE detector and computer are connected in an orderly manner. A suitable amount of Vaseline was used between the sensor and the specimen to obtain better acoustic coupling. 6 sensors were installed on the specimen for source localization, and the coordinates of sensors are recorded in Table 2. A series of points were selected as the AE sources on the upper surface and the internal surface of the specimens. The lead-breaking tests (brittle fracture of a 2H graphite lead, 0.5 mm in diameter) were carried out twice at each AE source. When the lead is broken, the angle between the lead and the surface is guaranteed to be 30°, and the elongation of the lead is 2.5 mm. The coordinates of AE source were recorded in Table 3. During AE data acquisition, the background noise was monitored, and its maximum value was found to be about 33dB. Then

| $R \times l$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------------|---|---|---|---|---|---|---|---|---|
| $D_2 \times l$ | 3.14 | 6.28 | 9.42 | 12.57 | 15.71 | 18.85 | 21.99 | 25.13 | 28.27 |
| $D_{ALM} \times l$ | 4.00 | 8.00 | 12.00 | 14.83 | 17.66 | 19.48 | 22.61 | 25.90 | 29.14 |
| $D_{NBLM} \times l$ | 2.83 | 6.47 | 9.66 | 12.65 | 15.48 | 19.32 | 22.16 | 25.45 | 28.38 |
the threshold was set to 35 dB to eliminate the influence of noise.

As shown in Fig. 5, the cylindrical structure with square hole was made of 2.5 mm cubes. According to the cube model, a node matrix $M$ can be formed with the size of $69 \times 69 \times 25$. A block matrix $m$ can also be formed with the size of $68 \times 68 \times 24$. Then, the NBLM was used to determine the source location based on the matrix $M$ and $m$, and the location results are presented in Tables 4 and 5. At the same time, ALM and TD are utilized to locate the AE source. The results are also recorded in Tables 4 and 5.

In order to further analyze the location results, the location errors are calculated and recorded in Tables 4 and 5. As shown in Fig. 3, the relative distance errors of paths searched by different models at the edges of arc-shaped holes with different curvatures.

![Figure 3](image3.png)

**FIGURE 3.** Relative distance errors of paths searched by different models at the edges of arc-shaped holes with different curvatures.

![Figure 4](image4.png)

**FIGURE 4.** Experimental device diagram.

![Figure 5](image5.png)

**FIGURE 5.** Location model of cylindrical structure with square hole. (a), the top view of the sample node model; (b), the block model top view of the sample diagram.

**TABLE 2.** Coordinates of sensor positions on the structure with square hole (mm).

| Number of sensors | 1   | 2   | 3   | 4   | 5   | 6   |
|-------------------|-----|-----|-----|-----|-----|-----|
| X                 | 85  | 0   | -85 | 0   | 67.5| 67.5|
| Y                 | 0   | 85  | 0   | -85 | 0   | 0   |
| Z                 | 10  | 50  | 10  | 50  | 60  | 60  |
TABLE 3. Coordinates of lead-breaking points on the structure with square hole (mm).

| No. | Upper Surface | No. | Upper Surface | No. | Internal Surface |
|-----|--------------|-----|--------------|-----|-----------------|
| x   | y   | z   | x   | y   | z   | x   | y   | z   |
| 1   | 27.5 | 67.5 | 60 | 13 | -47.5 | -47.5 | 60 | 25 | 0   | 27.5 | 50 |
| 2   | 27.5 | 47.5 | 60 | 14 | -27.5 | -47.5 | 60 | 26 | 0   | 27.5 | 30 |
| 3   | 47.5 | 47.5 | 60 | 15 | -27.5 | -67.5 | 60 | 27 | 0   | 27.5 | 10 |
| 4   | 47.5 | 27.5 | 60 | 16 | 47.5  | 27.5  | 60 | 28 | 0   | 27.5 | 50 |
| 5   | 67.5 | 27.5 | 60 | 17 | 67.5  | 27.5  | 60 | 29 | 0   | 27.5 | 30 |
| 6   | -27.5 | 67.5 | 60 | 18 | 27.5  | -47.5 | 60 | 30 | -27.5 | 0   | 10 |
| 7   | -27.5 | 47.5 | 60 | 19 | 47.5  | -67.5 | 60 | 31 | 0   | -27.5 | 50 |
| 8   | -47.5 | 47.5 | 60 | 20 | 27.5  | -67.5 | 60 | 32 | 0   | -27.5 | 30 |
| 9   | -47.5 | 27.5 | 60 | 21 | 0    | 47.5  | 60 | 33 | 0   | -27.5 | 10 |
| 10  | -67.5 | 27.5 | 60 | 22 | 0    | 27.5  | 60 | 34 | 0   | 27.5  | 50 |
| 11  | -67.5 | -27.5 | 60 | 23 | 0    | -47.5 | 60 | 35 | 0   | 27.5  | 30 |
| 12  | -47.5 | -27.5 | 60 | 24 | 0    | -67.5 | 60 | 36 | 0   | 27.5  | 10 |

