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DENOISING ACOUSTIC EMISSION SIGNAL USING WAVELET TRANSFORMS FOR DETERMINING THE MICRO CRACK LOCATION INSIDE OF CONCRETE

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ABSTRACT
Acoustic emission (AE) technique is developed to locate source of damage inside of concrete. However, the AE signal is interfered by much noise, which makes the determination of first time amplitude of AE signal is hard to be carried out. In fact, the determination of this parameter is a significant part for locating the source of damage in concrete. Therefore, one of the denoising methods called wavelet based denoising is proposed. In this case, some wavelet bases function are investigated to find out the proper wavelet bases function to perform the denoising of AE Signal. From the experimental data, the best wavelet basis function for this case is Coiflet, which is shown by providing the best SNR than the other wavelet families. In addition, the determining cracks locations on concrete can be performed easier on denoised AE signal than on noisy AE signal.

Keywords: Acoustic emission signal; Damage concrete; Denoising; SNR; Wavelet

1. INTRODUCTION
Noise is defined as any unpleasant or unexpected signal coming from some sources, which interfere the expected signal. Noise has to be neglected when performing further analysis. Denoising of signal can be defined as a process for separating a signal mixed with noise. For example, acoustic emission (AE) signal that is recorded by AE measurement is actually a combination of the signal representing the existing crack and noise.

AE signal can be used to evaluate existing micro-cracks in the inside of concrete through AE parameter-based analysis and AE signal based analysis. The former is qualitative while the latter is quantitative. AE parameters-based analysis works using first amplitude of AE signal. It means that AE parameters-based analysis needs AE signal without noise. On the other hand, onset time of AE signal is important parameter to determine the micro-crack locations. This parameter is easier and more accurately to be determined on a clean AE signal. In addition, clean AE signal is needed for calculate the micro-crack source location using SIGMA-AE source location procedure (Othsu, 1987). The less noise interferes AE signal the better AE parameters will be obtained. However, it is hard to obtain AE signal without noise.

In attempting to overcome noise problem on AE signal, a noise-reduction treatment is applied before further analysis. The main aim of this research is to find the proper wavelet-based denoising of AE signal which can provide best solution for determining the micro-crack source locations.

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This paper is organized as follows: the first section presents introduction of this work; the second section describes the related works; the third section explains AE signal phenomena; the fourth section explains the wavelet and how it used for denoising; the fifth section explains experimental result and discussion; and the rest presents conclusion and future work.

2. RELATED WORKS

The denoising process is required for further analysis (Grosse et al., 2002; Grosse et al., 2004). There are many methods that had been proposed for denoising of the AE signal such as Fourier ttransforms based method, DCT based method, and wavelet based method (Pan et al., 1999; Fang et al., 2004; Stollnitz et al., 1996; Misiti et al., 2009; Swe et al., 1999; Zhou et al., 2012; Harcarik et al., 2012).

Wavelet bases denoising methods are mostly related to this work (Grosse et al., 2002; Pan et al., 1999; Fang et al., 2004; Stollnitz et al., 1996; Misiti et al., 2009; Swe et al., 1999). The wavelet transformation has an ability to extract the frequency content (Fang et al., 2004; Stollnitz et al., 1996; Misiti et al., 2009), which exists in a signal. By using multi-resolution wavelet transformation, AE signal can be decomposed into several signals with different frequencies, which are called as average coefficients and several detail coefficients. The average coefficient corresponds to the low frequency component while the detail coefficient corresponds to the high frequency component. The multi-resolution wavelet transformation can be performed by implementing filter-bank decomposition, while the reconstruction can be done by implementing filter-bank reconstruction (Stollnitz et al., 1996; Misiti et al., 2009). The wavelet based denoising can be performed through the multi-resolution wavelet analysis.

