Elastic Wave Velocity and Attenuation Tomography Using Randomly-Induced Excitations for Damage Detection of RC Slab

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Abstract. As it is imperative for the damage evaluation of infrastructures to establish an efficient non-destructive testing (NDT), an acoustic emission (AE) tomography technique has been developed. Authors have been studying tomography techniques based on elastic-wave and acoustic emission (AE) to visualize the internal defects in concrete. In the result of AE tomography, it can reasonably be assumed that lower elastic-wave velocity corresponds to heavier deterioration. Thus, the AE tomography estimates wave velocity distribution, which is supposed to be decreased as the damage progresses, inside the reinforced concrete. The AE tomography combines an iterative AE source location algorithm with travel-time tomography to produce a 3D visualization of the elastic wave velocity. However, since the computation for the elastic wave ray-trace algorithm considering all potential detours of elastic waves takes up much time, and in the case that only a few AE signals are detected, AE tomography technique does not always work efficiently. In this paper, AE signals induced by random hammering and rain droplets, which provide elastic waves with a variety of frequency, on surface of RC deck are utilized as elastic waves’ excitations, and wave velocity and attenuation tomography assuming linear ray paths are performed in conjunction with AE source locations. Accordingly, random hammering lead to a hundred of AE events after in-situ measurement for a few minutes and rain-induced elastic waves also does to thousands of those as well for an hour. Consequently, the 3D tomography results show accurate and time-saving analysis, compared to the above-mentioned conventional AE tomography technique, for quantifying the damage of RC slab.

1. Introduction

It is generally recognized that preventive and proactive maintenance works are necessary for such infrastructure as bridges and tunnels. For reinforced concrete (RC) members, essential issues include establishing a maintenance system with the appropriate measures prior to extensive damage and failure.

As a result of budgetary restrictions, preventive and proactive maintenance of infrastructure is desired, and inspections by non-destructive testing (NDT) methods must be applied. In terms of damage assessment and estimation of repair and retrofit recovery in concrete structures, in addition to current NDT, innovative methods must be established.

Tomography techniques have been studied based on elastic-wave and acoustic emission (AE) to visualize, in three dimensions, internal defects in concrete. The applicability of these techniques has already been reported as elastic-wave tomography [1][2] and AE tomography [3][4].
Through the tomography technique, internal distributions are obtained using elastic-wave parameters such as amplitudes and elastic-wave velocities. In this study, elastic-wave velocity and attenuation rate are used as the parameters. In elastic-wave tomography, both the location of the excitation and the excitation time should be known, whereas they are unknown for AEs induced by random excitations such as steel ball hammering and rain fall hits. Specifically, tomography can evaluate the elastic-wave velocity and attenuation rate in each set-element over the structure, which is supposed to be theoretically associated with the modulus of elasticity. Because of the presence of such internal defects as cracks and voids, the values would vary as low-velocity zones.

2. Innovative non-destructive by means of AE analysis
With respect to NDT for quality evaluation of concrete structures, several methods are applicable to investigating structural degradation and internal damage. Authors have been intensively working on damage assessment with elastic-wave velocity distributions by AE measurement and AE tomography [2], where a main target is the damage of existing RC bridge slabs. The elastic-wave velocity tomography technique [1], which is based on the ray-trace algorithm considering detours of elastic waves due to reflection and diffraction, has been also developed. However, since the computation for the elastic wave ray-trace algorithm considering all potential detours of elastic waves takes up much time, and in the case that only a few AE signals are detected, AE tomography technique does not always work efficiently. Further, the attenuation-rate tomography [5] is developed, focusing on attenuation characteristics of the amplitudes of elastic waves. In this method, since the ray-path is assumed to be a straight line, the calculation time required for numerical analysis is drastically shortened. It is also clarified that the distribution of attenuation-rates could deduce the damaged zones inside concrete.

Moreover, an innovative non-destructive method for inspecting the interior of concrete has been introduced and applied to the RC slab of a bridge in service [6]. The method, referred to as single-side attenuation tomography, which is based on the principle that the elastic waves traveling through concrete are to impinge on the cracks. It could provide the tomogram on the attenuation rates inside the tested specimen. To summarize, single-side attenuation tomography must be understood as a very practical non-destructive testing method for identifying the parts of a reinforced concrete member which are very likely to present serious damages. If the tomograms cannot be used, in the present state, for directly assessing the structural safety of the tested specimen, they provide essential information for guiding further investigation.