TABLE 4. Location results and errors of lead breaking points on the internal surface of the cylindrical structure with square hole (mm).

| No. | NBLM | ALM | TD |
|-----|------|-----|----|
| x   | y   | z   | errors | x   | y   | z   | errors | x   | y   | z   | errors |
| 1   | 0   | 23.7 | 27.5 | 23.7 | 0   | 35  | 27.5 | 23.7 | 9.2  | 54.1 | 26.4 | 36.7 |
| 1   | 0   | 21.4 | 30   | 21.4 | 0   | 35  | 27.5 | 23.7 | 9.2  | 54.1 | 26.4 | 36.7 |
| 2   | 0   | 7.5  | 30   | 7.5  | 0   | 35  | 27.5 | 7.9  | 3.8  | 84.5 | 0.2  | 64.5 |
| 2   | 0   | 24.6 | 7.5  | 24.6 | 0   | 37.5| 7.5  | 24.6 | 3.8  | 84.5 | 0.2  | 64.5 |
| 3   | 0   | 10.3 | 7.5  | 10.3 | 0   | 37.5| 7.5  | 10.3 | 3.8  | 84.5 | 0.2  | 58.0 |
| 3   | 0   | 10.3 | 7.5  | 10.3 | 0   | 37.5| 7.5  | 10.3 | 2.6  | 84.1 | 0.8  | 57.4 |
| 4   | -27.5| 15.0 | 35   | 15.0 | -27.5| 0   | 35  | 15.0 | -77.9| 29.4 | 28.2 | 62.2 |
| 4   | -27.5| 15.0 | 35   | 15.0 | -27.5| 0   | 35  | 15.0 | -77.9| 29.4 | 28.2 | 62.2 |
| 5   | -30  | 17.7 | 12.5 | 17.7 | -30  | 0   | 12.5| 17.7 | -84.9| 5.7  | 27.1 | 57.8 |
| 5   | -30  | 17.7 | 12.5 | 17.7 | -27.5| 0   | 12.5| 17.5 | -84.9| 5.7  | 27.1 | 57.8 |
| 6   | -30  | 3.5  | 12.5 | 3.5  | -27.5| 0   | 12.5| 2.5  | -83.6| -8.4 | 5.5  | 56.9 |
| 6   | -30  | 3.5  | 12.5 | 3.5  | -27.5| 0   | 12.5| 2.5  | -84.6| -42.2| 29.4 | 73.6 |
| 7   | 0   | 26.1 | 25   | 26.1 | 0   | -35 | 25  | 26.1 | -1.7 | -40.9| 59.6 | 16.5 |
| 7   | -2.5 | 26.2 | 25   | 26.2 | -2.5| -35 | 25  | 26.2 | -3.6 | -40.2| 59.5 | 16.3 |
| 8   | -2.5 | 9.4  | 25   | 9.4  | -2.5| -35 | 25  | 9.4  | -2.9 | -49.7| 59.5 | 37.1 |
| 8   | -2.5 | 9.4  | 25   | 9.4  | -2.5| -35 | 25  | 9.4  | -2.9 | -49.7| 59.5 | 37.1 |
| 9   | -2.5 | 17.0 | 25   | 17.0 | -2.5| -35 | 25  | 17.0 | 1.7  | -33.4| 59.5 | 49.9 |
| 9   | -2.5 | 17.0 | 25   | 17.0 | -2.5| -35 | 25  | 17.0 | 1.7  | -33.4| 59.5 | 49.9 |
| 10  | 27.5 | 17.5 | 32.5 | 17.5 | 27.5| 0   | 32.5| 17.5 | 84.1 | -25.2| 54.7 | 62.1 |
| 10  | 30  | 17.7 | 32.5 | 17.7 | 30  | 0   | 32.5| 17.7 | 84.1 | -18.5| 52.9 | 59.6 |
| 11  | 30  | 20.2 | 10   | 20.2 | 30  | 0   | 10  | 20.2 | 83.8 | 25.6 | 39.2 | 62.5 |
| 11  | 30  | 20.2 | 10   | 20.2 | 30  | 0   | 10  | 20.2 | 83.8 | 25.6 | 39.2 | 62.5 |
| 12  | 30  | 2.5  | 10   | 2.5  | 30  | 0   | 10  | 2.5  | 84.4 | 28.6 | 29.7 | 66.7 |
| 12  | 30  | 2.5  | 10   | 2.5  | 30  | 0   | 10  | 2.5  | 84.4 | 28.6 | 29.7 | 66.7 |

