Fracture Mechanics of Concrete and Concrete Structures -
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Depth of through-thickness crack in concrete estimated by impact-echo

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ABSTRACT: Surface cracks are often observed in a tunnel and a retaining wall. It is not, however, easy to confirm whether the cracks are of through-thickness or not. For the maintenance of concrete structures, therefore, depths of surface cracks must be estimated by nondestructive evaluation (NDE). Although the depth of the crack can be estimated by several NDE techniques, a technique for the through-thickness crack is not well developed yet. In the present study, one NDE technique to identify the depth of the through-thickness crack is investigated. The impact-echo method was applied to artificial cracks. Impacts were driven by an impulse hammer and a pencil-lead break. The depths of cracks were first examined by frequency spectra. Then, Stack Imaging of spectral amplitudes Based on the Impact-Echo (SIBIE) procedure was applied to the impact-echo data. Thus, it is demonstrated that the depth of the through-thickness crack is reasonably estimated by the impact-echo method and a scanning SIBIE procedure.

1 INTRODUCTION

The Impact-echo method is nondestructive evaluation (NDE) to identify the presence of defects in concrete structures. The technique is based on detecting elastic waves due to a mechanical impact. Conventionally, extracting resonance frequencies responsible for the locations of reflectors, the presence and the depth of defects are estimated. Although it is demonstrated that the technique is available to evaluate defects in concrete, still several problems are reported in the application to concrete structures in service. In order to solve these problems, a new procedure to evaluate defects in concrete is developed by applying an imaging procedure to the impact-echo data, as stack imaging of spectral amplitudes based on impact-echo (SIBIE) (Ohtsu & Watanabe 2002). In the previous paper (Toaki et al. 2008), the depths of surface cracks were estimated by SIBIE. Here, the SIBIE was applied to estimate the surface-crack depths of actual cracks generated by a bending test. Because the cracks were created in a zig-zag manner, a scanning-SIBIE is newly developed and applied. It was demonstrated that irregular extension of the surface crack is reasonably estimated by the scanning-SIBIE.

In the present paper, the depths of through-thickness cracks are investigated. Concrete could be deteriorated due to cold joint, dry shrinkage and environmental attacks. As a result, innumerable cracks are observed due to damage on concrete surface. Cracks, which are harmful for the durability of a concrete structure, must be repaired. A through-thickness crack is one example to seriously degrade the durability. Thus, it is demonstrated that the progress level of the through-thickness crack is estimated by the impact-echo and SIBIE.

2 NDE TEQUNIQUES

2.1 *Impact echo*

In the impact-echo method, elastic waves are generated by a short-duration mechanical impact. The elastic waves are detected, and then peak frequencies are identified after FFT (Fast Fourier Transform) analysis of detected waves. Theoretically, frequency responses of a concrete member containing defects depend on the size of the member, the location of defects and P-wave velocity. Concerning the frequency spectrum, the following relationships between the resonance frequencies due to the reflections and the depths of a defect and a reflector are known (Sansalone & Streett 1997),

$$f_t = \frac{0.96C_P}{2T} \tag{1}$$

$$f_{crack} = \frac{0.96C_P}{2d} \tag{2}$$

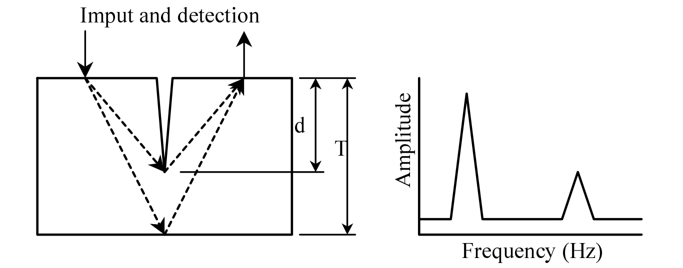


Figure 1. Frequency response of a crack specimen.

where f_t is the resonance frequency of a plate thickness T, f_{crack} is the resonance frequency of a defect in depth d, and C_p is the velocity of P-wave. 0.96 is a shape factor determined from geometry. The presence of these frequencies is illustrated in Figure 1.

