Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)

Acoustic emission visualization of micro-cracks induced by pulsed discharge in concrete

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ABSTRACT: Source location of micro-cracks in internal of concrete that damaged by dielectric breakdown was carried out by acoustic emission (AE) technique. The energy of 6.4 kJ was discharged at one shot into the concrete specimen by a Marx Generator to generate micro-cracks. AE testing measurement system with 8 AE sensors were used. During the AE measurement, uniaxial compressive load was applied to the specimen. In case of AE parametric analysis, AE sources due to friction of existing micro-cracks can be detected especially in lower loading stages (up to 60 kN). Therefore, AE signal which are produced within the load of 20 kN-60 kN are processed for source location. The visualization of domain area, which micro-cracks are scattering in internal concrete body, is presented in this paper by using de-noised AE signal.

1 INTRODUCTION

Understanding micro-cracks in internal of concrete has been studied extensively because the fracture of a concrete is initiated by micro-cracks inside the concrete. There are many methods have been develop to study about this. However, it is still difficult to determine the damage field which micro-cracks are scattering in interior of a concrete. This paper presents a visualization of micro-cracks configuration in internal of concrete body.

Many researchers have proposed some methods to visualize damage in concrete. Acoustic Emission (AE) is one of the methods which enable to visual the cracks location in concrete as well as the type of the crack itself (Ohtsu & Shigeishi 2002, Shigeishi & Ohtsu 2001). To this point, AE has been utilized to detect damage of concrete for the higher loading stage before concrete rupture. However, not much AE study has been found to concern about micro-cracks. Possibly, there is not much AE activity able to be recorded during lower loading level, which micro-cracks usually often generated.

To this reason, this research proposes a pulsed discharge treatment to generate micro-cracks in order can be detected by AE sensors. Micro-cracks generated by pulsed discharge are essentially the same as deterioration concrete by micro-cracking which is usually occurs in the boundary between cement and aggregate.

This paper is organized as follows: section 2 describes related works to this research which have been published, section 3 explains AE signal including de-noising of AE signal and source location algorithm, section 4 presents material and experimental method, section 5 explains result and discussion, and the last section concludes the paper.

2 RELATED WORK

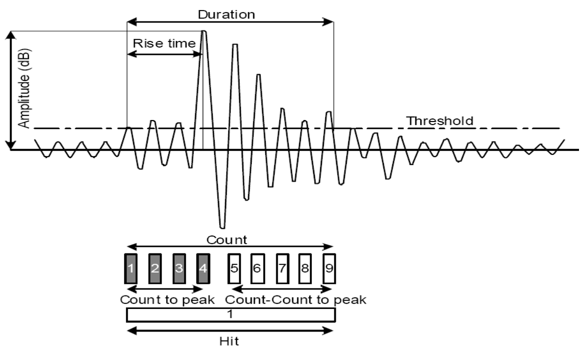
The related works to our research are about studying damage on concrete using AE as described in Shigeishi & Ohtsu 2001 and Ohtsu & Shigeishi 2002. The most related research is Shigeishi & Ohtsu 2001 which studied the development for crack identification in concrete material by using AE moment tensor analysis. An experimental method was conducted in plate specimens made from cement-mortar and concrete. Orientation of cracks, cracks types, and crack volumes are determined by SIGMA-AE analysis. SIGMA-AE is a simple AE moment tensor analysis which has been developed to clarify the quantitative analysis of AE signals (Ohtsu 1987). In this reference, the cracks are visualized at surface of the specimens. The other research is Ohtsu & Shigeishi 2002, which explains three-Dimensional Visualization of Moment Tensor Analysis by SIGMA-AE. In this paper the stage of crack growth is visualized using Virtual Reality Modeling Language (VRML). It is recognized that a small number of cracks were found in the low stage of loading. In fact, many micro-cracks should already present before concrete is loaded. And these micro-cracks will grow when the concrete is started to be loaded.

We proposed a concrete with micro-cracks is generated in advanced using pulsed discharge. The existing micro-cracks due to pulsed discharge will produce AE signal by rubbing of the surface. The friction of micro-crack surfaces will become the source of AE and recorded by AE sensors.