Average error 14.8 Average error 14.8 Average error 52.9

Standard deviation 7.5 Standard deviation 7.7 Standard deviation 15.6

in Table 4, the average error of NBLM and ALM are both 14.8 mm on the internal surface. Moreover, the error standard deviations of ALM and NBLM are almost the same. Because these points are far from the outer edge of the circular arc and the cut shape is regular cuboid, the path obtained by ALM is similar to that by NBLM and can fit the edge of the square hole perfectly. On the upper surface, the average location error of NBLM is 12.7 mm, while that of ALM is 15.1 mm (as shown in Table 5). The standard deviation location error of NBLM is 4.1mm, which is smaller than that of ALM. Since the lead-breaking point on the upper surface is close to the outer edge of the specimen, there is a certain deviation in the
TABLE 5. Location results and errors of lead breaking points on the upper surface of the cylindrical structure with square hole (mm).

| No. | NBLM x | NBLM y | NBLM z | ALM x | ALM y | ALM z | TD x | TD y | TD z |
|-----|--------|--------|--------|-------|-------|-------|------|------|------|
| 13  | 32.5   | 77.5   | 50     | 15.0  | 32.5  | 77.5  | 50   | 15.0 | 41.3 |
| 13  | 32.5   | 77.5   | 50     | 15.0  | 32.5  | 77.5  | 50   | 15.0 | 41.3 |
| 14  | 37.5   | 62.5   | 60     | 18.0  | 37.5  | 62.5  | 60   | 18.0 | 30.0 |
| 14  | 45     | 67.5   | 60     | 26.6  | 45    | 70    | 57.5 | 28.6 | 34.0 |
| 15  | 55     | 55     | 57.5   | 10.9  | 47.5  | 47.5  | 52.5 | 7.5  | 57.6 |
| 15  | 55     | 55     | 55     | 11.7  | 50    | 50    | 52.5 | 8.3  | 57.5 |
| 16  | 60     | 32.5   | 50     | 16.8  | 30    | 12.5  | 37.5 | 32.2 | 81.3 |
| 16  | 57.5   | 32.5   | 57.5   | 11.5  | 27.5  | 15    | 42.5 | 29.4 | 74.0 |
| 17  | 72.5   | 25     | 55     | 7.5   | 57.5  | 22.5  | 50   | 15.0 | 84.1 |
| 17  | 77.5   | 22.5   | 50     | 15.0  | 65    | 22.5  | 50   | 11.5 | 84.1 |
| 18  | -30    | 72.5   | 50     | 11.5  | -30   | 72.5  | 50   | 11.5 | -24.3|
| 18  | -30    | 75     | 52.5   | 10.9  | -30   | 75    | 52.5 | 10.9 | -24.3|
| 19  | -35    | 60     | 55     | 15.4  | -35   | 60    | 55   | 15.4 | -23.1|
| 19  | -35    | 62.5   | 60     | 16.8  | -35   | 62.5  | 60   | 16.8 | -27.1|
| 20  | -55    | 55     | 57.5   | 10.9  | -47.5 | 47.5  | 52.5 | 7.5  | -45.9|
| 20  | -55    | 55     | 55     | 14.6  | -55   | 55    | 50   | 14.6 | -45.9|
| 21  | -55    | 50     | 57.5   | 8.3   | -42.5 | 22.5  | 50   | 12.2 | -84.8|
| 21  | -55    | 50     | 57.5   | 8.3   | -42.5 | 22.5  | 50   | 12.2 | -84.8|