The Symlet wavelet basis function has been reported that could provide good noise reduction because the Symlet family has an excellent property for denoising signals (Fang et al., 2004; Swe et al., 1999). Other reasons are that the Symlet has good vanishing moment and smoothness factors. However, these characteristics do not provide yet what the best filter length and decomposition level is for denoising AE signal.

3. ACOUSTIC EMISSION

3.1. Phenomena of Electric Breakdown Deterioration on Concrete

A lightning is basically an electric spark on a huge scale. The voltage is around 100 million volts and the current is in the range of 3000 to 200000 amperes. The electric current occurs in a very short time period and may result damage to concrete during lightning. The force results from a negative charge at the bottom of a cloud, seeking a positive charge on the earth's surface or to another cloud. When two opposite charges are connected by a conductor and the electrical current flows from positive to negative, the discharge arises (Lanser et al., 1984; Kencanawati et al., 2011).

In concrete, before lightning yields damaging effect, the energy is converted into three different states: electrical, thermal, and mechanical energy. The phenomena are as follows. The temperature increases instantaneously (thermal energy) and penetrates through the concrete body when a high current electrical discharge at the point of contact hits the low conductivity material such as a concrete. The moisture, which usually exists in concrete, can be converted into steam by high temperature and cause explosive damage (mechanical energy). This energy creates cracks inside of concrete leading to structural damage.

In reinforced concrete corn silos, the discharge is passed through the concrete structure and then it travels through the high-moisture corn to reach the ground. The extreme heat of lightning discharge which causes rapid expansion of the reinforced concrete, generates some cracks, thereby, weakening the structural integrity (Lanser et al., 1984; Kencanawati et al., 2011).

3.2. AE Signal and Its Analysis

The AE signal is a phenomenon of released rapidly energy due to fracture, cracks or damage inside of material. Elastic waves can be produced during this process. These waves propagated inside of material can be detected by an AE sensor, which is usually attached in the surface of the material. The detected wave by AE sensor is called AE signal.

The analysis of AE signal has been studied both quantitatively and qualitatively (Shigeshi et al., 2001; Shigeshi et al., 2002). In addition, AE signal analysis is performed to distinguish between existing cracks and new cracks inside of concrete. AE hit is defined as a signal that exceeds from defined threshold and causes system channel to accumulate the data (Lanser et al., 1984). It is often used to show AE activity with based on a numerical count over a certain period (rate) or a cumulative set of numbers. Figure 1 shows waveform corresponding to one 'hit'. It means the first amplitude is important parameter on determining the micro-crack inside of concrete.

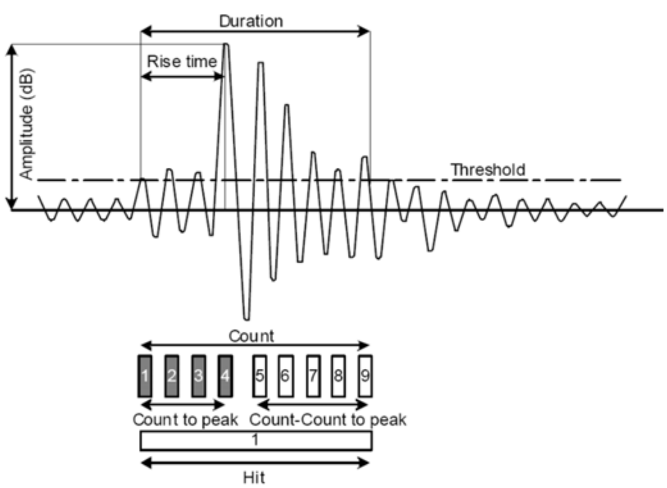


Figure 1 AE hit definition (Grosse et al., 2008)

3.3. Noises in AE Signal

Theoretically, there are many kinds of noises such as white, pink, proportional, and square-root noise, as shown in Figure 2. A noise having all frequencies and equal power at all frequencies is called white noise. Generally, white noise in acoustic domain sounds like a hiss, while pink noise sounds more like a roar (URL, 2013).

