Visualization of Damage in RC Bridge Deck for Bullet Trains with AE Tomography

Tomoki Shiotani, Satoshi Osawa, Shohei Momoki, and Hiroyasu Ohtsu

Abstract In recent years, a lot of accidents associated with infrastructures occur in Japan because of the remarkable deterioration of the infrastructures. Considering the expected reduction of construction investment year after year, it is important to repair and reinforce those structures with the limited budget as well as to extend their service life in the future. From the viewpoint of management and maintenance for those ageing infrastructures, preventive maintenance shall be taken rather than the reactive maintenance. In the preventive maintenance, repairing and reinforcing structures shall be implemented before any fatal deterioration to the structures. However, the reasonable diagnostic method for preventive maintenance has not been established so far. NDT approaches to diagnose the early internal damage of structures is thus in high demand. To solve these issues, the authors had proposed "AE tomography" which executes both AE monitoring and elastic wave tomography. The AE tomography enables to provide accurate AE source locations as well as velocity distribution with the tomography simultaneously. In this paper, in order to verify this proposed AE tomography for in situ infrastructures, deteriorated RC bridge deck for bullet trains was investigated.

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1 Introduction

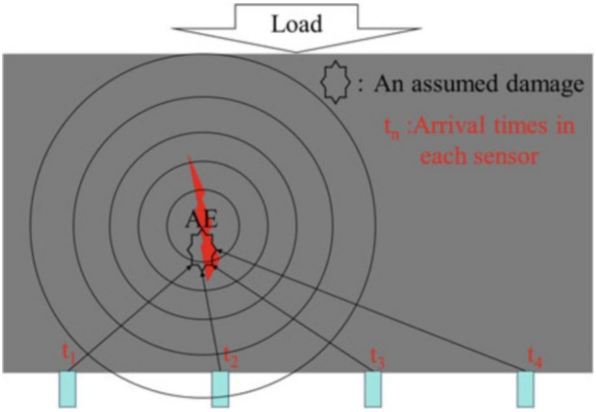
In recent years, a lot of accidents occur due to deterioration of infrastructures such as RC bridge and tunnels. This makes it more important to maintain and reinforce those deteriorated structures in a proper manner. In action plans for maintaining and managing the structures, there are two maintenance strategies, namely corrective maintenance and preventive maintenance. The former is the action plan for repairing and reinforcing structures when it becomes the fatal deterioration, while the latter is the action plan of which those shall be executed thereby preventing a remarkable damage. As the preventive maintenance is known as the best maintenance strategy because it enables to extend the life of structures with reasonable cost, the techniques to diagnose early internal damage of the structures are in high demand. NDT such as ultrasonic testing has so far been applied for the evaluation of early internal damage; however, as it was a spot assessment requiring a lot of time to test, the author's group has proposed "AE tomography" consisting AE monitoring and elastic wave tomography. The AE tomography allows implementing AE source location and tomography simultaneously. The AE tomography can evaluate the wide range of damage scale such as microscopic to macroscopic damage as to adapt sensors being suitable or corresponding to be frequency range to the damage scale. The AE tomography has been applied to some actual structures so far [1]; however, the number of application has been insufficient and the applicability for actual structures hasn't been verified. In this paper, in order to verify the AE tomography for in situ infrastructures, it was applied to the deteriorated RC bridge deck for bullet trains.

2 AE Tomography

AE tomography consists of AE monitoring and elastic wave tomography. Figure 1 shows the configurations of AE monitoring. AE (acoustic emission) occurs in association with the occurrence or progress of the crack. AE monitoring is the method to identify the detail of the AE source such as location by using arrival time differences among AE sensors, where AE sources were generated due to the crack occurrence by load applications. The conventional AE source locations are conducted assuming elastic wave velocity of the structure being homogeneous; however, in civil engineering materials or failure-progressed materials, the velocity was not distributed uniformly due to materials' heterogeneity. Therefore the AE source locations are not always accurate in actual structures or materials in which the velocity does not exhibit homogeneous or the failure evolves successively. Then elastic wave tomography is well used together with AE monitoring in many cases. Figure 2 shows the configuration of elastic wave tomography.