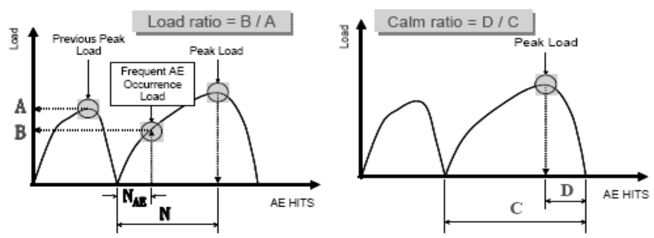
3 ACOUSTIC EMISSION (AE)

AE is phenomena rapid release energy due to fracture or cracks in a material and produces elastic energy which can propagate throughout the material and able to be recorded by appropriate sensors. AE has been applied to estimate the damage degree of existing concrete structure (Ohtsu & Shigeishi 2002, Shigeishi & Ohtsu 2001). There are two techniques of analysis can be applied to determine the deterioration of existing concrete which are parameter-based analysis and signal-based analysis. The former one is more as a qualitative analysis and the second one is more as a quantitative solution of AE detection. Both analysis methods have been successfully applied to provide information condition of existing concrete structure.

In this research AE parameter analysis is used to discriminate of AE source between existing micro-cracks and new cracks. These parameter are AE hit, calm ratio and load ratio. Their definition can be described by Figure 1 (Grosse & Ohtsu 2008).



(a)



(b)

Figure 1. AE parameter definition (a) and Calm ratio and Load ratio definition (b).

3.1 *Onset time of AE signal*

AE signal based analysis is required for source location calculation. Further analyzed of damage mechanism requires two parameters of AE which are first time arrival and first amplitude. Akaike Criterion Information (AIC) has been successfully applied to determine these significant parameters (Grosse & Ohtsu 2008). Its calculation is based on the variance of AE signal as described below:

$$AIC(t_w) = t_w * \log(var(R_w(t_{w,1}})) + (T_w - t_w - 1) * \log(var(R_w(1+t_w, T_w)))) \quad (1)$$

The index w from the series R_w indicates the chosen window containing the onset. T_w is the last samples of R_w and var indicates the variance function.

3.2 *De-noising AE signal*

The AE waveforms need to be recorded and the analyzed. According to Grosse & Ohtsu 2008, one of the biggest benefits using signal-based is enabling the user to distinguish between signals to noise after measurement which can not be done when using parameter-based analysis.

AE data are usually disturbed by noises of different frequency ranges. The noises can be from the measurement equipment (such as preamplifier, etc.) and also the surrounding. The noises are often found as high frequency noises. On the other hand, a low frequency signal caused by testing device often influence AE signal as well. The noise makes onset detection difficult.

Wavelet transform is an effective method of filtering and de-noising data (Grosse & Reinhardt 2002 & Grosse et al. 2004). This technique can be applied into acoustic emission raw data to improve signal to noise ratio effectively. This method is useful in case of signal-based analysis, where picking the onset times of the signal is important for source location (Grosse & Reinhardt 2002 & Grosse et al. 2004).

The general procedure of de-noising using wavelet transform by MATLAB as follow:
Load the AE signal

```
s = leleccum(1:2048);
  l_s = length(s);
```

Perform a multi-level wavelet decomposition of the signal

```
[C,L] = wavedec(s,8,'sym4');
```

Get de-noising parameter

```
[thr,sorh,keepapp] = ddencmp('den','wv',s);
```

Removing the noise

```
Clean = wdencmp('gbl',C,L,'sym4',8,thr,sorh,keepapp);
```

3.3 *AE Source location*

Source location of damage is calculated using an algorithm from AE-SIGMA (Simplified Green's functions for Moment tensor Analysis) procedure (Ohtsu 1987). This is a three dimensionally calculation. Principally, the crack location is determined from the arrival time differences between some points of observation, solving equations:

$$R_i - R_0 = v_p d_i \qquad (2)$$

where, v_p = the wave velocity of concrete; d_i = time differences between observation; and R is the distance between source location and point of observation. Next, Least Square Method is used for obtaining initial value of source location:

$$v_p d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \qquad (3)$$

The coordinates (x, y, z) represent the point at which the travel time to each sensor (x_i, y_i, z_i) is calculated. Next, Taylor series is uses for developing the exact source location.

$$r_i = \left(\frac{\partial t}{\partial x} * \Delta x\right) + \left(\frac{\partial t}{\partial y} * \Delta y\right) + \left(\frac{\partial t}{\partial z} * \Delta z\right) \qquad (4)$$

where r_i = travel time residual.