According to Hertz's theory, the contact time T_c of a mechanical impact due to a steel-ball drop depends on diameter D of the steel-ball, and a simplified equation is given,

$$T_C = 0.0043D \tag{3}$$

The frequency f_c , generated by the impact is,

$$f_C = \frac{1.25}{T_C} \tag{4}$$

Frequency response of elastic waves produced by the impact of a sphere on a solid with duration Tc is shown Figure 2.

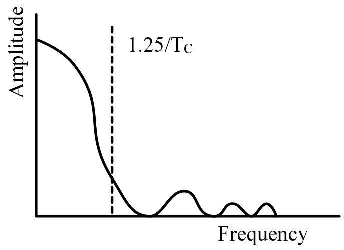


Figure 2. Frequecy spectrum of the force-time function.

To be able to identify resonance frequencies f_T and f_{crack} in the frequency spectra, the upper-bound frequency f_c should cover all of them.

2.2 *SIBIE*

Since it is often not easy to identify the particular peaks in the frequency spectrum in the impact-echo method, an imaging procedure is applied to the result of FFT analysis as SIBIE (Stack Imaging of Spectral Amplitudes Based on Impact-Echo). This is an imaging technique for detected waveforms in the frequency domain. In the procedure, first, a cross-section of concrete is divided into square elements as shown in Figure 2. Then, resonance frequencies due to reflections at each element are computed. The travel distance from the input location to the output through the element is calculated as shown in Figure 2,

$$R = r_1 + r_2 \tag{5}$$

Resonance frequencies due to reflections or diffractions at each element are calculated from,

$$f_{crack} = \frac{C_P}{R} \tag{6}$$

$$f'_{crack} = \frac{C_P}{2R} \tag{7}$$

Spectral amplitudes corresponding to these two resonance frequencies in the frequency spectrum are summed up. Thus, reflection intensity at each element is estimated as a stack image. The minimum size of the square mesh Δ for the SIBIE analysis should be approximately equal to $C_p\Delta t/2$, where C_p is the velocity of P-wave and Δt is the sampling time of a recorded wave.

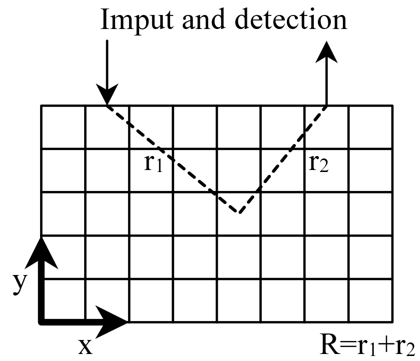


Figure 2. Spectral imaging model.

2.3 *Scanning SIBIE procedure *2*

Original SIBIE method had two problems due to one-point detection. Firstly, a two-dimensional image always becomes symmetry. Secondly, a complicated extension of the surface crack into the inside can not be drawn. Thus, a scanning SIBIE method is developed to solve these problems. The scanning SIBIE method is explained, referring to Figure3.

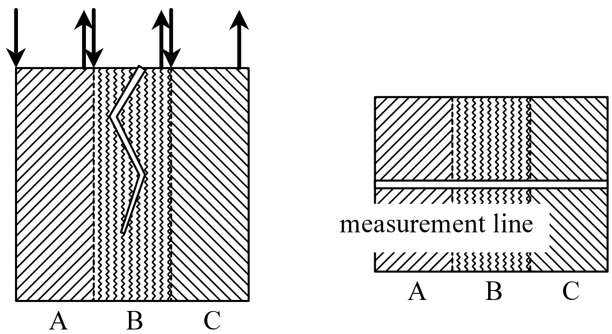


Figure 3. Scanning SIBIE model.

1) A cross-section to be measured is divided into the zones of the width from 30mm to 50mm.

2) The impact echo method is applied to the each section, and frequency spectrum is calculated.