2.1. Attenuation and wave velocity tomography procedure
Assuming that the propagation path of P-wave is a straight line, the tomography analysis via the attenuation-rate and the wave-velocity distribution was carried out in order to identify the lateral cracks in RC slab. Figure 1 shows the flow chart to compute the attenuation-rate and the wave-velocity distribution. The data processing flow is followed so as extracting AE events. As summarized in the figure, first, the source locations of all AE events are used as input, where a constant wave velocity (m/s) and attenuation-rate (dB/m) across the tested member is assumed for calculation. Second, the amplitude and the excitation time at the source of the considered AE event is estimated on the basis of the arrival times and the amplitudes recorded by the sensors. Third, the attenuation rates and wave velocities along all straight ray-paths between the source and the receiving sensors are computed.

2.2. Source location algorithm
The algorithm for AE source location is based on the Inglada’s method, which is used in seismic engineering for locating the epicenter of earthquakes [7][8]. By assuming a constant wave velocity inside the tested specimen, the source location of an AE event is determined from the arrival times of their associated elastic waves at the locations of several sensors. In this paper, 3000 m/sec was set as the consent value in consideration of averaged speed in intact and deteriorated concrete.
2.3. Estimation of travel time and peak amplitude at AE source

For each AE event, the peak amplitude of the elastic wave at the source is unknown. Consequently, it can be approximated to calculate wave velocity and attenuation rate along the considered wave paths. In the tomography algorithm, they are generally estimated from a relation represented in Fig.2. First, the arrival time and the peak amplitude of the signal recorded by each sensor is plotted as a function of the distance between the source and the sensors. Second, a linear regression between the arrival time and the peak amplitude of the elastic wave and the distance from the source is computed. The AE dispatched time and the peak amplitude at the source is referred to as equal to the value for the case that the distance is equal to zero.

![Figure 1. Flow chart to compute wave-velocity and attenuation-rate tomography.](image)

![Figure 2. Linear estimation on travel time amplitude from AE source to sensors.](image)

2.4. SIRT algorithm for tomography computation

Tomography computation is carried out based on elastic wave parameters with the velocity and the attenuation rate in this paper. In the tomography based on the attenuation, the area of interest and analyzed must be divided into mesh elements characterized by their own wave velocities and attenuation rates. Then, a first estimate on distribution of the wave velocities and the attenuation rates is to be provided as input. By comparing those values along each wave path to its calculated value of the assumed distribution, the SIRT algorithm could lead to proper distribution of the wave velocities and the attenuation rates.

First, the measured travel time and attenuation rate along each ray path is estimated from equation (1).
\[
AR_{\text{measured},i} = \frac{A_{\text{source}} - A_{\text{sensor},i}}{N_i \sum d_{i,j}}
\]

Where:
\(AR_{\text{measured},i}\): measured average attenuation rate along the wave path from the source to the \(i^{th}\) sensor
\(A_{\text{source}}\): estimated peak amplitude of the elastic wave associated to the considered AE event at its source
\(A_{\text{sensor},i}\): peak amplitude of the elastic wave measured at the \(i^{th}\) sensor
\(N_i\): mesh number of elements crossed by the wave path from the source to the \(i^{th}\) sensor
\(d_{i,j}\): length of the wave path from the source to the \(i^{th}\) sensor in the \(j^{th}\) element

Second, the attenuation rate along each wave path based on distribution of the attenuation rates in the mesh elements is computed by equation (2).

\[
AR_{\text{calculated},i} = \frac{\sum M_j AR_j d_{i,j}}{\sum M_j d_{i,j}}
\]

Where:
\(AR_{\text{calculated},i}\): calculated average attenuation rate along the wave path from the source to the \(i^{th}\) sensor (dB/m)
\(AR_j\): attenuation rate in the \(j^{th}\) element (dB/m)
\(M\): mesh number of elements crossed by the ray path from the source to the \(i^{th}\) sensor