4 EXPERIMENT

4.1 *Material*

The mix proportion of concrete is shown on Table 1.

Table 1. Concrete mix proportion.

Max. agg. size (mm)	Slump (cm)	Water-cement ratio (%)		
20	8	55		
Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	AE agent (cc)
175	318.2	742.1	1134.1	95.4

The specimen is concrete prism (150 mm x 150 mm x 300 mm). After passing a 28 day curing time, concrete specimen was tested for obtaining its mechanics properties such as compressive strength, poisson's ratio and wave velocity.

4.2 *Method*

Pulsed-electric discharge is a technology which enables to separate the constituent of inhomogeneous solid material such as concrete. As reported by (Akiyama et al. 2003) fundamentally and (Narahara et. al. 2003) practically for concrete, this method has been applied into a waste concrete to separate between matrix and aggregate. The final aims of these studies were to produce higher quality recycle concrete aggregate. As shown in Figure 2, concrete fracture by inducing of electrical pulsed discharge originates with destruction of the transition zone between aggregate and matrix. It is recognized that the fractured zone dielectric breakdown is essentially the same as deteriorated area by cracking in interior of concrete which is occurs at the boundary between aggregate and matrix. The fractured zones, which contain many micro cracks, exist along the current pass at the breakdown.

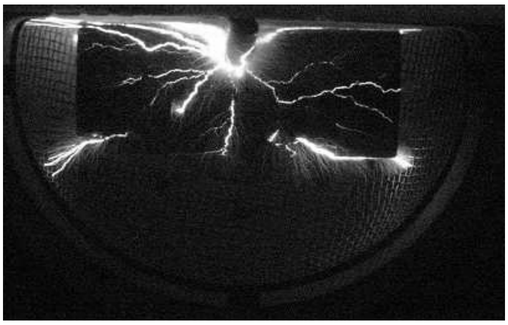


Figure 2. Pulsed dielectric breakdown on concrete.

The energy of discharge can be determined by following equation:

$$E = \frac{1}{2} xCxV^2 xMxN \qquad (5)$$

where E = energy (kJ); C = capacitance of capacitor (μF); V = voltage per stage per one capacitor (kV); M = number of capacitor; and N = frequency of discharge. Furthermore, Akiyama et all, 2007 explains that a Marx generator whose capacity of 0.8 μF-40 kV, 10 stages is capable to separate a block of concrete into seven pieces with six time discharge treatment. Therefore, this research uses the same generator as well as the capacity with one shot discharge treatment to generate micro-cracks in internal the concrete specimen.

Concrete was put into reactor to obtain the discharge as can be seen on Figure 3. The energy of 6.4 kJ was discharged into the concrete one time by using a Marx Generator. This generator's capacity was 0.8 μF and 40 kV per stage. It consisted of 10 stages. One time of discharge produced 6.4 kJ of energy.

After discharging, cracks were generated and these were as sources of AE signal. AE measurement system was sensor based acoustic multichannel operation system (PAC SAMOS) associated with AE win for the software. The AE signals need to be amplified before transmission. Therefore, preamplifiers model 1221 with gain 40 dB were used.

Specimen was concrete prism whose size and the coordinate center for source location calculation are written in Figure 5. This point was also where the electrode position was placed during discharging. Eight channels of R15 type of sensors with maximum

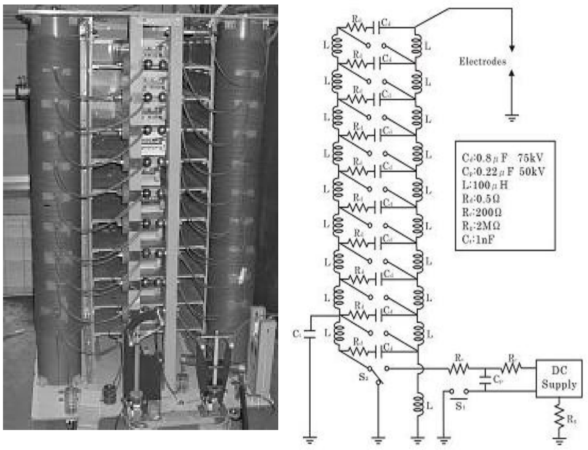


Figure 3. Marx Generator and its circuit.