3) The SIBIE analysis is applied to each frequency spectrum, and two-dimensional image is drawn. Then all two-dimensional images are arranged crosswise.

3 EXPERIMENTS

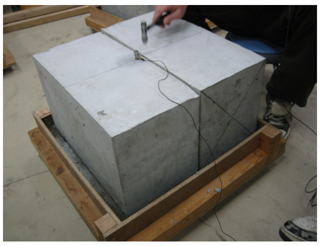
3.1 *Specimen*

Experiments were carried out in the laboratory on two different concrete specimens. The artificial through-thickness cracks were produced by two concrete blocks and compacted soil. Two concrete blocks were fixed on compacted soil by cement paste. Then concrete blocks were placed with gap of 40mm. The depth of compacted soil is 50mm. The concrete blocks prepared were of two dimensions : 250mm (W) x 500mm (L) x 100mm (H) and 250mm (W) x 500m (L) x 300mm (H). Thus, depths of through-thickness are 100mm and 300mm. The thicknesses of the total of the specimens are 340mm and 140mm, respectively. The specimen is shown in Photograph 1.

1. Compaction soil.

2. Concrete blocks.

3. Concrete blocks fix on the compaction soil.



4. The artificial through-thickness.

Photograph 1. Specimen.

Mixture proportion of concrete is given in Table 1 along with properties of fresh concrete. Mechanical properties of concrete were tested at 28 days after moisture-curing in the standard room. Table 2 shows mechanical properties of concrete.

3.2 *Experimental detail*

The experiment was performed on two kinds of through-thickness cracks with respect to the following items;

1) examination by the Impact Echo method.

2) analysis by the scanning SIBIE.

Table 1. Mixture proportion and properties of fresh concrete.

Weight per unit volume (kg/m^3)				Max. gravel size (mm)
Water (W)	Cement (C)	Sand (S)	Gravel (G)	
190	441	643	992	20

W/C (%)	Slump (cm)	Air content (%)
43	8	8

Table 2. Mechanical properties of concrete at 28days.

Compressive strength (MPa)	P-wave velocity (m/sec)
31.1	4200

3.3 *Impact-echo test*

Impact tests were conducted by an impulse hammer and a pencil-lead break against the concrete surface. Surface elastic waves due to the impact were recorded by an accelerometer. The accelerometer used was of flat type and had flat sensitivity up to around 50 kHz. The accelerometer and shooting point are arranged as shown in Figure 4. The impact test for the scanning SIBIE method was conducted by three-point detection. A distance between input and output was set to 50mm. Fourier spectra of accelerations were analyzed by FFT (Fast Fourier Transform). Sampling time was 4 μsec and the number of digitized data for each waveform was 2048.

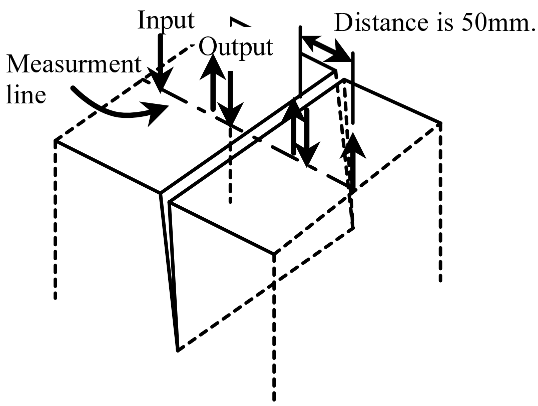
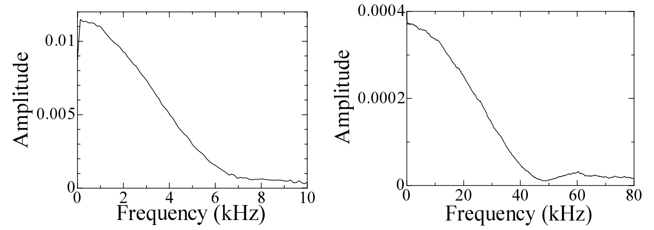


Figure 4. Location of impact test.