Elastic wave tomography is the method to evaluate the distribution of elastic wave velocity over the structures. In the principle procedure, elastic wave is excited

Fig. 1 AE monitoring



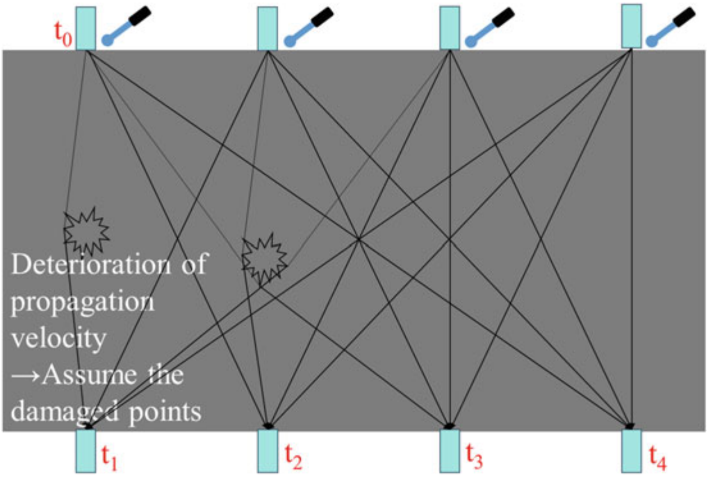


Fig. 2 Elastic wave tomography

at the specific location near the sensor as to provide the excitation time for the first, and the excited elastic waves were to be received by all sensors in the opposite surface. In this way, both the excitation time and the time of arrivals in all of the sensors can be obtained. In order to obtain the individual velocity over the structures, the structures are divided into some cells. Initially, elastic wave velocity is assumed to be the same in each cell. Then it can be possible to calculate the elastic wave velocity of each cell by using both excitation time and the time of arrivals in all of the sensors.

As shown above, it has been necessary for examining internal damages with high accuracy to use both AE monitoring and elastic wave tomography so far, leading to take a lot of time and cost to assess the structures. In order to solve this issue, author's group has proposed "AE tomography" which implements AE monitoring