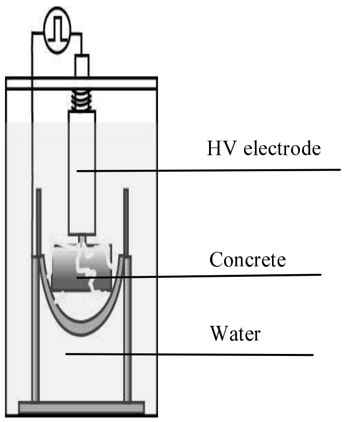
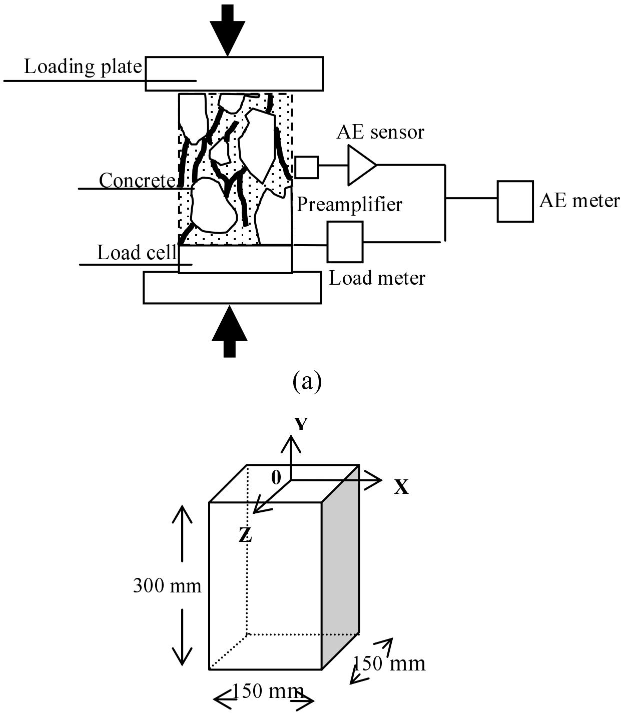


Figure 4. Concrete discharging process.

frequency of 150 kHz were attached onto the specimens. During AE measurement testing, uni-axial compressive loading of 20 kN – 200 kN was loaded to the specimen.



(b)

Figure 5. AE measurement system (a) and concrete specimen (b).

5 RESULTS AND DISCUSSION

5.1 *Concrete properties*

Mechanics properties of concrete after curing of 28 days are figured in Table 2.

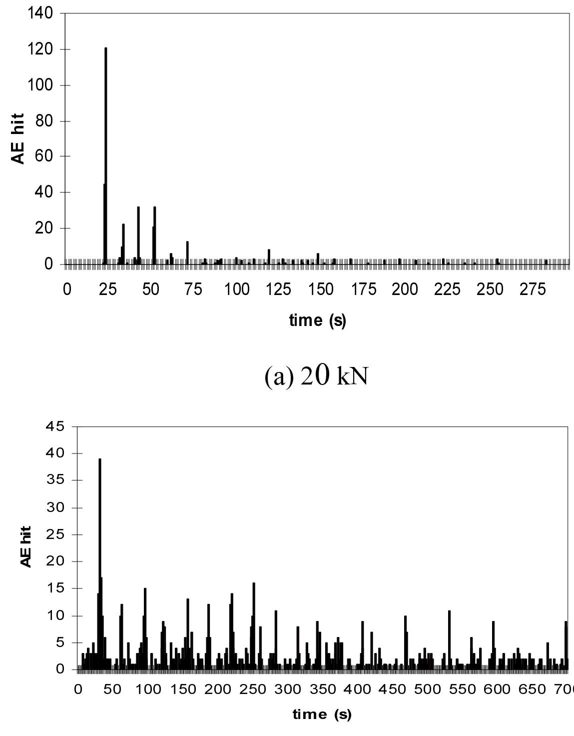
Table 2. Concrete mechanics properties.