3.4 *Impactor response*

Two types of the impactors were tested. One is an impulse hammer with built-in accelerometer. The frequency response of the impulse hammer shows Figure 5 (a). The upper-bound frequency f_c is approximately 5 kHz. The other is a pencil-lead break. Elastic wave is detected at surface of an accelerometer. The frequency response of the pencil-lead break is shown in Figure 5 (b). The upper-bound frequency f_c is approximately 35 kHz.



(a) Impulse hammer (b) Pencil-lead break

Figure 5. Impactor responses of an impulse hammer and a pencil-lead break.

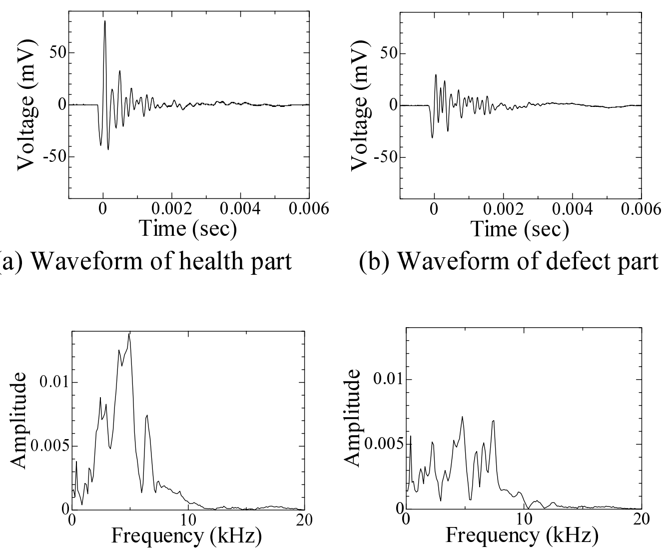
4 RESULTS AND DISCUSSION

4.1 *Results of impact echo*

Waveforms and frequency spectra obtained by the impact-echo in the cases of the through-thickness cracks are shown in Figures 6, 7, 8 and 9. An impulse hammer and a pencil-lead break were applied as the impactor. Results obtained via non-cracked path (health part) are shown in graphs of (a) and (c) of each Figure. Graphs of (b) and (d) show results of cracked paths (defect part).

4.1.1 *Applying an impulse hammer*

Comparing the two waveforms in Figure 6 detected at a health part and a defect part, the effect of crack is not explicitly observed. It seems that attenuation of the waves is higher at the defect part than the health part. Although elastic wave could propagate through the compacted soil, the effect of the through-thickness crack might be observed in frequency spectrum. It seems that amplitude of peak frequency at around 4 kHz is higher at the health part than the defect part.

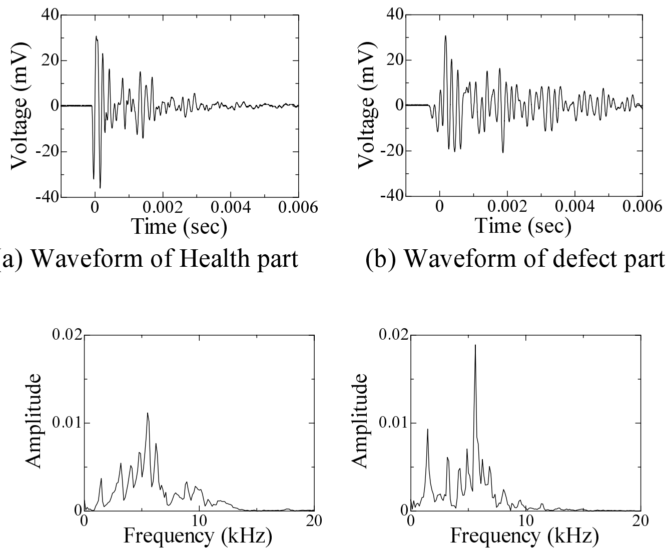


(a) Waveform of health part (b) Waveform of defect part

(c) Frequency of health part (d) Frequency of defect part

Figure 6. Waveforms and frequency spectrum. (depth of through-thickness crack is 100 mm).

