Damage Detection and Optimization of Concrete Structure Based on Acoustic Emission Technology

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Abstract. Concrete material is a cement-based material widely used in various projects. Under the load, the concrete structure will be damaged to produce cracks. Therefore, it is very necessary to accurately locate the damage point during detection. Acoustic emission (AE), as a nondestructive testing technology that monitors concrete damage, can be used to record and analyze the transmitted acoustic signal through a sensor so as to determine the source of the wave. Time difference location method is a commonly used sound source location algorithm at present. It regards the propagation of sound wave in concrete as a fixed value and does not consider the effect of acoustic wave attenuation, resulting in poor positioning accuracy. Resulting in poor accuracy of location point. This paper firstly introduces the principle of time difference positioning method. Following that, an analysis and summary of the influence on the water-cement ratio, sand rate, including aggregate particle the magnitude of sound wave attenuation is provided. The existence of acoustic attenuation is verified by the designed test scheme, and the optimization algorithm is obtained by using exhaustion method and interval dichotomy method. Compared with the time difference localization method, this algorithm can locate the damage point more accurately.

Keywords: Acoustic emission; acoustic attenuation; source location; concrete damage; exhaustive method.

1. Introduction

Acoustic emission (AE) is a kind of nondestructive dynamic testing technology which can make the internal damage of concrete be monitored in real time [1-5]. As AE is an associated phenomenon of uneven deformation of materials or crack cracking and expansion process, pores, micro-cracks and cracks in concrete materials will develop along with the degradation of concrete properties. The transmitted acoustic signals are recorded by various sensors and properly analyzed to determine the source of these sound waves, and this process is commonly referred to as source localization technology.

When using AE to detect and monitor the health of concrete structures, it is one of the main tasks of this technology to accurately locate AE sources. Most of the existing source localization algorithms are time difference localization. By extracting the time of the AE source arriving at the sensor and the distance numerical value between each sensor, the location coordinates of the AE source can be solved, i.e., the location point of AE [6-7]. Thus, the possible damage point of the material can be predicted. Existing time difference positioning algorithms regard the propagation of wave velocity as a constant value. However, existing studies have shown that, for artificial composite materials such as concrete, wave attenuation is serious during internal propagation, resulting in that wave velocity does not propagate at a constant value, and there is a large error between location and actual damage.

Therefore, this paper studies the characteristics and evolution of AE wave velocity in concrete, the sound attenuation in concrete is eliminated, the attenuation characteristics of wave velocity is explored, the wave velocity attenuation test scheme of concrete specimen is designed, and the optimization algorithm is got [8-11]. The precision of positioning is improved by using exhaustive method and interval dichotomy method.

2. AE Source Location Method

2.1. One-dimensional (linear) Positioning

One-dimensional positioning is to determine the location coordinates of AE source in one-dimensional space, also known as linear positioning method. It is assumed that the axial length of the measured object is much larger than the radial length, and the radial length can be ignored relative to the axial length. The following requires linear positioning of the area between sensor1 and sensor2 sensors. The distance between the sensors is s, the distance between the signal and the two sensors is s_1 and s_2 respectively, and the arrival time is t_1 and t_2 respectively. One-dimensional positioning uses at least two sensors and a single time difference, which is the simplest time difference positioning method. The principle is shown as Fig.1.

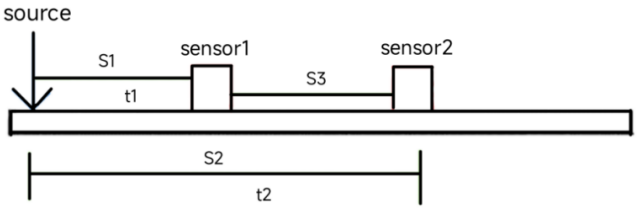


Fig. 1 AE one-dimensional localization

Since the product of the time difference value between the signal reaching the sensors and the propagation speed of the signal is equal to the difference in the distance between the signals reaching the two sensors, the equation can be listed:

$$s_2 - s_1 = s_3; \tag{1}$$

$$s_2 - s_1 = v * (t_2 - t_1). \tag{2}$$

2.2. Two-dimensional Plane Positioning

The principle of plane positioning is the same as that of linear positioning. This paper defines a two-dimensional coordinate system with the XY axis on the surface. The position of sensor1is set as (x_1, y_1), the position of sensor2 is (x_2, y_2), and the position of sensor3 is (x_3, y_3). The three sensors are not in a straight line, the distance from the signal source to the sensors are s_1, s_2 and s_3. The arrival times of the signal source to the sensor are t_1, t_2 and t_3, respectively. The principle is shown in Fig. 2.