Compressive strength (MPa)	Poisson's ratio	Elasticity modulus (MPa)	P-wave velocity (m/s)
39.05	0.186	23300	3653

Compressive strength and Poisson's Ratio are obtained from the compression testing of concrete cylinder whose size 100 mm diameter and 200 mm height. Meanwhile, P-wave velocity value is obtained from an experiment using oscilloscope and function generator to record the time of wave propagation from the edge of concrete specimen to the opposite edge. The wave velocity is calculated from the length of specimen divided by wave time propagation.

5.2 *Distinguishing of AE signal due to friction of micro-cracks*

AE signals which are obtained from the experiment are not only produced from friction of existing micro-cracks but also from new nucleated cracks because of the loading. Therefore, the distinction of these two sources should be done in advanced by analyzing some AE parameter analysis. In this paper, we figure 20 kN for representing lower level of loading and 150 kN for representing higher level of loading.

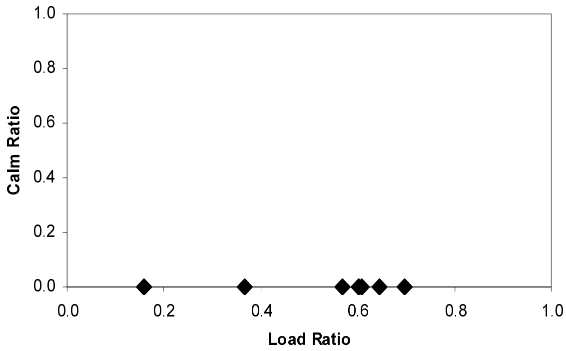


(b) 150 kN

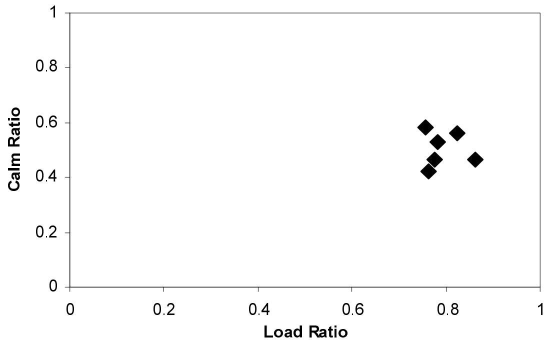
Figure 6. AE-hit and time relationship for (a) low loading level and (b) high loading level.

It is recognized that from 20 kN until 60 kN of loading level, AE activities appear in the early of loading stage because of the rubbing at the existing cracks surfaces due to pulsed power.

Otherwise, when loading level is increased over the 60 KN, there are significant acoustic emission activities enable to be recorded in all time period of testing. It is assumed that, in the beginning of the test, acoustic emission activities due to pulsed power damage appears and along with the loading is continued, the newly nucleated cracks also occur which can produce other AE activities as the result. It is also assumed that these activities are triggered by the extension of existing micro-cracks of damage concrete due to pulsed power. This phenomena also can be found at relationship between calm and load ratio.



(a) 20 kN



(b) 150 kN

Figure 7. Calm ratio and load ratio relationship for (a) low loading level and (b) high loading level.

Most of value of the clam ratio is zero on the loading stage up to 60 KN. It is because no AE activity occurs during unloading process. Only during loading process AE activities can be recorded due to friction of existing micro-cracks surfaces. Meanwhile, the higher of calm ratio is found on the loading level over than 60 kN. During loading process, new tensile cracks also occur and during unloading these cracks turn into shear cracks. All of these enable us to record AE activity during both loading and unloading process. As the result, calm ratio around 0.5 is obtained.

According to AE parameter analysis above, we conclude that AE activities which occur within the loading of 20 kN – 60 kN are because of sliding friction of existing micro-cracks surfaces and during the loading over than 60 kN, the AE activities are not only yielded by extension of existing micro-cracks, but also by new nucleated cracks due to the loading. Therefore, for source location of existing micro-cracks will be focused on loading level between 20 kN and 60 kN.

5.3 *AE signal de-noising*

AE signal which produced from friction of existing micro-cracks is processed further for noise removing using wavelet transform. Wavelet packet for one dimensional discrete signal is used. Sym 4 is selected as mother wavelet because this window is appropriate for AE signal. Maximum level of decomposition is applied to decompose the signal. In addition, soft threshold is applied into the detail coefficient while approximation coefficient is kept. Figure 8 is showing the comparison between AE raw signal and AE de-noised signal.