Comparing two waveforms in Figure 7, a difference between waveforms is clearly observed. The duration of the defect part is longer than that of the health part. In the frequency spectrum of the defect part, the maximum peak frequency is observed at approximately 5.9 kHz in Figure 7 (d). The resonance frequency due to thickness f_T is calculated from Equation (1) as 6.0 kHz. Consequently, the peak frequency is in agreement with the theoretical value of f_T. On the other hand, in the case of depth D = 300 mm, the corresponding frequency f_{crack} calculated is 7.0 kHz. Although the peak frequency could be confirmed around of 6.8 kHz in Figure 7 (d), the amplitude is quite small. Thus, it seems difficult to find the peak frequency responsible for the crack depth.



(a) Waveform of Health part (b) Waveform of defect part

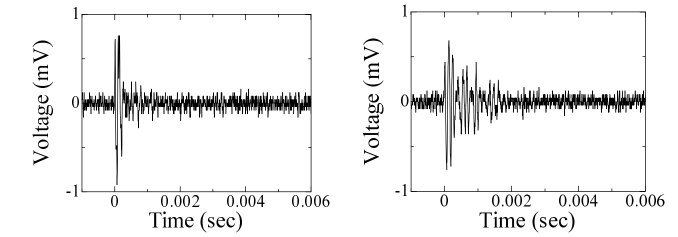
(c) Frequency of health part (d) Frequency of defect part

Figure 7. Waveforms and frequency spectrum. (depth of through-thickness crack is 300mm)

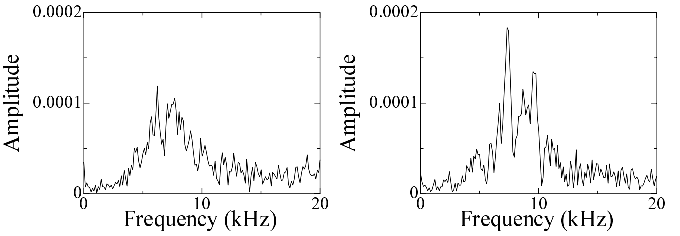
4.1.2 *Applying a pencil-lead break.*

An impact of high frequency contents can be generated by a pencil-lead break. However, a power of the impact is very low. Thus, an intense noise was included in the waveforms. In waveforms, also the duration of the defect part is also longer than that of the health part. Comparing the two frequency spectra in Figure 8, spectral amplitudes of the defect part between 6 kHz and 10kHz are higher than those of the health part. In Figure 8 (b), the peak frequency is observed at approximately 7.4 kHz. The depth of the crack estimated from the second-order resonance frequency f'_{crack} is 280 mm. Because a correct depth is 100mm, it shows the difficulty to identify the depth from the spectral peak.

Two waveforms in Figure 9 are compared. Although the oscillation of the health part is attenuated smoothly, that of the defect part is continuously observed as long train. One peak frequency is observed at 6 kHz in Figure 9 (d). As previously indicated,



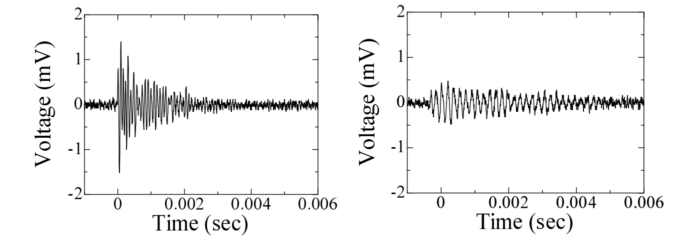
(a) Waveform of health part (b) Waveform of defect part



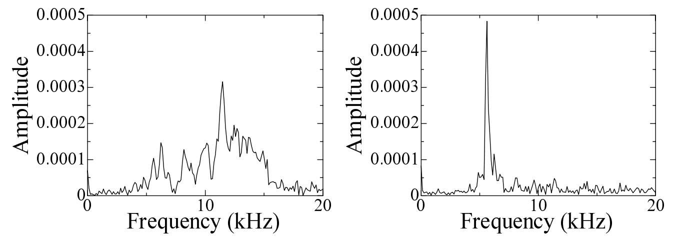
(c) Frequency of health part (d) Frequency of defect part

Figure 8. Waveforms and frequency spectrum. (depth of through-thickness crack is 100mm)

this peak frequency could correspond to thickness frequency f_T.