The AE signal, which is recorded by the AE tool, tends to be interfered by the noise from the instrumental devices. The common noises from instrumental devices have more power at low frequencies than at high frequencies which is called as "pink noise". This kind of noise is not only complex but also difficult to be characterized.

In addition, high frequency noise is often found on AE signal. However, a low frequency noise caused by instrumental devices also frequently influences AE signal. The noise makes onset time detection be difficult and reduces accuracy of determining source location. Therefore, a denoising technique has to be applied for cleaning the noise of AE signal before further analysis.

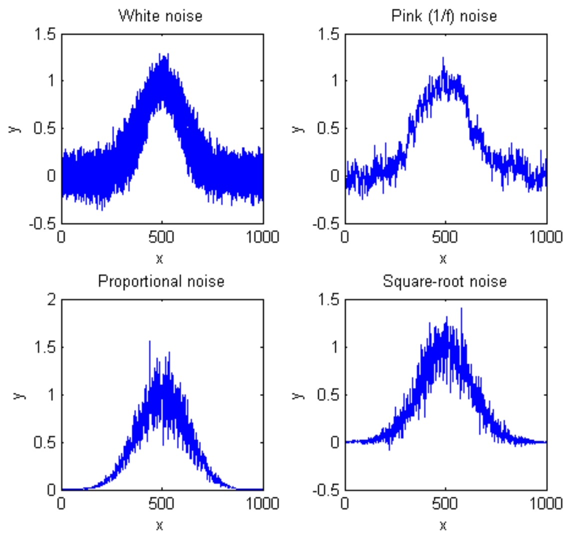


Figure 2 Noises interferences a signal (url, 2013)

4. WAVELET BASED DENOISING

Similar to other transformation methods (Fourier and Discrete Cosine Transforms (DCT)) wavelet transform converts the data from time domain into time-scale (frequency) domain. The wavelet transform decomposes a signal into a set of bases functions. Dilating and translating mother of wavelet can determine the bases function.

The wavelet transform becomes important tool in signal processing and has been applied for filtering, features extraction, compression, etc. It happen because wavelet transform has two main advantages: firstly, it can efficiently extract both time and frequency information from a time-varying signal, which can provide not only frequency domain but also their location simultaneously; and secondly, it also shows the coarser low-frequency features which is collection of dominant information in low frequency component.

Wavelet transform has been reported that it is effective method of filtering and de-noising data (Grosse et al., 2002; Pan et al., 1999). According to this information, this technique can be applied into AE raw data to improve signal to noise ratio effectively. Generally, the wavelet function $w(t)$ can be written as a linear combination of the scaling function $\phi(t)$ as shown in the following equations (Fang et al., 2004):

$$\phi\left(\frac{t}{2}\right) = \sqrt{2}\sum_n h_n \phi(t-n) \tag{1}$$

$$w\left(\frac{t}{2}\right) = \sqrt{2}\sum_n g_n \phi(t-n) \tag{2}$$

h_n is a coefficient related to low-pass filter and g_n is a coefficient related to high-pass filter extracted from wavelet bases function. The algorithm of multi-level of discrete wavelet transforms (MDWT) is shown in Figure 3. By this algorithms, the input signal (I) is decomposed into low frequency component (y_{n+1}) and high frequencies components (y_1, y_2, …, y_n) using low and high pass filter (LP, HP respectively).