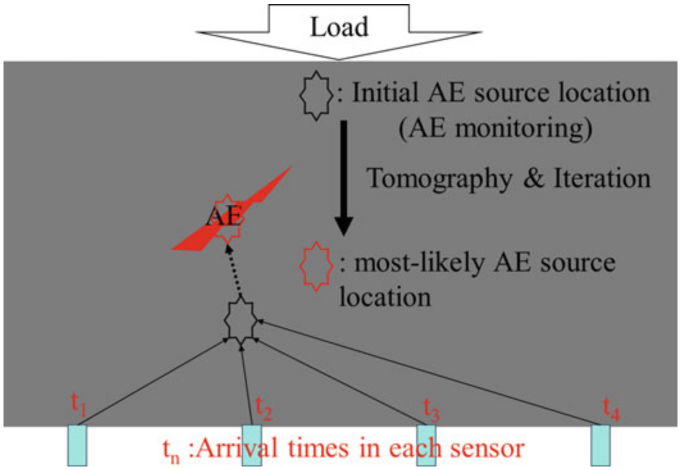


Fig. 3 AE tomography

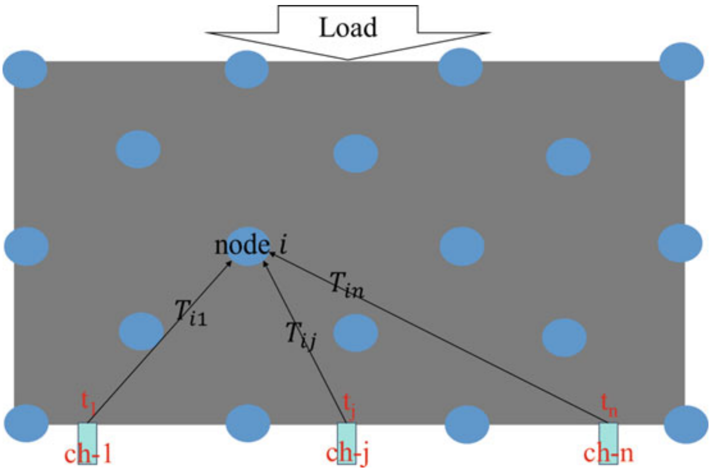


Fig. 4 Overview of ray-trace technique

and elastic wave tomography simultaneously. Figure 3 shows the configuration of AE tomography. AE tomography does not use elastic wave excited actively, but the AE wave generated within structures. It is possible to obtain the exact excitation time in elastic wave tomography; however, it is impossible to get the generation time of AE wave in AE tomography, so that the way of estimation of generation time of all AE waves is crucially important.

As shown in Figs. 4 and 5, in AE tomography, the area of interest is divided into some elements consisting of three cell nodes forming triangular shape. In addition, each side with two nodes is divided into smaller parts to increase source location

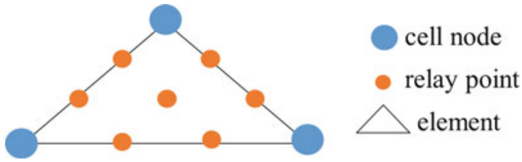


Fig. 5 Composition of an element

candidates by adapting relay points as shown in Fig. 5. Again, both of cell nodes and relay points can be the candidate for AE sources. Figure 4 shows the configuration of ray-trace technique. As shown in Fig. 4, firstly, theoretical propagation time: T_{ij} is calculated from receiver point: j to all cell nodes: i and relay points. Then, T_j which defines the difference between the obtained time of arrivals and theoretical propagation time: T_{ij} in receiver point: j is calculated. Subsequently, above process is conducted in each location of receiver (from receiver 1 to receiver n). And, by using the Eqs. (1) and (2), source locations giving the smallest variance are identified. Here T_{im} is average of estimated occurrence time and σ_i is the variance of estimated occurrence time in the case of nodal point: i.

$$T_{im} = \frac{\Sigma_j \left(T_j - T_{ij}\right)}{N} \tag{1}$$

$$\sigma_i = \frac{\Sigma_j \left(T_j - T_{ij} - T_{im}\right)^2}{N} \tag{2}$$

Based on the renewed AE source locations, the elastic wave velocity of each element is updated. This process is the one cycle for getting renewed both of AE source locations and elastic wave velocity. Finally it is possible to obtain the most likely AE source locations and elastic wave velocity of each cell by iterating this process. This is the principle of ray-trace technique. In this way, unlike the conventional AE monitoring, the AE source location in consideration of the heterogeneity of the elastic wave velocity in the structures is successfully identified.

3 Application of AE Tomography in RC Bridge Deck for Bullet Train

In our past studies, the AE tomography has been applied for the concrete specimens in the laboratory and the applicability of AE tomography for the specimen has been verified [2]. In this study, as one of the actual structures, the RC bridge deck for bullet train was assessed by the AE tomography. In the RC deck of the investigation site, some exfoliations are estimated in the shallow areas by impact acoustic test as shown in Fig. 6. It is noted that the only damage near the surface doesn't always reflect the situation of the internal damage. Accordingly Rayleigh wave tomography, which could examine more internal damage than the impact acoustic test, was also carried out for the verification of the AE tomography.