| 22  | -72.5  | 25     | 55     | 7.5   | -57.5 | 22.5  | 50   | 15.0 | -78.5|
| 22  | -72.5  | 25     | 55     | 7.5   | -57.5 | 22.5  | 50   | 15.0 | -78.5|
| 23  | -75    | -25    | 60     | 7.9   | -55   | -22.5 | 50   | 16.8 | -78.4|
| 23  | -75    | -25    | 60     | 7.9   | -60   | -22.5 | 52.5 | 11.7 | -78.4|
| 24  | -75    | -32.5  | 57.5   | 11.5  | -42.5 | -22.5 | 50   | 12.2 | -58.5|
| 24  | -50    | -30    | 57.5   | 8.3   | -42.5 | -22.5 | 50   | 12.2 | -58.5|
| 25  | -50    | -50    | 52.5   | 8.3   | -47.5 | -47.5 | 52.5 | 7.5  | -47.6|
| 25  | -55    | -55    | 55     | 11.7  | -50   | -50   | 50   | 10.6 | -35.8|
| 26  | -37.5  | -60    | 60     | 16.0  | -37.5 | -60   | 60   | 16.0 | -51.2|
| 26  | -32.5  | -55    | 55     | 10.3  | -35   | -57.5 | 57.5 | 12.7 | -51.2|
| 27  | -32.5  | -77.5  | 50     | 15.0  | -27.5 | -70   | 45   | 15.2 | -36.1|
| 27  | -32.5  | -77.5  | 47.5   | 16.8  | -32.5 | -77.5 | 47.5 | 16.8 | -36.1|
| 28  | -37.5  | -60    | 60     | 14.6  | 35    | -60   | 60   | 14.6 | 39.0|
| 29  | 37.5   | -62.5  | 60     | 18.0  | 35    | -62.5 | 60   | 16.8 | 24.7|
| 30  | 55     | -55    | 60     | 10.6  | 47.5  | -47.5 | 55   | 5.0  | 73.9|
| 31  | 50     | -52.5  | 55     | 7.5   | 50    | -52.5 | 55   | 7.5  | 43.6|
| 32  | 30     | -75    | 50     | 12.7  | -27.5 | -72.5 | 47.5 | 13.5 | 29.7|
| 32  | 30     | -75    | 50     | 12.7  | 27.5  | -70   | 47.5 | 12.7 | 29.4|
| 33  | 0      | 70     | 47.5   | 12.7  | 0     | 70    | 47.5 | 12.7 | 13.4|
| 33  | 2.5    | 72.5   | 42.5   | 18.4  | 2.5   | 70    | 42.5 | 17.9 | 7.5  |
| 34  | 0      | 55     | 42.5   | 19.0  | 2.5   | 47.5  | 40   | 20.2 | 0.1  |
| 34  | 2.5    | 55     | 42.5   | 19.2  | 2.5   | 52.5  | 40   | 20.8 | 5.5  |
| 35  | 2.5    | 55     | 42.5   | 19.2  | 2.5   | 52.5  | 40   | 20.8 | 5.5  |
| 36  | 0      | -50    | 50     | 10.3  | -2.5  | -47.5 | 47.5 | 12.7 | -11.4|
| 36  | 0      | -70    | 45     | 15.2  | 0     | -70   | 42.5 | 17.7 | 7.5  |
| 36  | -2.5   | -70    | 47.5   | 13.0  | -2.5  | -70   | 45   | 15.4 | -8.7 |

Average error: 12.7  Average error: 15.1  Average error: 26.3
Standard deviation: 4.1  Standard deviation: 5.8  Standard deviation: 16.1
path obtained by NLBM and ALM. Hence, NBLM is more accurate than ALM on the upper surface.

As for TD, there is a considerable deviation between the location result and the actual position since TD cannot bypass the empty region. The average location errors of TD on the upper surface and the inner surface are 26.3 mm and 52.9 mm respectively, and the corresponding standard deviations are 15.6 mm and 16.1 mm.