From the graph, we can see noise can be reduced effectively and at the de-noised signal, it makes arrival time easily be determined as well. Arrival time is used for calculating source location.

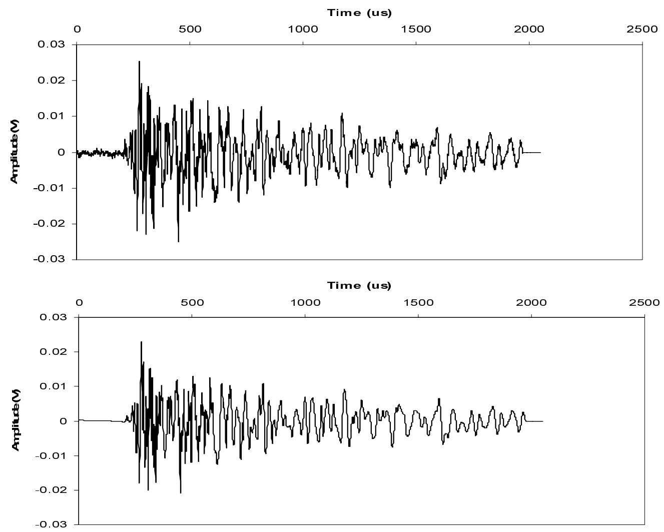


Figure 8. AE signal of 30 kN loading: raw signal (upper) and de-noised signal (lower).

5.4 *Source location result*

Source location coordinates can be seen from Table 3. Seeing zero point at Figure 5, this is the location of electrode position during pulse discharging.

Table 3. Source location of micro-cracks coordinates.

X(mm)	Y(mm)	Z(mm)
-46.682	-56.003	-33.36
-51.622	-208.73	-39.556
54.093	-273.4	-46.715
12.416	-152.57	-17.85
-34.472	-93.586	26.749

Five locations of micro-cracks are found in internal of concrete. The micro-cracks occur not only in the area near by electrode position but also distributed throughout the body of specimen. Some figures below present the location of micro-cracks position.

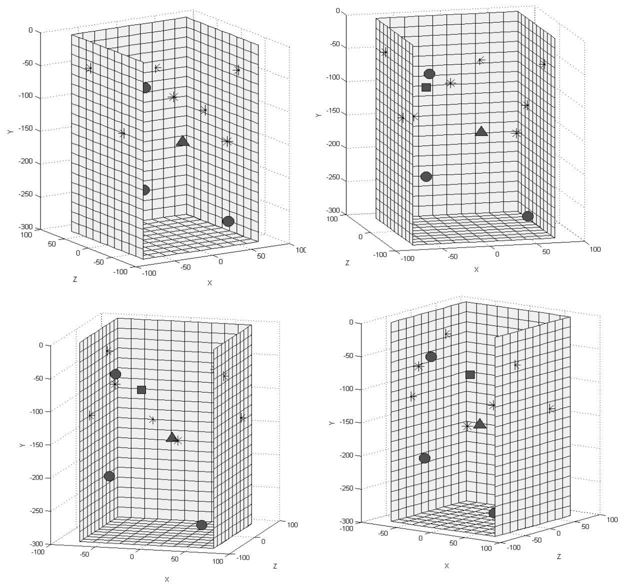


Figure 9. Micro-crack location in some views.

The asterisk shows the sensors location during the experiment. The circle shows micro-cracks which detected during loading of 20 kN, the triangle refers to 30 kN, and the square refers to 60 kN. The purpose method can present the domain areas, in which existing micro-cracks are scattering in internal concrete body.

6 CONCLUSION AND FUTURE WORK

The detection of acoustic emission signal due to friction of existing micro-cracks can be found at the low stages of loading between 20 kN – 60 kN. The micro-cracks occur not only in the area near by electrode position but also distributed throughout the body of specimen. The visualization of domain area, which micro-cracks are scattering in internal concrete body, can be presented successfully by using de-noised AE signal

For future work, we need to calculate the volume of the micro-cracks as well as to progress the denoising technique in order to improve the accuracy of source location calculation.

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