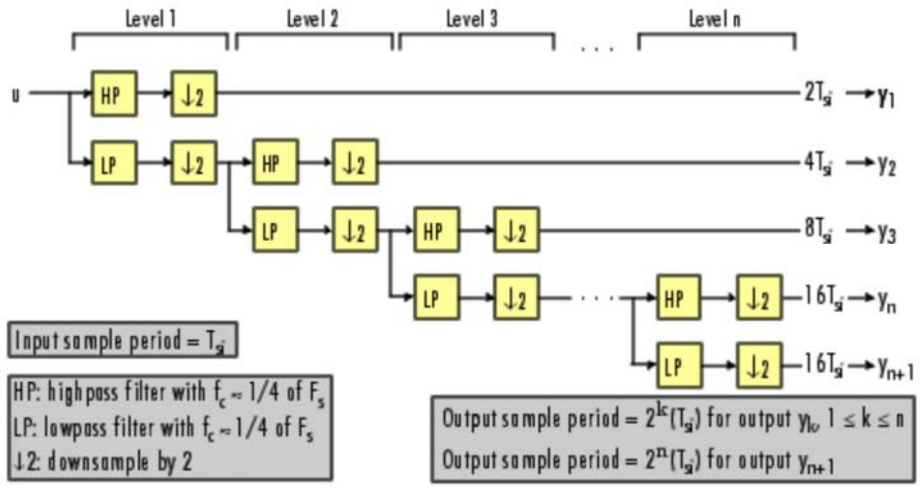


Figure 3 MDWT algorithm (Masiti et al., 2009)

From MDWT algorithm, the denoising is performed by removing some non-significant information in the detail transformation coefficients. The non-significant information is the coefficients having less magnitude value than defined threshold. The denoising algorithm is shown in the following flowchart.

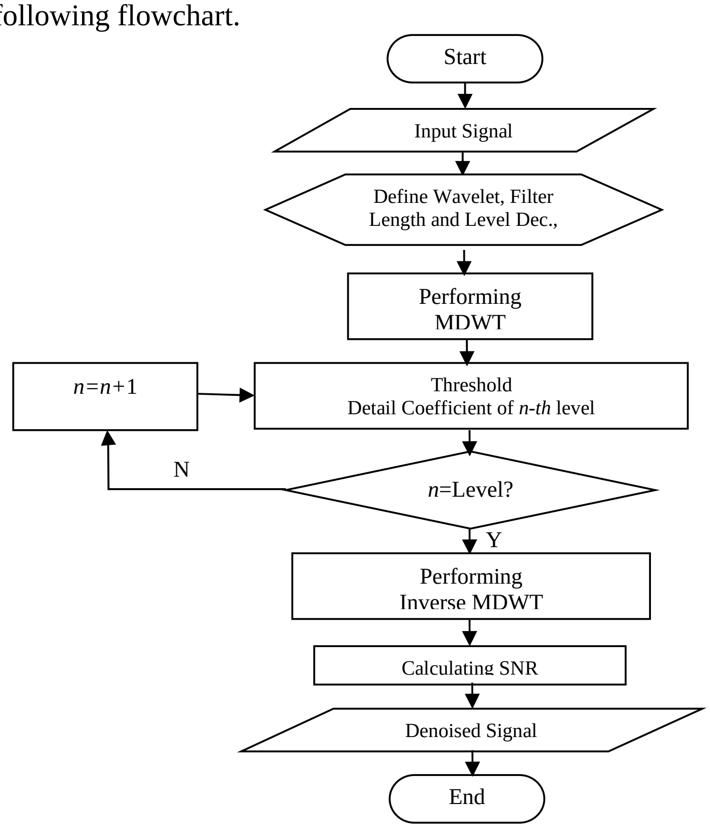


Figure 4 Flowchart of wavelet based denoising

In order to know the performance of the proposed denoising method, the SNR is employed as indicator parameter. Theoretically, according to Equation 3, the higher SNR is, the better the denoising performance is. There are two models of SNR equation that can be used, as follows:

$$SNR_1 = 10\,log_{10}\left(\frac{\sum_n I_n}{\sum_n (I_n - I_n^{'})}\right) \tag{3}$$

Where I is the original signal, $I^{'}$ is denoised signal, and n is length of the signal.

$$SNR_2 = \frac{S}{N} = \frac{Mean\,Signal}{Standard\ Deviation} \tag{4}$$

The Equation 3 is employed when the original and noise signals are defined clearly, while the Equation 4 is used not only when original signal and noise are defined clearly but also when input signal is already interfered by noise (noise or the original signal is unknown). According to Equation 4, the smaller SNR is the better denoising performance is achieved.