**B. CYLINDRICAL STRUCTURE WITH CIRCULAR HOLE**

The sandstone specimen is a cylindrical structure with circular hole, which was cut with a waterjet. It has an inner diameter of 102 mm, an outer diameter of 192 mm and a height of 153 mm, as shown in Fig. 6(a). The grid is divided by 3 mm cubes. According to the cube model, a node matrix $M$ can be formed with the size of $65 \times 65 \times 52$ in two different colors. A block matrix $m$ can also be formed with the size of $64 \times 64 \times 51$, as shown in Fig. 6(b-c). In Fig. 6(d), 8 sensors were installed on the cylindrical rock test piece for source localization, and the coordinates of sensors are shown in Table 7. The lead-breaking tests were performed three times at the positions of selected points. The coordinates of the broken lead-breaking point are recorded in Table 6. NBLM, ALM and TD were respectively used to locate the position and the results were recorded in Tables 8 and 9.

The location results of NBLM, ALM and TD are compared with the actual position of AE source, and the location errors are recorded in Tables 8 and 9. As shown in tables,

**FIGURE 6.** Rock specimens and models. (a) rock specimen; (b) node model top view of the specimen; (c) block model top view of the specimen diagram; (d) sensor layout on the specimen (triangle represents sensor).
the maximum location error of TD is 56 mm, which is much larger than that of NBLM and ALM. Fig.7 is a visualization of the locating results and errors of the three methods. The circle size represents the error of AE location results. It can be clearly seen that most points’ size for NBLM are much smaller than other two methods. In other words, NBLM is far superior to ALM and TD.