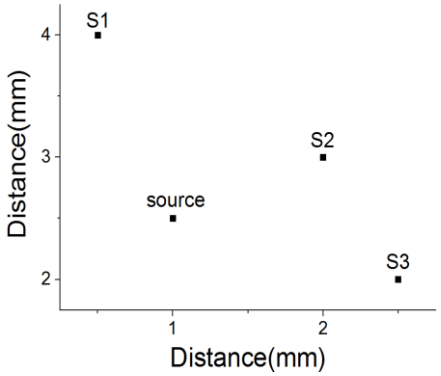


Fig. 2 AE two-dimensional localization

According to the principle that the product of speed and time difference equals distance difference, it can be obtained:

$$s_1 - s_2 = (t_1 - t_2) * v; \tag{3}$$

$$s_1 - s_3 = (t_1 - t_3) * v; \tag{4}$$

$$s_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \ (i = 1, 2, 3). \tag{5}$$

2.3. Three-dimensional Space Positioning

For theoretical tests in three-dimensional space, the three directions of XYZ should be considered. For isotropic materials with uniform wave velocity, the principle is shown in Fig. 3.

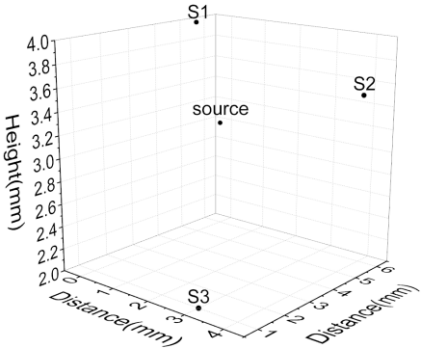


Fig. 3 AE three-dimensional space localization

The travel time equation of AE signal propagation is:

$$\sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} = (t_i - t)v \tag{6}$$

In this formula: x_i, y_i, z_i, t_i are the three-dimensional coordinates and arrival time of the i-th sensor respectively. t is the time for the signal to exit from the AE source, and v is the speed v_0 for the signal to transmit in the material. When the wave velocity is undetermined, there are 5 unknowns in the three-dimensional positioning, which are x, y, z, t and v, respectively. In general, the propagation speed of AE signals in materials can be measured by lead breaking test, so that three-dimensional positioning can be achieved by at least 4 spatial distributions of 5 sensors.

Although the principle of AE source location is simple, due to the influence of inaccurate arrival time identification, uneven wave velocity and other factors, the positioning accuracy is often not high. In order to solve this problem, the law of acoustic attenuation should be explored and the positioning method of AE should be optimized.

3. Characteristics of Acoustic Attenuation

3.1. Effect of Water Cement Ratio on Wave Velocity Attenuation

When the sand rate and the maximum diameter of the aggregate particulates are the same and the water-cement ratio is changed, the standard AE wave velocity in concrete shows a tendency of attenuation with the increase of distance. As shown in Fig. 4, when the water-cement ratio is 0.3, the wave velocity attenuation rate decreases most obviously, and when the water-cement ratio is 0.6, the wave velocity attenuation rate decreases least. That is, with the increase of water-cement ratio, the effect of concrete on acoustic attenuation is reduced [12].