5. EXPERIMENTAL RESULT AND DISCUSSION

5.1. The performance in Defined Signal

In order to know the performance of the proposed denoising algorithm for denoising signal, the first experiment was carried out using sinusoidal signal and random noise (see Figure 5) which was generated by defined function. In this case, the input signal had SNR input almost 25 dB. The proposed denoising algorithm can effectively remove the random noise as shown in Figure 6 when the Daubachies 4 wavelet basis and 4 decomposition level were implemented. It visually shows that the input signal (Figure 5) and denoised signal (Figure 6) are similar with SNR of input signal by about 36.31 dB. From this experimental result, it can be concluded that the proposed wavelet based denoising algorithm can work well to remove the noise from the noisy signal. This result can be achieved because the wavelet has good ability to separate the information existing in low frequency component and flavor of the signal existing in high frequency component. By setting a threshold value around high frequency components, which is placed in the detail coefficients of wavelet transforms, the noise can be cleaned as shown in Figure 6.

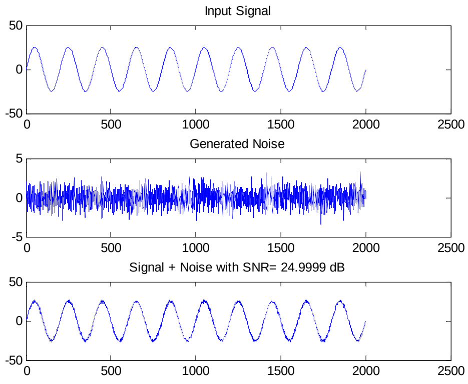


Figure 5 Input signal and its noise

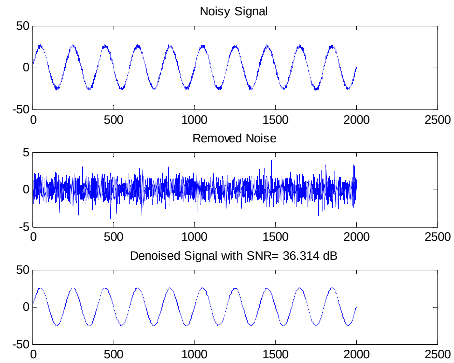


Figure 6 The noisy and denoised signal

5.2. Determining the Best Wavelet Bases Function

In this case, three wavelet bases function namely Daubachies, Symlet and Coiflet were investigated by performing AE signal denoising. In addition, the SNR parameter (Equation 4) was used to know the performance of the denoising algorithm. By using the Equation 4, the smaller SNR is the cleaner signal from the noise is gotten.

The experimental results shows that Coiflet basis for filter length three and four provide smaller SNR than the others basis for AE signal denoising as shown in Figure 7. It means the most appropriate basis for AE signal denoising is Coiflet.

In the next experiment, we investigated the appropriate decomposition level of wavelet transforms for AE signal denoising. In this experiment, three wavelet basis with filter length four was used by varying decomposition level from 2–20. The experimental result shows that the decomposition level more than 12 give smaller SNR for all wavelet bases, as shown in Figure 8. However, the most stable and smallest SNR are given by Coiflet wavelet basis for decomposition level more than 15. It means that, this result is in line to our previous achievement. From this result, we can understand that the noise of AE signal is concentrated in detail coefficients of wavelet transformation. By removing some of the detail coefficients of wavelet transformation through threshold algorithm, the noise of AE signal can be removed, as shown in Figure 9. From the two experiments, we can understand that Coiflet basis function is appropriate wavelet basis for denoising of AE signal.