As shown in Table 8 and Table 9, the average location errors of NBLM, ALM and TD on the upper surface are 11.3mm, 12.0mm and 13.3mm, and those on the internal surface are 7.7 mm, 10.5 mm and 32.8 mm. The average location accuracy of NBLM is higher than that of ALM and of TD. Especially in the internal surface, the location accuracy of NBLM has been improved about 26.7% than that of ALM.
| No. | NBLM | ALM | TD |
|-----|------|-----|-----|
|     | x    | y   | z   | errors | x    | y   | z   | errors | x    | y   | z   | errors |
| 1   | 54   | 39  | 153 | 9.5    | 48   | 36  | 153 | 6.7    | 56.2 | 41.8 | 150.4 | 13.1   |
| 1   | 48   | 33  | 141 | 12.7   | 48   | 33  | 144 | 9.9    | 54.6 | 40.3 | 148.0 | 12.0   |
| 1   | 48   | 33  | 147 | 7.3    | 48   | 33  | 147 | 7.3    | 54.2 | 38.0 | 147.0 | 10.5   |
| 2   | 51   | 57  | 150 | 6.7    | 48   | 51  | 147 | 6.7    | 55.2 | 63.3 | 153.0 | 12.9   |
| 2   | 51   | 54  | 147 | 6.7    | 48   | 51  | 147 | 6.7    | 56.0 | 62.8 | 153.0 | 12.8   |
| 3   | 27   | 51  | 147 | 6.7    | 24   | 45  | 147 | 10.4   | 33.8 | 66.6 | 153.0 | 16.1   |
| 3   | 24   | 48  | 147 | 9.0    | 24   | 45  | 147 | 10.4   | 32.4 | 64.6 | 152.2 | 13.8   |
| 3   | 27   | 51  | 147 | 6.7    | 24   | 45  | 147 | 10.4   | 32.3 | 63.3 | 151.3 | 12.7   |
| 4   | -30  | 57  | 138 | 16.2   | -24  | 48  | 138 | 16.4   | -34.9 | 60.7 | 143.1 | 14.7   |
| 4   | -30  | 57  | 138 | 16.2   | -24  | 48  | 138 | 16.4   | -38.2 | 63.8 | 145.0 | 17.2   |
| 5   | -51  | 51  | 144 | 10.8   | -24  | 45  | 141 | 14.7   | -38.2 | 63.2 | 145.6 | 16.5   |
| 5   | -51  | 51  | 144 | 9.0    | -45  | 45  | 141 | 14.7   | -57.0 | 57.0 | 143.7 | 12.6   |
| 5   | -48  | 48  | 144 | 9.9    | -45  | 45  | 141 | 14.7   | -54.4 | 54.2 | 143.8 | 10.3   |
| 5   | -48  | 48  | 141 | 12.7   | -45  | 45  | 138 | 17.2   | -56.3 | 56.1 | 143.5 | 12.1   |
| 6   | -57  | 36  | 141 | 14.7   | -57  | 36  | 141 | 14.7   | -62.6 | 39.5 | 141.5 | 18.8   |
| 6   | -60  | 39  | 153 | 12.7   | -51  | 33  | 147 | 6.7    | -60.9 | 36.8 | 145.4 | 14.2   |
| 6   | -54  | 30  | 144 | 9.5    | -51  | 30  | 144 | 9.0    | -60.2 | 35.5 | 144.6 | 13.6   |
| 7   | -69  | -45 | 153 | 23.4   | -54  | -33 | 141 | 12.7   | -62.7 | -36.2 | 145.2 | 15.4   |
| 7   | -72  | -45 | 153 | 25.8   | -54  | -33 | 141 | 12.7   | -65.2 | -35.1 | 144.8 | 17.2   |
| 7   | -63  | -56 | 144 | 16.2   | -57  | -33 | 141 | 13.7   | -64.3 | 34.3 | 145.5 | 15.9   |
| 8   | -60  | -60 | 144 | 15.6   | -54  | -54 | 141 | 12.7   | -64.7 | -64.6 | 148.5 | 19.8   |
| 8   | -57  | -60 | 144 | 14.1   | -54  | -54 | 141 | 12.7   | -69.8 | -61.5 | 147.2 | 15.4   |
| 8   | -51  | -54 | 141 | 12.4   | -48  | -51 | 141 | 12.4   | -55.9 | -59.5 | 144.9 | 12.7   |
| 9   | -36  | -57 | 141 | 14.7   | -27  | -45 | 138 | 16.4   | -38.1 | -61.2 | 140.8 | 17.8   |
| 9   | -33  | -54 | 141 | 12.7   | -27  | -45 | 138 | 16.4   | -37.3 | -61.4 | 142.3 | 16.6   |
| 9   | -33  | -54 | 141 | 12.7   | -27  | -45 | 138 | 16.4   | -37.6 | -59.2 | 143.0 | 15.0   |
| 10  | 24   | -48 | 147 | 9.0    | 24   | -45 | 147 | 10.4   | -29.3 | -52.6 | 145.8 | 7.4    |
| 10  | 24   | -48 | 138 | 16.4   | 24   | -48 | 141 | 13.7   | 31.7  | 56.9 | 145.0 | 10.0   |
| 10  | 27   | -48 | 144 | 9.9    | 27   | -48 | 144 | 9.9    | 31.5  | 56.3 | 144.9 | 9.8    |
| 11  | 54   | -33 | 150 | 5.2    | 51   | -33 | 147 | 6.7    | 56.9  | -33.3 | 146.7 | 9.2    |
| 11  | 54   | -33 | 147 | 6.7    | 51   | -33 | 147 | 6.7    | 55.6  | -33.9 | 145.8 | 9.4    |
| 11  | 54   | -33 | 150 | 5.2    | 48   | -30 | 147 | 6.7    | 56.2  | -33.1 | 146.0 | 9.3    |
| 12  | 48   | -54 | 150 | 5.2    | 42   | -48 | 147 | 11.2   | 46.2  | -52.2 | 144.0 | 10.3   |
| 12  | 45   | -51 | 147 | 8.5    | 39   | -45 | 144 | 16.2   | 47.1  | -51.9 | 146.5 | 7.6    |
| 12  | 45   | -51 | 147 | 8.5    | 36   | -42 | 141 | 21.2   | 46.1  | -50.2 | 144.2 | 10.1   |

Average error: 11.3
Average error: 12.0
Average error: 13.3

Standard deviation: 4.8
Standard deviation: 3.8
Standard deviation: 3.2
TABLE 9. Location results and errors of each lead-breaking point on the internal surface of the rock specimens (mm).

