THEORY AND APPLICATION OF MEM PROCESSED IMPACT-ECHO FOR DETECTING VOID IN PC DUCT

T. Kanno[1], T. Sakai[2], and K. Gokudan[3]
[1] Japan Highway Public Corporation, Tokyo, Japan; [2] Applied Research Co, Tsukuba, Japan; [3] Tokai University, Hiratsuka, Japan

Abstract: The authors have already developed the practical measurement system of concrete thickness using the maximum entropy method (MEM) in waveform analysis for the impact-echo. In this paper, the applicability of this impact-echo system to evaluation for PC duct grout is discussed via experiment and analysis. Partially grouted sheaths arranged in an actual-size girder were measured by the MEM based impact-echo. Moreover, the measurement theory was validated by finite element analysis and the kind of vibrations measured on surface was discussed. The MEM spectrograms of the echo allowed diagnose of grout filling.

Introduction: Aging of infrastructure has become a problem and sharing the costs required for maintenance of infrastructure is debated. With regard to the maintenance of a pre-stressed concrete structure, the lack of pre-stressed concrete sheath grout is one of structural problems. A tendon in a sheath that is not filled with grout will corrode, soon break. This causes deformation of a structure and ultimately leads to the collapse of a structure.

The authors have already developed the practical measurement system of concrete thickness using the maximum entropy method (MEM) in waveform analysis for the impact-echo[1)]. Furthermore, the theory was researched and measurement system was improved for the application to evaluation of grout. Thus, the current research performed in the same manner as actual examination using an actual-size girder with partially grouted sheaths for the development of evaluation system and investigated the applicability of the impact-echo.

The impact-echo postulates that elastic waves entering the measurement plane undergo multiple reflections in the direction of the thickness of the structure. The impact vibrations of a concrete surface being stuck by an object like a steel ball. For the vibration response of a concrete structure, the concrete surface displacement is measured by the impact echo device developed by Sansalone et al.[2)] while acceleration is measured by the authors' method. When the wave undergoes multiple reflections, a specific frequency with the travel time as the period appears. Assuming T is the period of the vibration in the concrete surface measured and V_P is the longitudinal wave velocity in concrete, the thickness D of the concrete is given by the following equation, so if the period is measured, thickness can be estimated.

$$D = \frac{1}{2} V_p T \qquad \text{Equation 1}$$

A full view of test girder is shown in photo 1. A side view noting sheath arrangement in the test girder used in measurement and measurement positions (lines 1 to 6) are shown in Fig. 1. The test girder has a length of 35 m and web width of 0.35 m; height is 1.8 m. Five sheaths with a diameter of 65 mm were arranged and filled portions and unfilled portions were prepared by partially filling mortar.

Measurement was, with a starting point at a position 0.1 m from the bottom of the girder for each measurement line, performed from bottom to top in 0.02 m intervals along measurement lines. Examination work is shown in photo 2. The specifications of applied impact-echo system are tabulated in table 1. The measurement frequency range of accelerometer was limited to less than 25 kHz.

Analysis of measured echo was performed by a method that determines an auto-correlation function by the maximum entropy method (MEM) and that determines the frequency component based on the Fourier integral. In addition, analyzed frequencies were converted to the distance from the measurement plane using the relationship in Eq. 1. The dilatational wave velocity in the test girder was 3800 m/s.