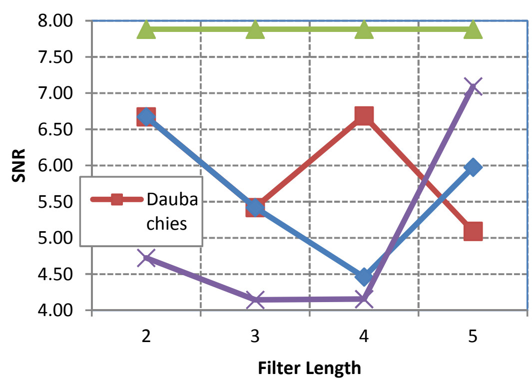


Figure 7 The effect of filter length to SNR

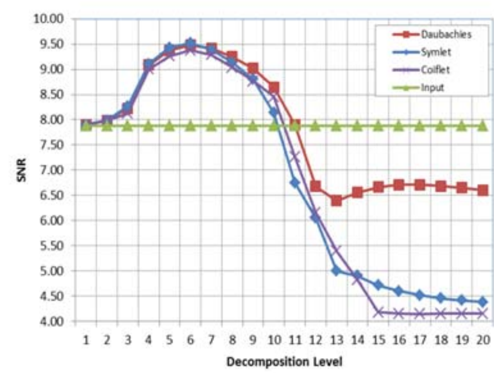


Figure 8 The effect of decomposition level to SNR

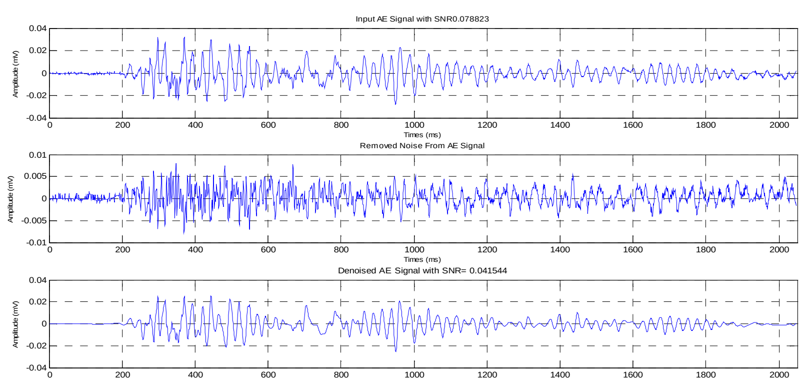


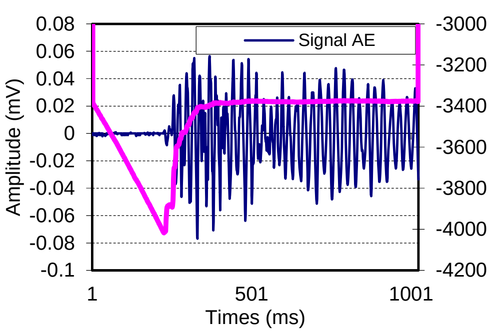
Figure 9 The example of denoising process using Coiflet 3 and decomposition level 18

These achievements are in line to properties of wavelet, in which a wavelet having good vanishing moment and smoothness is good for denoising. The Coiflet bases function has highest number of vanishing moments, therefore it provides the best performance for denoising of AE signal.

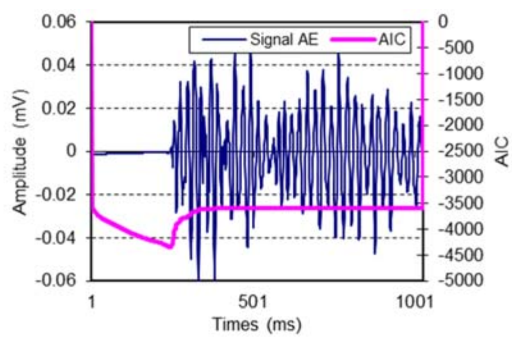
5.2. Implementation for Defining Source Location Micro Crack

In this experiment, we applied the best wavelet bases, filter length and decomposition level for determining the cracks locations. The AE parameters were determined to define the cracks locations inside the concrete. One of important parameters for determining the cracks locations is onset time, which depends on the first amplitude of AE signal. In this case, Akaike Criterion Information (AIC) (Ohno et al., 2009; Kencanawati et al., 2011) is employed for calculating the onset time.