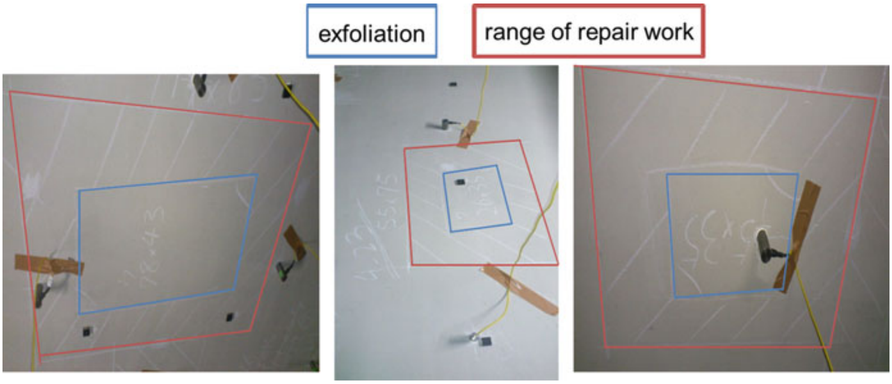


Fig. 6 Exfoliations and range of repair work in the surface of RC bridge deck

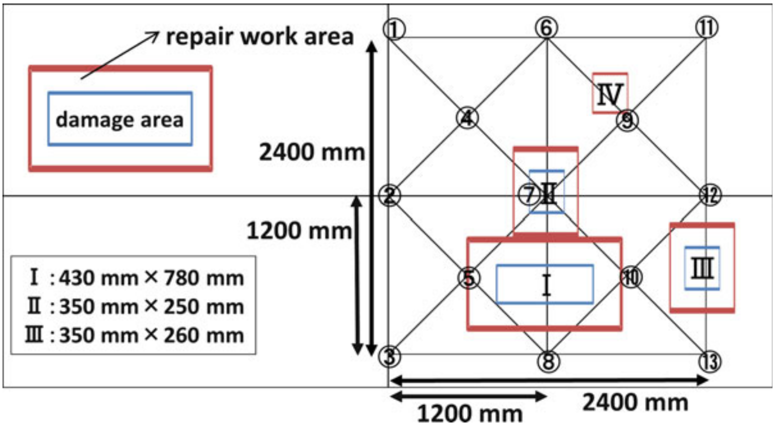


Fig. 7 Sensor array of AE tomography

3.1 Experimental Setup

This experiment was held in the repair work site near H Station. The objective area of the investigation was 2,400 × 2,400 mm on the surface of RC bridge deck for bullet train. In Fig. 7, 13 AE sensors are arranged, and an array of 16 accelerometers can be found in Fig. 8 for the Rayleigh wave tomography.

3.2 Rayleigh Wave Tomography

There are several wave modes such as P-wave, S-wave, and Rayleigh wave in the elastic wave propagation. Rayleigh waves propagate along the surface of materials