Photo 1 Actual-size pre-stressed girder

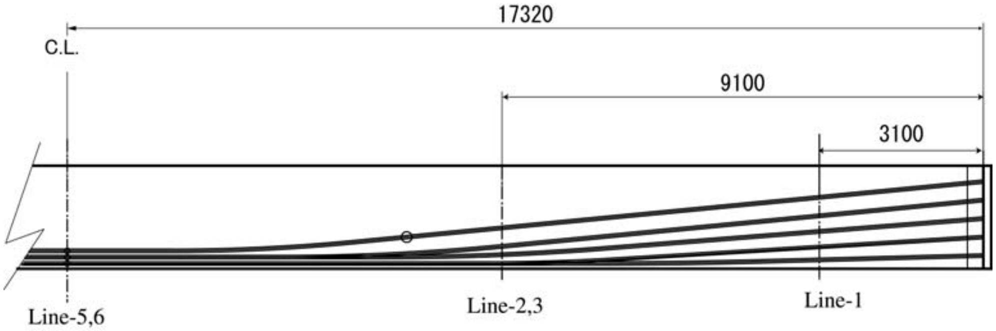

Figure 1 Arrangement of PC cables and examined lines

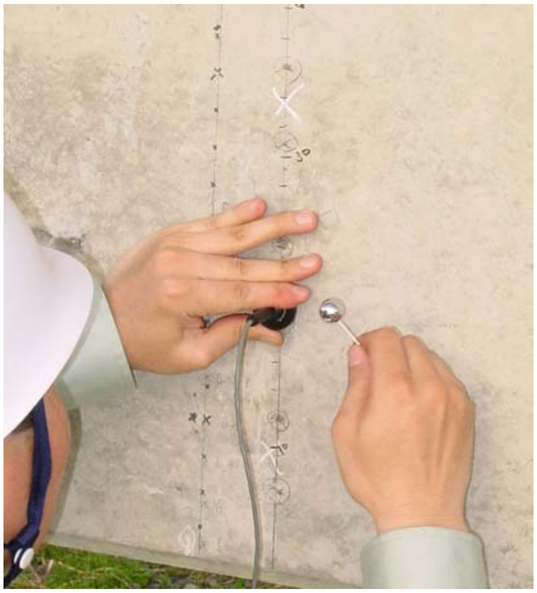

Photo 2 Impact-echo examination

Table 1 Specifications of Impact-echo system

Term	Specifications
Impacter	Steel ball, Diameter 15mm, Weight 14g
Accelerometer	$10mV/m/s^2$
Sampling rate	10μs
Record length	8ms
Digital accuracy	12bit
Signal processing	Maximum entropy method

Results: Measurement results at line 1 are shown in Fig. 2. With the girder cross-section for line 1, all sheaths were arranged in the center of the direction of the web's width.

The figure shows the intensity of the spectrum with frequency (converted to distance) as the horizontal axis and the measurement position (with the girder's bottom end as the starting point) as the vertical axis. The spectrum increases in intensity as the color. Analysis has been performed by a method of analyzing the spectrogram with MEM and determining the average (time-weighted MEM). This method of analysis is characterized by its accentuating a spectrum with a long duration and is used as a method of measuring the thickness of concrete slabs.

As is clear from Fig. 2, the spectrum is concentrated around 0.34 m from the measurement plane, although the thickness of the web is 0.35 m, so closed spectra can be determined to be frequency components of multiple reflection attributed to the thickness of the web. In contrast, a somewhat intense spectrum can be seen at 1/2 the depth of the thickness of the web or in the vicinity of 0.25 m, 0.4 m, 0.6 m, and 1.1 m from the flange undersurface. This is an unfilled sheath. In addition, positions where spectra can be seen at a depth besides the thickness like these indicate a tendency for the measured thickness to increase. This is conjecture to be because the apparent elastic wave velocity decreases due to the flexural vibration[3)] of the covering in instances where there is a defect inside.

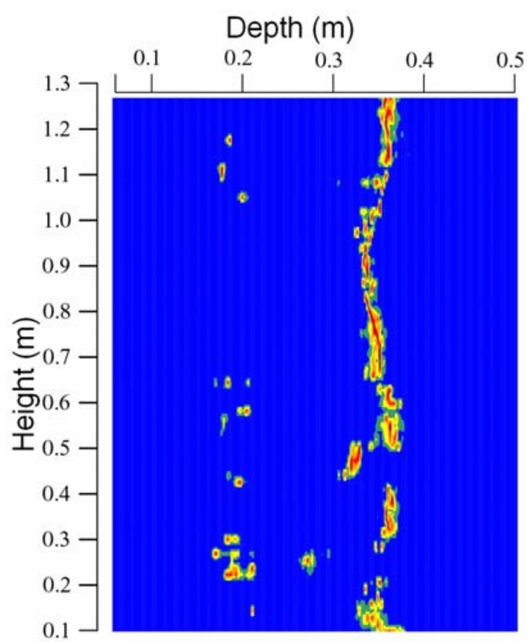

Figure 2 Measurement results for line 1

Measurement results are shown in Table 2. Number indicates the sheath and position is the distance from the flange undersurface. The designed filling indicates the actual state of filled grout. The diagnosed filling is carried out from the measurement results in Fig. 2. In addition, items marked U in diagnosis were those diagnosed as being neither completely filled nor unfilled.