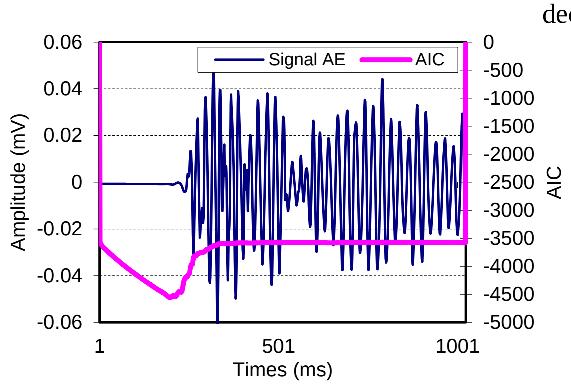
The onset time can be defined easier and more accurately on denoised AE signal (see Figure. 10) than on original signal (without denoising). It happens because the original AE signal, which is interfered by noise, can obscure the first amplitude of the AE signal. From Figure 10(a), the first amplitude is detected on 233 ms, while in the Figures 10(b), 10(c) the first amplitude is detected on 250 ms. This is happen because the noise affected the existence of small amplitude to be higher. By using this clear first amplitude, the analysis determining the cracks locations can be done easily (Ohno et al., 2009; Kencanawati et al., 2011).



(a) Original AE signal



(b) Denoised AE signal using Symlet 4 and level dec. 18



(c) Denoised AE signal using Coiflet 4 and level dec. 18

Figure 10 The example of onset time determination for determining the cracks locations

From several AE signal which were formed from five to eight sensor locations, the source location coordinates of existing cracks can determined by AE parameter analysis (Kencanawati et al., 2011). From AE parameter analysis including AIC, five existing crack locations are found inside of the concrete. The locations of existing cracks are plotted in Figure 11. The star represents detected micro-cracks on concrete prism during loading.

By visual inspection, the cracks appeared at the area close to the pulsed electrode. However, the breakdown of concrete also enables crack to spread into the lower part of specimen and through the entire concrete body. The crack locations representing the damage that was found in this analysis is similar to those of previous research on the effects of lightning on concrete. (Lanser et al., 1984).

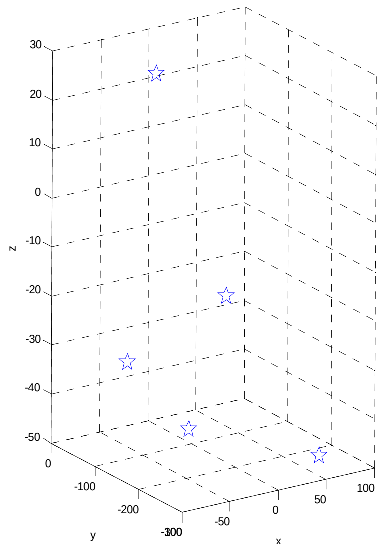


Figure 11 The example crack locations on concrete prism

6. CONCLUSION

Based on SNR parameter evaluation of AE signal denoising, the best wavelet basis for denoising of AE signal is Coiflet with filter length 4. The denoised AE signal using Coiflet with filter length 4 and decomposition level 18 is easier to be analyzed for determining the micro crack than original AE signal (without denoising). In addition, the denoised AE signal, which is analyzed by AE parameter, has been successfully performed to determine the crack locations inside of the concrete.

For future work, this research requires more experiments and validation to determine valid crack locations through x-ray analysis of concrete.

7. ACKNOWLEDGEMENT

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