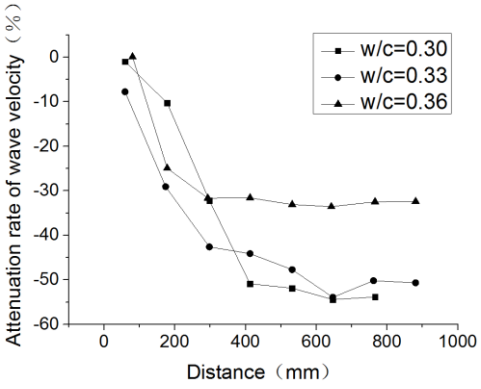


Fig. 4 Attenuation of wave velocity along propagation distance under different water-cement ratio [12]

3.2. Effect of Sand Rate on Wave Velocity Attenuation

In the propagation process of cement concrete with different sand rate, the wave velocity of standard AE shows a trend of attenuation with the increase of distance. As shown in Fig. 5, when the sand rate is 0.47 and 0.55, there is no significant difference in wave velocity attenuation. It can be seen that the sand rate has no significant influence on wave velocity attenuation.

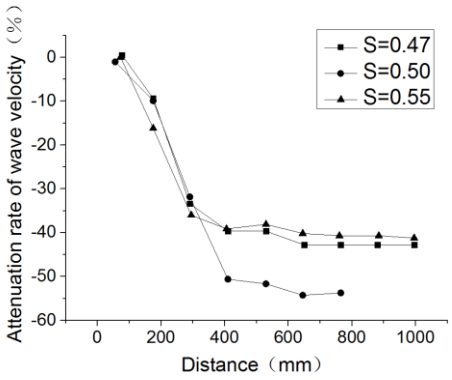


Fig. 5 Attenuation of wave velocity along propagation distance under different sand rate [12]

3.3. Effect of Aggregate Particle Size on Wave Velocity Attenuation

The AE wave velocity of concrete test-pieces with the same water-cement ratio and sand rate under different maximum particle sizes of aggregate is shown in Fig. 6. The results show that when the water-cement ratio and sand content are the same, the wave velocity attenuation of the aggregate with maximum particle size of 20 is significantly greater than that of the aggregate with maximum particle diameter of 10. Therefore, the larger the aggregate particle size, the more significant the attenuation of AE wave velocity with distance.

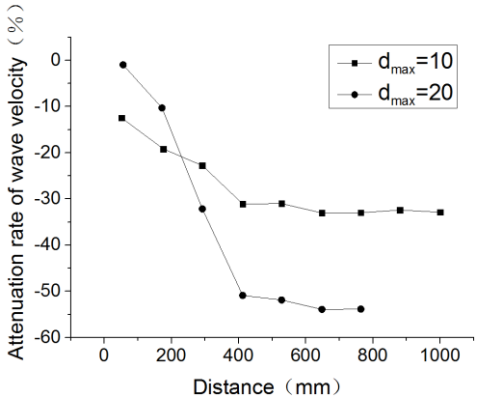


Fig. 6 Attenuation of wave velocity along propagation distance under different aggregate conditions [12]

4. Experimental Proof of Wave Velocity Attenuation

4.1. Experimental Scheme

The following are the test protocol steps to prove the existence of acoustic attenuation:

(1) The test builds a standard cube model.

(2) A sound source is placed in the center of the cube.

(3) The six receivers are placed at the center of the side of the cube, the center of the edge, and the vertex, as shown in Fig. 7.

(4) The distance between the sound source and the receiver in the center of the side is set to s1, the source distance from the sensor placed at the apex of the center of the edge is set to s2 and the distance between the sound source and the receiver at the vertex as s3.

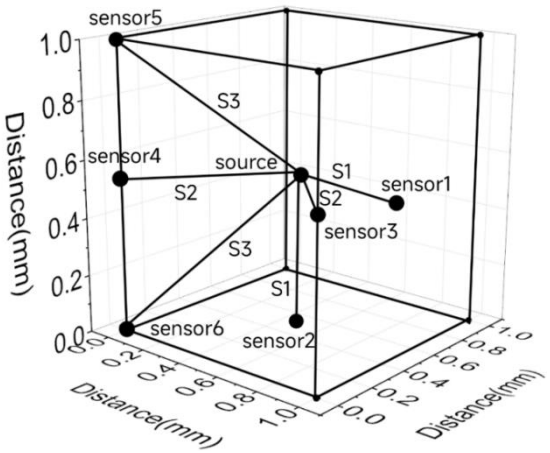


Fig. 7 Proof wave velocity attenuation test

4.2. Experimental Calculation

(1) Assuming that the medium is evenly distributed, let the height of the cube member be x, which can be obtained from the geometric relation of the cube:

$$s_1 = \mathrm{x}/2; \tag{7}$$

$$s_2 = \sqrt{(\mathrm{x}/2)^2 + (\mathrm{x}/2)^2} = \sqrt{2}x/2; \tag{8}$$

$$s_3 = \sqrt{(\mathrm{x}/2)^2 + (\sqrt{2}x/2)^2} = \sqrt{3}x/2. \tag{9}$$

As $\mathrm{x}/2 > \sqrt{2}x/2 > \sqrt{3}x/2$, it can be concluded that $s_3 > s_2 > s_1$.

(2) The SAEU3H integrated AE signal acquisition system is used to detect the arrival time of sound source to each sensor($t_1. t_2. t_3 \ldots$), the formula can be used as:

$$\mathrm{v_i} = \mathrm{s_i}/\mathrm{t_i}, (\mathrm{i}=1, 2, 3, ..., \mathrm{n}.) \tag{10}$$

It can be concluded that there are 3 paths and 6 wave velocities through s_1-s_3. From the comparison, it can be seen that the two wave velocities through the same path are nearly equal. The wave velocity through s_1 is the maximum, while that through s_3 is the minimum. The theoretical result is:

$v_1 \approx v_2 > v_3 \approx v_4 > v_5 \approx v_6$

Thus, the further apart the source and receiver are, the longer the path the sound waves take through the medium, and the more wave speed is lost. Therefore, the wave velocity cannot be regarded as a fixed value in the calculation. Considering the existence of acoustic attenuation, locating the sound source based on the acoustic attenuation correction formula can improve the positioning accuracy.

4.3. Optimization Algorithm

The distance of the AE source from the i-th receiver s_i:

$$s_i = \sqrt{(\mathrm{x_i} - \mathrm{x})^2 + (\mathrm{y_i} - \mathrm{y})^2 + (\mathrm{z_i} - \mathrm{z})^2}, (\mathrm{i}=1, 2, 3, ..., \mathrm{n}.) \tag{11}$$

$$\mathrm{t_i} = \mathrm{s_i}/\mathrm{v_i} \tag{12}$$

The theoretical value of the duration of propagation from the AE source to the i-th reception signal sensor is $\mathrm{t_i}$, the measured value of SAEU3H AE signal acquisition system for AE source propagation to the i-th sensor is $\mathrm{T_i}$, then the error between the theoretical value and the experimental value is e:

$$\mathrm{e} = |\mathrm{T_i} - \mathrm{t_i}| \tag{13}$$

For the calculated results, interval dichotomy is used:

(1) This algorithm determines the interval [a, b], verify f(a)-f(b)＜0, and the accuracy ξ is given.

(2) Point c is the midpoint of (a, b), and c is figured out.

(3) f(c) is calculated. If f(c)=0, then c is the zero of the function, if f(a)*f(c)<0, then b=c, and if f(c)*f(b) < 0, then a=c.

(4) Accuracy ξ is determined whether is achieved: when | a - b | < ξ, hen the zero-approximation a (or b) is obtained; otherwise, (2) -(4) should be repeat.

In this paper, the exhaustive method was used to divide concrete specimens into equal grids along the x, y and z directions, and sensors were placed at the intersection of the grids. The coordinates of the sensor are substituted into the above formula to obtain the minimum value, and then the grid value obtained is the coordinates of the AE source [13].

5. Conclusion

(1) This paper introduces the time difference positioning method from one dimension, plane and space, and explains its disadvantages. The concept of acoustic attenuation is explained and the law of wave velocity attenuation is summarized.

(2) In this paper, an experimental design scheme is proposed to verify the existence of acoustic attenuation, and the optimization algorithm is obtained by using the exhaustive method and the interval dichotomy method. The method can make the accuracy of the locating point is significantly higher than that of the time difference locating method.

(3) As the water-cement ratio, aggregate particle size and sand ratio of concrete components used in actual engineering are different, whether this experimental conclusion is applicable to the AE characteristics analysis of other concrete components in the process of loading needs to be further studied and demonstrated.

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