Table 2 Comparison of measurement results for line 1

Sheath number	Designed height	Measured height	Grout filling	
			Design	Diagnosis
1	1.352	1.20	V	U
2	1.001	1.05	F	F
3	0.706	0.65	V	V
4	0.410	0.42	F	U
5	0.169	0.22	V	V

F: Filled, V: Void (Unfilled portion), U: Unknown

Measurement results for lines 2 and 3 are shown in Figs. 3 and 4. Line 2 was measured from the left to the right of the web in the same measurement cross-section. Line 3 was located on opposite side of web. Two figures are measured depths in opposite direction. In this cross-section, as shown in Table 3, sheaths 4 and 5 pass through the same cross-section, Sheath 4 (filled) is located on the side of line 2 and sheath 5 (unfilled) is located on the opposite side, although marked differences in Figs. 3 and 4 can not be found.

Measurement results are shown in Table 3. Even if there is an unfilled portion in a sheath that passes through the same cross-section, the fact that its position cannot be determined is indicated.

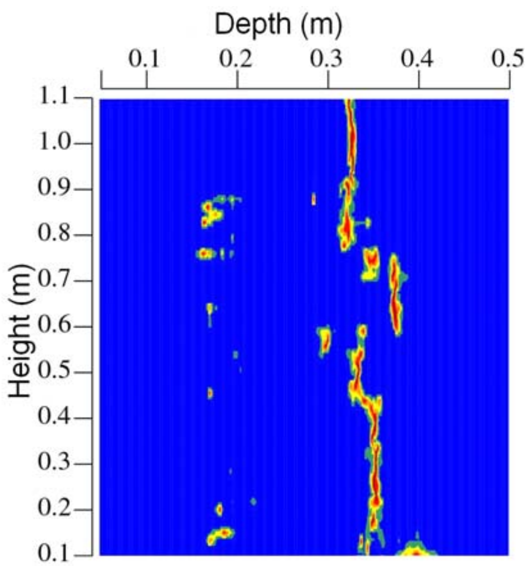

Figure 3 Measurement results for line 2

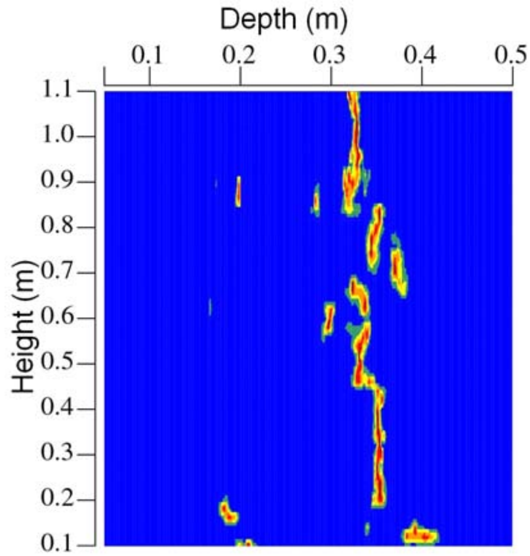

Figure 4 Measurement results for line 3

Table 3 Comparison of measurement results for line 2 and 3

Sheath number	**Designed height**	**Measured height**	**Grout filling**	
			Design	Diagnosis
1	0.775	0.85	V	U
2	0.423	0.65	F	F
3	0.267	-	V	F
4	0.101	0.15	F	V
5	0.101	0.15	V	V

F: Filled, V: Void (Unfilled portion), U: Unknown

Measurement results for line 6 are shown in Fig. 5 and 6. At the center of girder, sheath 1 was arranged in the center of the direction of the cross-section's width; sheaths 2 to 5 were arranged with covering of 78.5mm.