Afterwards, the difference between the measured and the calculated attenuation rates is calculated for each wave path by using equation (3).

\[
\Delta AR_i = AR_{\text{measured},i} - AR_{\text{estimated},i}
\]

In a similar manner to Equation 1, the differences of the attenuation rates on all the wave paths are estimated by equation (4).

\[
\Delta AR_j = \frac{\sum_{i=1}^{N} \Delta AR_i d_{i,j}}{\sum_{i=1}^{N} d_{i,j}}
\]

Where \(N\) is the number of wave paths crossing the \(j^{th}\) element. The attenuation rate in each element is then updated with equation (5).

\[
AR_{j,\text{updated}} = AR_j + \Delta AR_j
\]

The procedure from equation (2) through equation (5) is repeated until the convergence is reached. As for wave velocity as the parameter of SIRT algorithm, the same manner as attenuation rate is applied for computing wave velocity distribution in the area of interest and analysed.

3. Random hammering and rain-induced AE detection at existing RC slab
A real RC bridge deck was selected as study targets which has deterioration such as rebar corrosion, breaking by salt damage, and deck fatigue. AE measurement was carried out in the RC bridge deck. 15 AE sensors are set on the bottom side of RC bridge decks. Resonance frequency of AE sensor is 30 kHz. AE sensors arrangement on the RC deck is shown in Figure 3. Thickness of both RC bridge decks is 235 mm. Large crack with water leakage trace was confirmed. Threshold value of LUCY (location uncertainty) is set on 300 mm as half spacing of two adjacent sensors in this study. LUCY means source location accuracy and is the root-mean-square of the difference between calculated and observed distances between source and sensor [9].
The data was extracted during the rain peak and analysed the source locations. Figure 4 shows the results of the measured panel. Source locations considered to have low reliability has been filtered. 45 AE sources with 11mm dia. steel sphere ball random hits for a few minutes and 859 AE sources with rain droplets for approximately 10 minutes were extracted [10], in which enough amounts of AE sources for analysis are identified. In the figures, relatively low-density areas surrounded by dashed lines can be seen in the panel. Concrete damages of No.1, No.2, No.3 and No.4 were confirmed as shown in Figure 5 with core sampling results which were taken out from the deck to verify the results and visually observe the presence of lateral crack. Red line shows the sensor arrayed area. This low-density area is suspected to be heavily deteriorated, since AE is generated on the road surface and it travels through the deck and detected by the AE sensors attached on the bottom surface of the deck.

**Figure 3.** Sensor arrangements for AE measurement on the real RC bridge decks.

**Figure 4.** Result of AE source location analysis.

4. Random hammering and rain-induced AE detection at existing RC slab
As expected, a sufficient number of rain-induced AE events respecting the quality criteria has been found. The wave velocity and attenuation rate distribution by means of AE tomography, as explained above, in this panel have been successfully computed from these data and the results are presented for wave velocity by conventional AE tomography considering ray-path detours, wave velocity and attenuation rate respectively by AE tomography considering linear ray-path, with core sampling results to show the presence of damage due to lateral crack as well. Tomography results show top,
middle and bottom layer of 117.5mm each in the deck depth (235mm) since 3D computation was performed in this paper. In the figures, Figure 6 is tomograms using AE events by random hammering excitation and Figure 7 is tomograms using AE events by rain-induced excitation.

![Figure 5](image5.png)

**Figure 5.** Visual observation of damage due to lateral crack.

![Figure 6](image6.png)

**Figure 6.** Tomography results using AE events by random hammering excitation.

![Figure 7](image7.png)

**Figure 7.** Tomography results using AE events by rain-induced excitation.
The lateral cracks were located at 150 mm or less from the surface of the deck (mostly in the top layer) by visual inspection of the cored samples as shown in Figure 5. Therefore, it is reasonably understood that wave velocities and attenuation rate in top layer are lower than bottom layer.

Using random hammering excitation in Figure 6, no correlations visually cannot be validated between tomograms in different computation procedures with geometrical and parametrical information of elastic wave travels. On the other hand, although they are not perfectly corresponding with each other in Figure 7 using rain-induced excitation, top to middle layer are correctly showing lower velocity and higher attenuation. In addition, the area colored in yellow to red, where velocity is 2800-3000 m/sec and attenuation rate is 20-30 dB/m, is supposed to indicate the presence of lateral crack and crack observed positions are mostly lying in the area.