| No. | NBLM x | NBLM y | NBLM z | NBLM errors | ALM x | ALM y | ALM z | ALM errors | TD x | TD y | TD z | TD errors |
|-----|--------|--------|--------|-------------|-------|-------|-------|------------|------|------|------|------------|
| 13  | 51     | 0      | 102    | 6.0         | 0     | 105   | 4.2   | 89.2       | 3.5  | 110.9| 38.4 |
| 13  | 51     | 0      | 105    | 3.0         | 51    | 0     | 105   | 3.0         | 84.6 | 5.1  | 100.6| 34.8       |
| 13  | 51     | 0      | 105    | 3.0         | 51    | 0     | 108   | 0.0         | 80.7 | 0.7  | 111.3| 29.9       |
| 14  | 48     | 30     | 105    | 7.3         | 48    | 30    | 105   | 7.3         | 61.8 | 40.5 | 106.8| 23.6       |
| 14  | 45     | 27     | 102    | 6.7         | 51    | 30    | 105   | 9.0         | 68.4 | 40.8 | 105.5| 28.9       |
| 14  | 51     | 30     | 105    | 9.0         | 51    | 30    | 105   | 9.0         | 61.0 | 35.2 | 106.5| 19.6       |
| 15  | 24     | 45     | 105    | 3.0         | 24    | 48    | 108   | 3.0         | 36.1 | 64.2 | 103.1| 23.2       |
| 15  | 24     | 45     | 105    | 3.0         | 24    | 48    | 108   | 3.0         | 36.1 | 64.3 | 104.0| 23.1       |
| 15  | 21     | 48     | 105    | 5.2         | 21    | 48    | 108   | 4.2         | 34.8 | 64.8 | 103.5| 23.0       |
| 16  | 0      | 51     | 102    | 6.0         | 0     | 57    | 105   | 6.7         | -9.7 | 96.0 | 102.3| 46.4       |
| 16  | 0      | 51     | 99     | 9.0         | 0     | 63    | 102   | 13.4        | -9.1 | 96.0 | 100.6| 46.5       |
| 16  | -18    | 48     | 105    | 7.3         | -15   | 51    | 111   | 11.2        | -43.0| 80.6 | 109.0| 40.4       |
| 17  | -6     | 51     | 99     | 21.0        | -6    | 60    | 105   | 23.6        | -45.3| 96.0 | 106.7| 55.3       |
| 17  | -12    | 51     | 99     | 16.2        | -9    | 57    | 102   | 20.1        | -46.9| 96.0 | 110.4| 56.0       |
| 17  | -57    | 36     | 105    | 17.2        | -57   | 36    | 105   | 17.2        | -67.2| 41.1 | 107.2| 28.0       |
| 18  | -57    | 33     | 108    | 15.0        | -57   | 33    | 108   | 15.0        | -67.1| 39.3 | 107.4| 26.9       |
| 18  | -57    | 33     | 108    | 15.0        | -57   | 33    | 111   | 15.3        | -66.4| 38.2 | 107.9| 25.7       |
| 18  | -54    | 33     | 105    | 13.1        | -54   | 33    | 105   | 13.1        | -66.5| 40.1 | 107.2| 26.8       |
| 19  | -60    | 0      | 108    | 9.0         | -60   | 0     | 108   | 9.0         | -76.9| -2.0 | 111.2| 26.2       |
| 19  | -57    | 0      | 108    | 6.0         | -60   | 0     | 108   | 9.0         | -85.4| -2.0 | 112.5| 34.7       |
| 19  | -60    | 3      | 105    | 9.9         | -63   | 3     | 105   | 12.7        | -88.7| 6.2  | 106.1| 38.3       |
| 20  | -48    | -27    | 102    | 7.3         | -60   | -33   | 108   | 17.5        | -74.0| -40.3| 111.0| 33.4       |
| 20  | -45    | -24    | 105    | 3.0         | -54   | -30   | 108   | 10.8        | -57.0| -37.1| 109.2| 25.6       |
| 20  | -48    | -24    | 105    | 4.2         | -66   | -33   | 108   | 22.8        | -71.1| -41.2| 108.4| 31.3       |
| 21  | -27    | -45    | 102    | 6.7         | -33   | -57   | 108   | 15.0        | -51.6| -76.2| 106.7| 41.7       |
| 21  | -27    | -45    | 102    | 6.7         | -33   | -54   | 108   | 12.7        | -51.4| -75.9| 106.3| 41.3       |
| 21  | -24    | -45    | 102    | 6.0         | -33   | -57   | 105   | 15.3        | -50.2| -77.1| 105.5| 41.5       |
| 22  | 0      | -51    | 102    | 6.0         | 0     | -66   | 105   | 15.3        | 8.4  | -96.0| 101.6| 46.2       |
| 22  | 0      | -51    | 105    | 3.0         | 0     | -63   | 108   | 12.0        | 2.6  | -96.0| 101.8| 45.5       |
| 23  | 0      | -51    | 105    | 3.0         | 0     | -66   | 108   | 15.0        | -9.8 | -96.0| 102.2| 46.4       |
| 23  | 24     | -45    | 108    | 0.0         | 24    | -45   | 108   | 0.0         | 38.4 | -67.1| 106.2| 26.5       |
| 23  | 24     | -48    | 108    | 3.0         | 24    | -48   | 111   | 4.2         | 34.8 | -68.1| 107.4| 25.5       |
| 23  | 21     | -48    | 105    | 5.2         | 21    | -48   | 108   | 4.2         | 31.6 | -70.7| 106.0| 26.8       |
| 24  | 45     | -24    | 96     | 13.4        | 48    | -24   | 102   | 6.7         | 61.3 | -38.2| 107.5| 17.5       |
| 24  | 45     | -27    | 102    | 9.0         | 45    | -27   | 105   | 7.3         | 60.4 | -36.7| 106.7| 15.9       |
| 24  | 45     | -30    | 102    | 10.4        | 45    | -30   | 105   | 9.0         | 60.3 | -42.3| 106.7| 20.6       |