With time-weighted MEM, spectra other than that in the proximity of the thickness were rarely measured. In contrast, spectra besides the thickness can be seen at positions 0.2 m and 0.35 m from 0.1 with MEM. In addition, estimated thickness is more than 0.4m at a position 0.2 m below; a frequency component lower than the frequency of multiple reflection in the direction of the thickness is considered to have occurred. The sheath covering for line 6 is actually thinner than the cross-section for line 1. Thus, the acceleration of the flexural vibration for the covering is larger than for line 1 and is easily measured.

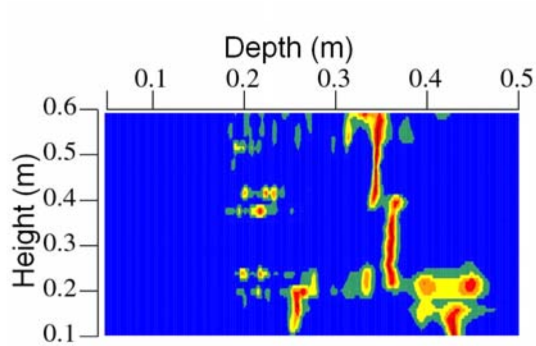

Figure 5 Time-weighted MEM processed measurement results for line 6

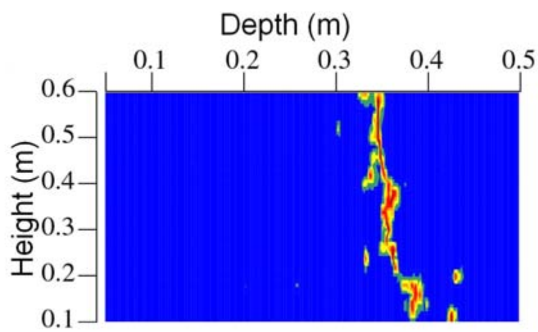

Figure 6 MEM processed measurement results for line 6

Table 4 Comparison of measurement results for line 6

Sheath number	**Designed height**	**Measured height**	**Grout filling**	
			Design	Diagnosis
1	0.340	0.25	F	F
2	0.220	0.24	F	V
3	0.220	0.24	V	V
4	0.100	0.10	F	V
5	0.100	0.10	F	V

F: Filled, V: Void (Unfilled portion), U: Unknown

Discussion: Finite-element transient response analysis was performed to validate the applicability of the impact-echo. Two models, one in which a sheath was filled with grout mortar and one with a void that was not filled, were created. Impulsive external force was applied and wave propagation was examined. Figure 7 is finite elements for the unfilled model. The filled model is a rectangular cross-section with no void. The widths of both models are 340 mm. Symmetry was considered in cross-sections which were the same in both tests, and the half of height was modeled. The height of the model is 511 mm and sufficiently large. Typical length of the mesh is 1 mm. For the upper end of the model, all degrees of freedom were fixed; for the model’s bottom end, out-of-plane degrees of freedom were restricted. The number of nodes is 174592 in the sound model and 146437 in the void model. The number of elements is similarly 173740 and 147171.

The cross-section was defined using a plane strain model for both the sound model and void model with a Young's modulus for concrete of 2.8×10^{10} N/m^2, a Poisson's ratio of 0.17, and density of 2.35×10^{10} kg/m^3. Dilatational wave propagation velocity in concrete derived from mechanical property is 3600 m/s.

Single-step Houbolt method is used for transient response analysis. The elastic wave frequency of concrete is less than 100 kHz, so a time interval of 2 μsec was used in order to cover this. The arrival time of the reflection wave from the defect in the sheath is 44 μsec, so this is a sufficiently short time interval even when looking at a reflection. In addition, the typical length for elements of 1 mm corresponds to the elastic wave proceeding 7 elements in the time interval. For the force of impact, a rectangular pulse of 2 μsec entered at a position at the bottom left of the model at a time from 2 μsec to 4 μsec in order to examine elastic wave propagation in the cross-section. MSC.Marc is used for the analysis code.