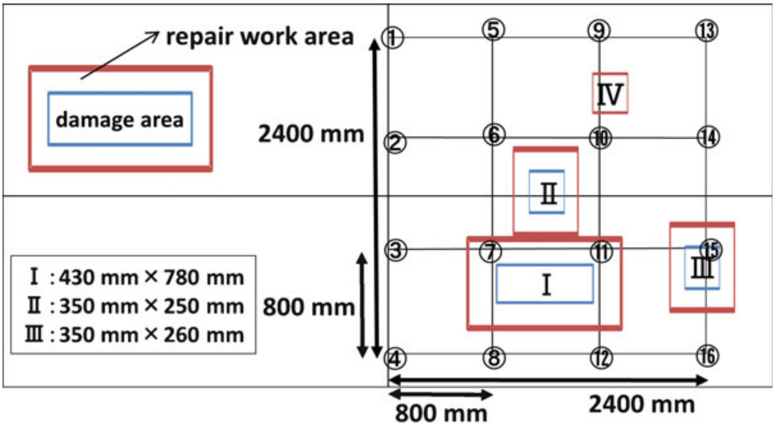


Fig. 8 Sensor array of Rayleigh wave tomography

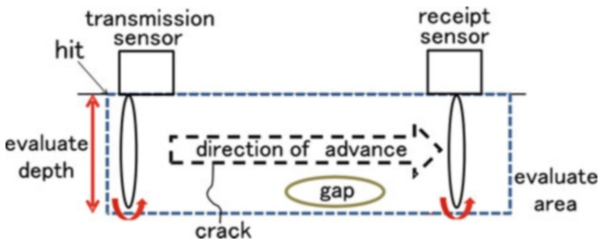


Fig. 9 Rayleigh wave tomography

with rotation in an elliptical orbit manner. Among those wave modes, Rayleigh wave exhibits the largest energy which accounts for 70 % of the whole energy, with lower attenuation rate than those of other wave modes. Based on these characteristics, Rayleigh wave tomography has been proposed which can diagnose the inner part of structures from the surface [3, 4]. Figure 9 shows the overview of the Rayleigh wave tomography. Firstly, Rayleigh waves have been excited on the surface with hammering. Then when internal damages such as cracks and voids exist in the shallow layer, reflection and dispersions of Rayleigh wave are generated, resulting in the longer propagation distance than the shortest propagation path. As shown in the figure, as it takes more time to reach the sensor, the resulted propagation velocity shows smaller than that of intact. Accordingly it is possible to evaluate the inner damage widely by calculating the propagated velocity corresponding to the dominant frequency of Rayleigh wave adapting the tomography procedure. In this technique, the effective maximum depth of Rayleigh wave corresponds to the wavelength calculated by the dominant frequency. Specifically the diameter of hammer edge changes the frequency, enabling to adjust the measurement depth. It is noted, however, that the evaluation depth is limited to the half of thickness at most.

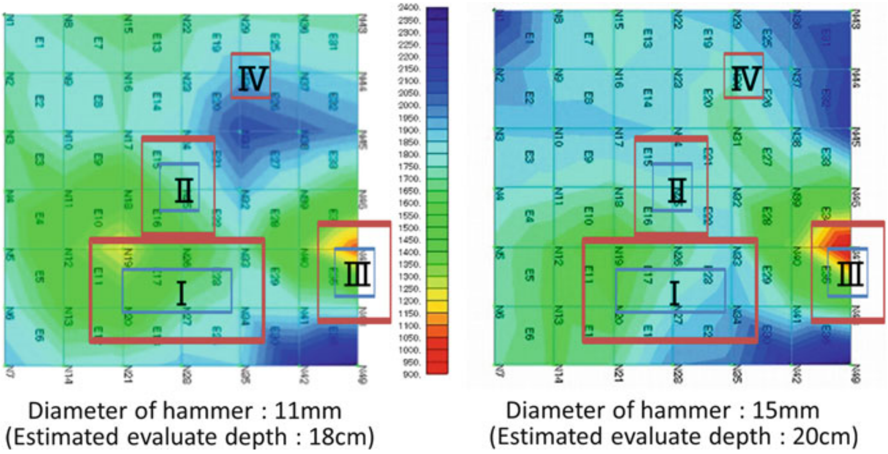


Fig. 10 The result of Rayleigh wave tomography

3.3 *Result of Rayleigh Wave Tomography*

Figure 10 shows the result of Rayleigh wave tomography, where the result of impact acoustic test is overlaid additionally. The damage areas from I to IV were highlighted in advance, specifically from I to III were evaluated by impact acoustic test; however, no information could be obtained for the IV damage. With the result of the two methods, it is confirmed that there are several damages located near the lower right, III and the center area, I and II in the measurement area. However, as explained the two methods can evaluate only the shallow layer, and it is impossible to evaluate the deeper area. In other words, the damage areas shown in Fig. 10 exhibit the damage area located shallower than the evaluation depth.

3.4 *AE Measurement*

AE wave monitoring was conducted repeatedly corresponding to 10 times passage of bullet trains. As the AE waves obtained from the measurement consisted of background noises, mechanical vibrations caused by trains passage, and secondary AE activity, it was important to extract only the secondary AE activity generated from existing damages, where only the secondary AE activity can serve as AE data to AE tomography analysis. It has been already reported that the AE activity induced by the background noises has small energy, so that the noise-related AE activity was eliminated by filtering the AE waves having small energy. After that filtering, the secondary AE waves were eliminated from those due to the vibrations. Figure 11 shows the AE wave due to vibration of the train, while in Fig. 12, the AE wave generated from the existent damage, namely secondary AE activity is