(a) Waveform of health part (b) Waveform of defect part



(c) Frequency of health part (d) Frequency of defect part

Figure 9. Waveforms and frequency spectrum. (depth of through-thickness crack is 300mm)

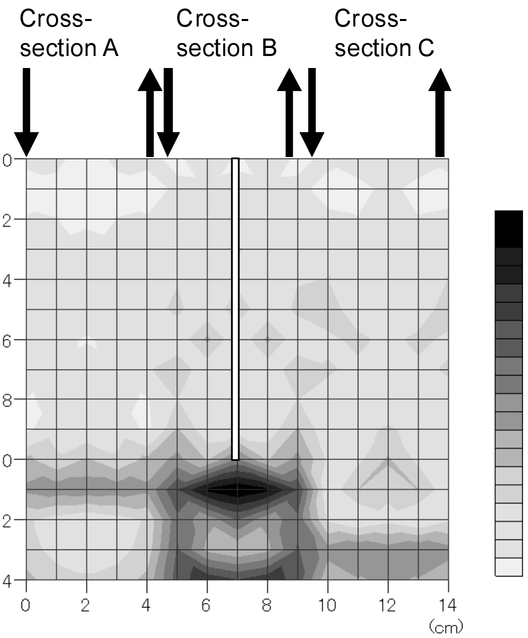
4.2 *Results of scanning SIBIE*

4.2.1 *Applying an impulse hammer*

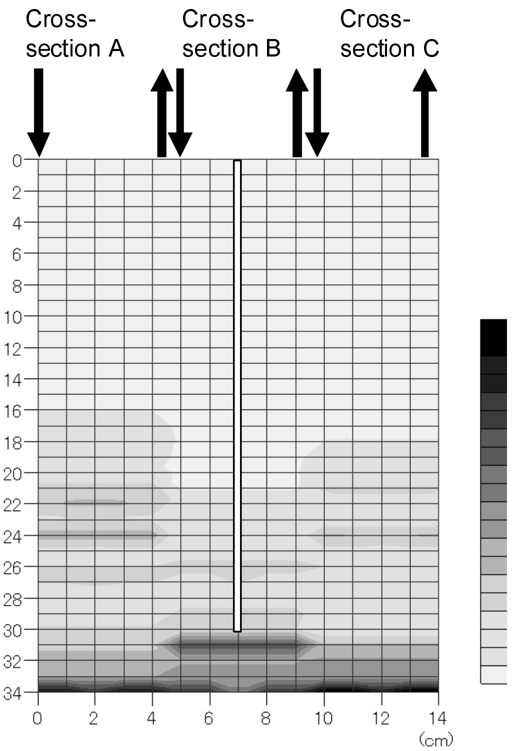
SIBIE method could be improved by introducing the scanning procedure. The crack is located at cross-section B in Figure 10. Results of the scanning SIBIE are given. A cross-section is divided into three zones every 50mm. The tests were conducted from the left to the right in the figure, as illustrated in Figures 3 and 4.

The through-thickness crack is indicated as an open slit. The meshes are regularly arranged at 10-mm pitch. In the graphs, dark color regions indicate the high intense regions due to the resonance of diffraction. Arrows show the impact and the detection points.

In Figure 10 (a), black color regions are clearly observed at 110mm depth. In Figure 10 (b), black color regions are observed at 310mm depth. It is also observed a slight reflection at the bottom in each graph. This is because the bottom at 40 mm in the specimen corresponds to compacted soil .