**Average error**: 7.7, **Average error**: 12.0, **Average error**: 13.3

**Standard deviation**: 4.8, **Standard deviation**: 5.9, **Standard deviation**: 10.4
It shows that NBLM can be carried out effectively in the cylindrical structure with circular hole.

The location error standard deviations of NBLM, ALM and TD on the upper surface are 4.8 mm, 3.8 mm and 3.2 mm, and those on the internal surface are 4.8 mm, 5.9 mm and 10.4 mm. The results show that the standard deviation of NBLM is small both on the upper surface and on the lower surface, which shows that NBLM has good robustness for AE source localization.

To make the comparison more intuitive, all the average location errors and standard deviations are shown in Fig. 8. Obviously, the location result of NBLM is more competitive than that of ALM and TD. If higher location accuracy is required in the cylindrical structure with complex hole, more accurate arrivals should be picked up by some reliable methods (such as Carpinteri’s improved AIC [26]), which is useful for AE source localization.

IV. CONCLUSION

The traditional source location method assumes that the elastic wave velocity is a fixed value and the traveling path between the source and the AE sensor is a straight path. However, these assumptions are not satisfied in the actual engineering, such as tunnels, deep wells and other similar quasi-cylindrical structure with complex hole.

In this paper, NBLM is proposed for the quasi-cylindrical structure with complex hole. It optimizes the “pass” condition of the improved A* search algorithm to obtain the fastest path, which is more applicable to the structure with complex curved surface. Lead-breaking tests were carried out as AE source on two different specimens to evaluate the effectiveness of NBLM. According to the arrival, The AE source coordinates were inverted by NBLM, ALM and TD, respectively.

As shown in the experimental results, the location results of NBLM and ALM are quite similar on the internal surface of the cylindrical structure with square hole. Because ALM and NBLM can both fit the structure with the square hole perfectly. However, on the internal surface of the cylindrical structure with circular hole, the average location accuracy of NBLM is increased by 26.7% compared with that of ALM. Because NBLM build the shape of location region better than ALM to search more accurate wave path. As for TD, there is a considerable deviation between the location result and the actual position since TD cannot bypass the empty region. It can conclude that NBLM is more effectively applied in cylindrical structure with curved hole and achieve higher precision requirements of source location. As for the quasi-cylindrical structure with arbitrarily complex hole, it can be formed by multiple planes and curved surfaces. Therefore, the NBLM is suitable for source location in the quasi-cylindrical structure with complex hole.

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