![Wave velocity comparison for computation methods](image)

**Figure 8.** Wave velocity comparison for computation methods.

![Ray path density distribution](image)

**Figure 9.** Ray path density distribution.

In order to quantitatively clarify the relationship between the accuracy of tomography technique using random hammering excitation and that using rain-induced excitation, wave velocity obtained by conventional technique considering ray path detours and newly proposed technique considering linear
ray path are compared in Figure 8 for random hammering and rain-induced excitation. In the case of random hammering, computation results from linear ray path assumption gives totally scattered values against the results from ray tracing algorithm considering the path detours. Contrarily, in the case of rain-induced excitations, the similar values outcome from both computation procedures. Figure 9 is ray path density, which is framed in by red line of Figure 4, can be calculated as sum of ray path lengths in each sensor arrayed grid. Since the ray path density is not quite enough when random hammering excitations are used for AE sources, approximately 5 times less compared with the ray path density using rain-induced excitations, information amount needed to get appropriate accuracy are missing in the result based on random hammering for a few minutes.

5. Conclusion
AE signals induced by random hammering and rain droplets on surface of RC deck are utilized as elastic waves’ excitations, and wave velocity and attenuation tomography assuming linear ray paths are performed in conjunction with AE source locations. Accordingly, random hammering can lead to a hundred of AE events after in-situ measurement for a few minutes and rain-induced elastic waves also does to thousands of those as well for an hour. Consequently, the 3D tomography results show relatively enough accurate and time-saving analysis, compared to the above-mentioned conventional AE tomography technique considering ray-path detours, for quantifying the damage of RC slab.

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References
[1] Y. Kobayashi, T. Shiotani and H. Shiojiri, Damage identification using seismic travel time tomography on the basis of evolitional wave velocity distribution model, Structural Faults and Repair 2006 (CD-ROM), 2006.
[2] Y. Kobayashi, T. Shiotani, D. G. Aggelis, H. Shiojiri.: Three-Dimensional Seismic Tomography for Existing Concrete Structures, Proceedings of Second International Operational Analysis Conference, Vol. 2, pp. 595-600, 2007.
[3] Y. Kobayashi and T. Shiotani, Seismic tomography with estimation of source location for concrete structure, Structural Faults and Repair 2012, CD-ROM, 2012.
[4] H. Asuae, T. Shiotani, T. Nishida, K. Watabe, H. Miyata, Applicability of AE Tomography for Accurate Damage Evaluation in Actual RC Bridge Deck, Structural Faults & Repair Conference, No.1743, 2016.
[5] Chai, H. K., Momoki, S., Kobayashi, Y., Aggelis, D.G., and Shiotani, T., Tomographic reconstruction for concrete using attenuation of ultrasound, NDT and International - Non-Destructive Testing and Evaluation, Vol. 44, No. 2, pp. 206-215, 2011.
[6] Granier, G., Shiotani, T., Hashimoto, K., and Nishida T., Visualization of internal damage in RC slab with single side access attenuation tomography, Proceedings of IAES-23, IIIAE2016 Kyoto and ICAE-8, pp. 383-387, 2016.
[7] Ge, M., Analysis of source location algorithms, Journal of Acoustic Emission, Vol. 21, pp 14-28, 2003.
[8] Salinas, V., Vargas, Y., Ruzzante, J. And Gaete, L., Localization algorithm for acoustic emission, Physics Procedia, Vol. 3, pp 863-871, 2010.
[9] Hamstad, M.A., Acoustic emission source location in a thick steel plate using lamb modes, J. Acoustic Emission, Vol. 25, pp. 194-214, 2007.
[10] Takamine, H., Watabe, K., Miyata, H., Asaue, H., Nishida, T., Shiotani, T., Efficient Damage Inspection of Deteriorated RC Bridge Deck with rain-induced AE Activity, Proceedings of IAES-23, IIIAE2016Kyoto and ICAE-8, pp.231-236, 2016.