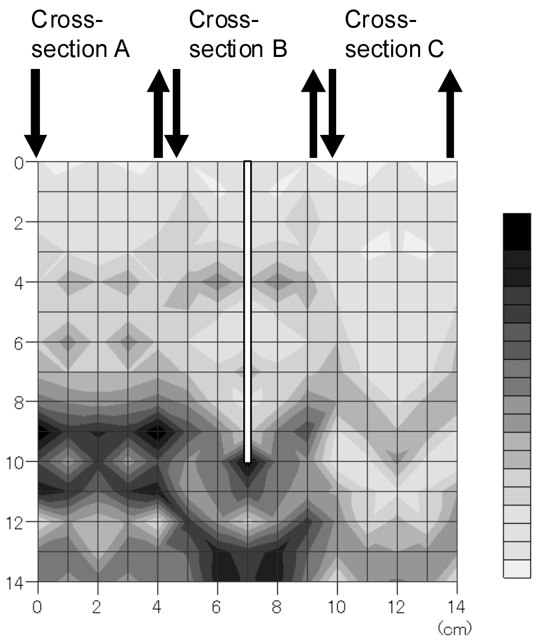
(a) Scanning SIBIE result of through-thickness crack 100mm depth.



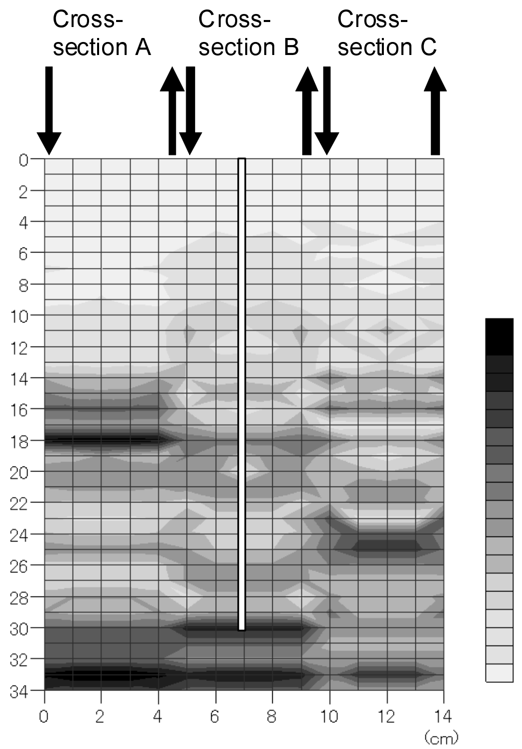
(b) Scanning SIBIE result of through-thickness crack 300mm depth

Figure 10. Scanning SIBIE images by an impulse hammer.

Since the color is darker at the crack-tip, it is thought that an elastic wave is more diffracted at the crack-tip than the bottom. Thus, by applying the scanning SIBIE procedure, the depth of through-thickness crack is reasonably estimated.



(a) Scanning SIBIE result of through-thickness crack 100mm depth.



(b) Scanning SIBIE result of through-thickness crack 300mm depth

Figure 11. Scanning SIBIE images by a pencil-lead break.

4.2.2 *Applying a pencil-lead break.*

In Figure 11 (a), black color regions are observed at 100mm depth of cross-section B and at 90mm depth of cross-section A. In Figure 11 (b), black color regions are observed at 300mm depth of cross-section B and at shallower depths of other elements. Although the depth of the through-thickness crack is clearly estimated, a lot of black color regions are drawn due to noises and reflections at compacted soil. Thus, the noises must be removed, because the power of the pencil-lead break is small.

5 CONCLUSIONS

(1) By employing the conventional impact-echo, it is difficult to determine a particular peak frequency responsible for the crack tip.
(2) By applying an impulse hammer to the scanning SIBIE, the depths of through-thickness cracks are reasonably estimated.
(3) By applying a pencil-lead break to the scanning SIBIE, results are slightly stained by noises. The noises must be removed and the power of the impact is to be magnified well.

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