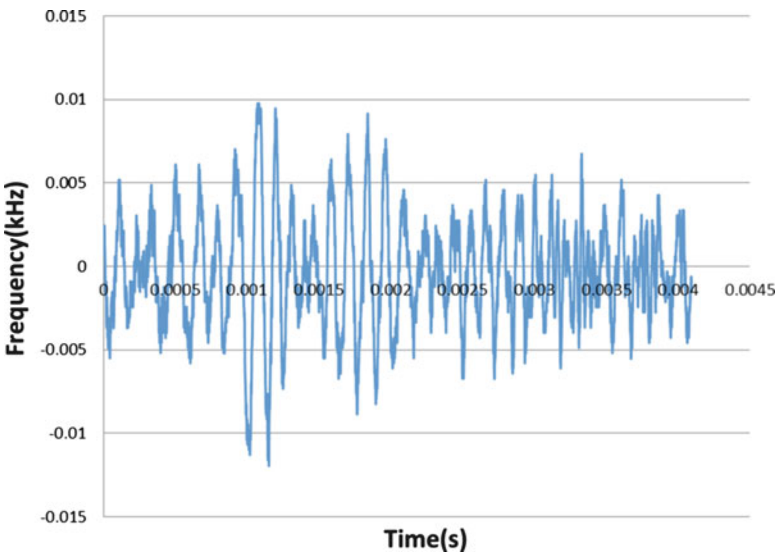


Fig. 11 Vibration-related AE wave

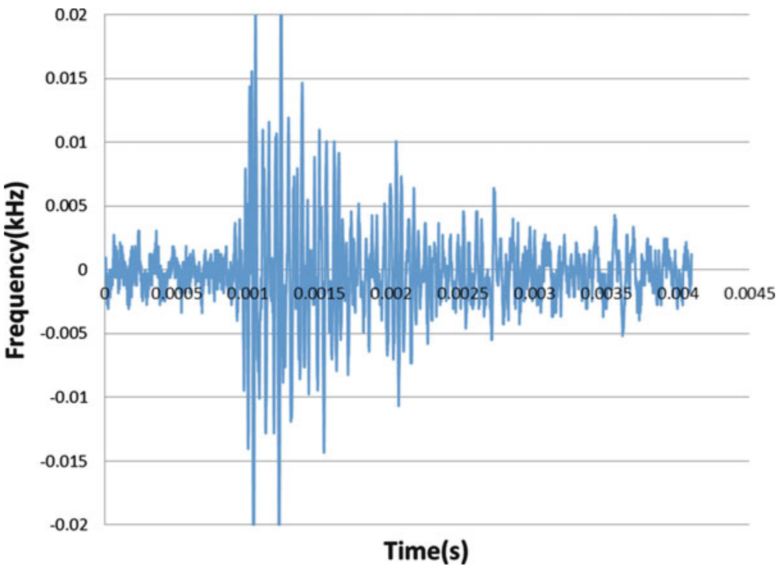


Fig. 12 AE wave generated from existing damages

exhibited. As shown in these figures, the AE wave from the existent damage has short rise time and exponential attenuation behavior over the time, whereas vibration-induced AE activity has longer rise time and lower frequency in comparison to the secondary AE wave [5, 6].

Table 1 The result of two AE parameters

Passage		Energy	Average FRQ	Center FRQ	Peak FRQ
First	AE wave	30.6	14.3	32.8	18.4
	Vibration wave	54.123	6.875	33	6.75
Second	AE wave	101	13.75	28.91667	21.66667
	Vibration wave	95	10	29.36364	7.181818
Third	AE wave	117.1667	11.83333	31.66667	21.83333
	Vibration wave	100.2	9.9	30.8	7

Based on these qualitative characteristics of waveform features, ten typical two types of AE waves were extracted and averaged for each parameter as shown in Table 1. This process was carried out with regard to three times passages of bullet trains respectively.

As shown in Table 1, obvious differences between two types of AE activity were verified with peak frequency, and therefore the peak frequency was used for classifying the two types of AE waves. Specifically AE waveforms with higher peak frequency were extracted as the secondary AE waves, and these were used for the AE tomography.