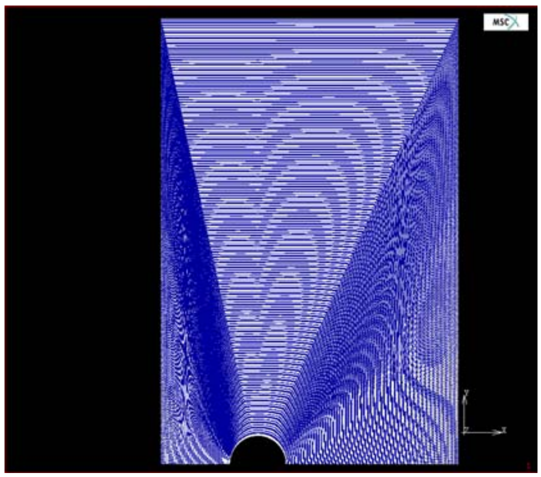

Figure 7 FEA Model with void

Figures 8 and 9 show the time history of the acceleration response in the concrete surface around observed point. The sound model has only an echo from the opposite side of web; in contrast, a relatively high echo from the sheath after surface vibration by impulsive load was detected for the void model. Remarkable multiple reflection is clearly observed at the 44 μsec interval. Thus, the possibility of sheath position detection by impact-generated elastic waves has been indicated.

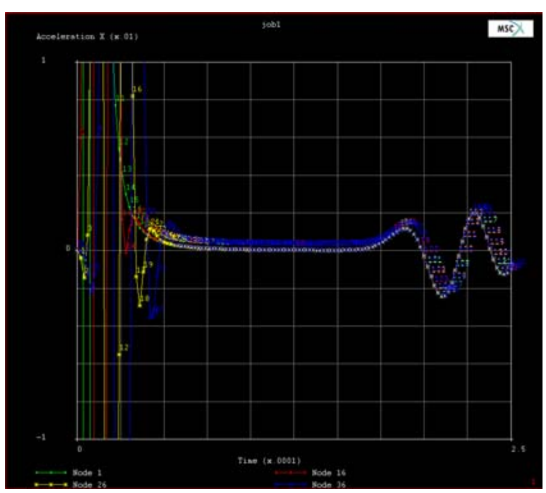

Figure 8 Acceleration responses on surface of sound model

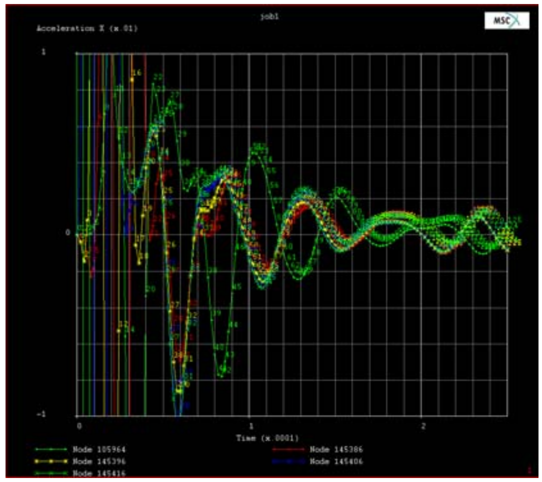

Figure 9 Acceleration responses on surface of model with void

Conclusions: Two methods of analysis, MEM spectrum and ensemble average of MEM spectrum were used as methods to analyze measured waves. Concrete thickness and unfilled sheath depth are readily analyzed by ensemble average of MEM spectrum. In concrete section with shallow void, flexural vibration disturbs measured spectrum and the depth of void and the thickness are shallowly observed.

References:

1. K. Gokudan, M. Nose, S. Iwano, and T. Sakai: Integrity and Thickness Detection of Concrete Structures by Frequency Response Analysis, Structural Faults and Repair 2001, July 2001.
2. M. J. Sansalone and W. B. Streett: Impact- Echo, Bullbrier Press, 1997.
3. D. J. Gorman: Free Vibration Analysis of Rectangular Plates, Elsevier North Holland, 1982.
4. C. Zienkiewicz and R. L. Taylor: The Finite Element Method Fifth Edition, Butterworth-Heinemann, 2000.