3.5 The Result of AE Tomography

Figure 13 shows the result of AE tomography. The blue dots in the figure show the original source locations based on the conventional source location algorithm, while the red exhibits the improved source locations with proposed AE tomography. In the figure, the damage areas estimated by AE tomography correspond well with the damage areas I, II, and III confirmed by the impact acoustic test and the Rayleigh wave tomography. The AE tomography can also estimate the damage area IV, presumably located in the deeper area which is difficult to be detected by both of the impact acoustic test and the Rayleigh wave tomography. That's because the damage area IV wasn't verified by the two methods, but estimated by AE tomography enabling to diagnose the deeper area in comparison to the two methods. Thus it is clarified that the AE tomography can evaluate not only the damages near the surface but also the damages lurked in the deeper areas. As a result, it is clarified that AE tomography can evaluate the internal damage which cannot be confirmed by the acoustic impact test, and this will effectively contribute to the proactive maintenance which needs to identify the early damage evolving inside of the materials.

3.6 Future Works

Issues to be settled in the future are listed below.

1. It is necessary to accumulate more data when applying AE tomography to more in situ structures.

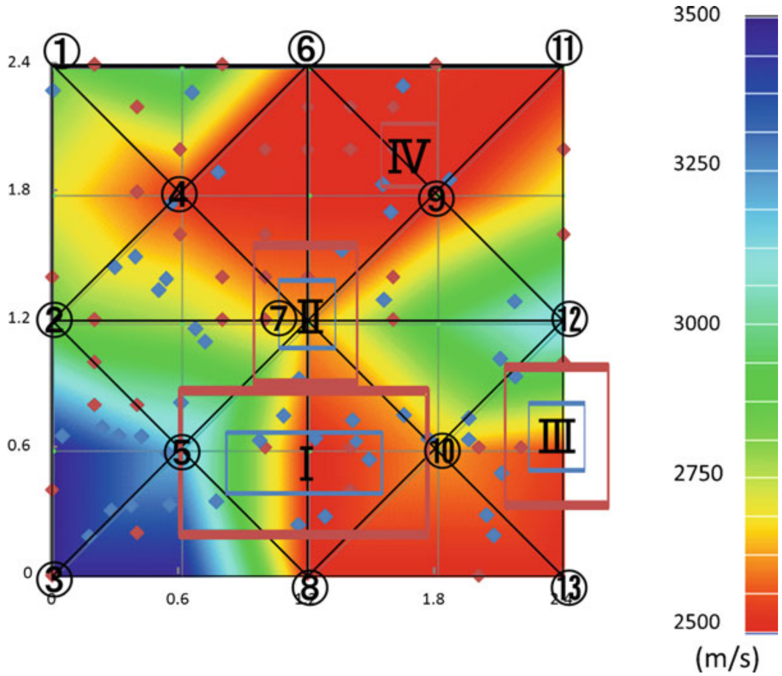


Fig. 13 The result of AE tomography

2. The internal damages can be evaluated by using AE tomography, namely velocity distribution; however, in order to contribute more on proactive maintenance program, the velocity shall be quantified with damage. The study of the elastic wave parameters relating to the damage can be found in our paper [7].

4 Conclusions

In this study, we investigated the deterioration of RC bridge deck for bullet trains with the proposed AE tomography. The result can be summarized as follow:

1. Only AE waves were extracted from three types of waves: background noises, mechanical vibrations, and secondary AE waves in order to enhance the accuracy of AE tomography. AE tomography was applied to the in situ structure with only AE waves. In addition, to verify application of AE tomography, investigation with impact acoustic test and Rayleigh wave tomography was carried out. The two methods exhibited the damages in shallow area. As a result, the compatible result was obtained by AE tomography, so that it was clear that AE tomography could identify the damages in shallow area.

2. AE tomography could examine the damage in the area where the damage was not examined by both impact acoustic test and Rayleigh wave tomography; however, the two methods could evaluate only the damages in the shallow layer. Accordingly using AE tomography, it might be possible to examine damages in deeper area beyond the evaluation depth of impact acoustic test or Rayleigh wave tomography.
3. Identification of the internal damages in RC bridge deck for bullet train was possible with AE tomography, extracting only the secondary.
4. AE waves occurred in the deck and utilizing the data into AE tomography, AE tomography could evaluate the internal damage which could not be confirmed by conventional methods. Accordingly AE tomography will effectively contribute to the proactive maintenance which needs to identify the early damage evolving inside of the materials.

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