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STUDY ON SECONDARY AE TECHNIQUE FOR SEISMIC DIAGNOSIS OF RAILWAY SUBSTRUCTURES

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SUMMARY

One difficult task for the seismic diagnosis of existing structures is to nondestructively evaluate the damage degree of invisible substructures as foundations in ground. For efficient diagnosis of substructures, a method of nondestructive inspection is developed by applying acoustic emission (AE) technique. For the proposed method, characteristics of secondary AE induced by a train in service are investigated. AE experiments with model piles and in-situ AE monitoring of railway bridges are conducted under railroad traffic. It is demonstrated that the proposed method is practicable enough to detect the invisible defects in structures. Furthermore, a new index named RTRI (ratio of **R**epeated **T**rain load at the onset of AE activity to **R**elative maximum load for **I**nspection period) is proposed for the evaluation of structural integrity. The applicability of the proposed method is confirmed through in-situ AE monitoring.

INTRODUCTION

While inspecting the earthquake-induced damage in invisible structures such as foundations with visual methods, it is generally needed to excavate the ground surrounding the foundation. As to railway structures this kind of excavation is impractical, because it costs high and also influences the running safety of trains. When active nondestructive inspection (NDI) methods such as ultrasonic testing and X-ray radiography are applied to foundations, input power should be strong enough against the decay due to high damping of massive concrete and soil around the foundations. In fact, generation of strong input waves is not easy. In particular, harmful radiation rays may threaten the safety of workers and environment. Therefore, theses active NDI methods are normally unsuitable for bridge substructures which consist of massive concrete and/or are embedded in the ground.

Different from active NDI, AE inspection is passive as elastic waves are generated due to fracturing or emitted directly from damaged portions. As for the fracture process of concrete structures, it is well understood that AE events due to both crack initiation and crack growth can be observed. Further AE source characterization can be performed with crack location, crack classification and crack orientation, Ohtsu [1]. In damaged concrete structures, secondary AE events due to fretting at existing crack surfaces

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would be generated. Seismic diagnosis of concrete piles has been developed by paying attention to the secondary AE signals. Its applicability has been testified by Shiotani [2]. Moreover, AE characteristics of concrete piles with micro-cracking was investigated, and better performance of AE monitoring was confirmed by comparing it with the Pile Integrity Test, Shiotani [3].

So far, there are some problems existing in applying the conventional AE inspection to foundations. For example, large-scale loading and setting wave-guide rods in ground are necessary. These could make the cost higher, the testing period longer and routine inspection of railway structures impractical. To overcome these shortcomings, a new methodology suitable for the seismic diagnosis of railway structures is proposed from the viewpoint of engineering practice, where the large-scale loading is replaced with train-induced loading and the arrays of AE sensors on the surface of footing are employed instead of wave guides, Luo [4–5]. In this study, AE experiments are conducted and AE indices for evaluation of structural integrity are investigated to estimate the applicability of the proposed method.

There are two parts consisted in the paper. In the first half, a fundamental study on the characteristics of secondary AE is discussed based on AE experiments of model piles. In experiments, the secondary AE was generated by simulated train loading exerted onto the pile head. In the second half, applicability of secondary AE technique is examined based on in situ AE monitoring. Concrete piers of existing bridges with severe damage zones were selected as objective structures. The examination was conducted by comparing the results of AE measurement with the real damage inspected in the piers. Moreover, practical indices for evaluating the structural damage degree are developed, which are suitable to and calculated from in situ AE monitoring.

Since the aim of the study is to develop an effective seismic diagnosis method for substructures consisted of piers and foundations, experiments focused on the following points.
1) Detectability of the secondary AE signals under train loading generated by fretting at surfaces of existing cracks in concrete;
2) Location ability of the defects in the vicinity of pile head through a two-dimensional (2-D) array of AE sensors on the surface of footing;
3) Characteristics of secondary AE induced by train loading as AE activity, cumulative AE hit, AE peak amplitude etc.;
4) Indices suitable to in situ AE monitoring for evaluating damage degree of railway structures.

DIFFERENCE BETWEEN CONVENTIONAL AND PROPOSED AE METHODOLOGY

The conventional AE technique for damage diagnosis of piles is illustrated in Fig. 1, where large-scale loading due to vibrators is applied and wave-guide rods are used. So far, this AE method was confirmed to be suitable for structures damaged severely in the 1995 Great Hanshin Earthquake. Since the method needs a rather high expense and a long period for inspection, it is difficult to apply it to routine inspection of structures. In order to overcome these shortcomings and make it suitable to general seismic diagnosis of railway structures, a new method is considered as shown in Fig. 2. The procedure is improved as follows: (i) applying the load due to in-service trains to replace the external load-vibration, and (ii) damage diagnosis of piles by using an array of AE sensors set on the footing surface, without embedding the wave-guide rod in ground.

According to the previous report by Yuyama [6], AE signals from existing cracks in a horizontal concrete member as a beam of viaduct could be detected under train loading. AE activities were observed during loading and unloading resulted from the friction of existing crack surfaces, which occurred due to the opening and/or closure of cracks under bending deformation of the member.

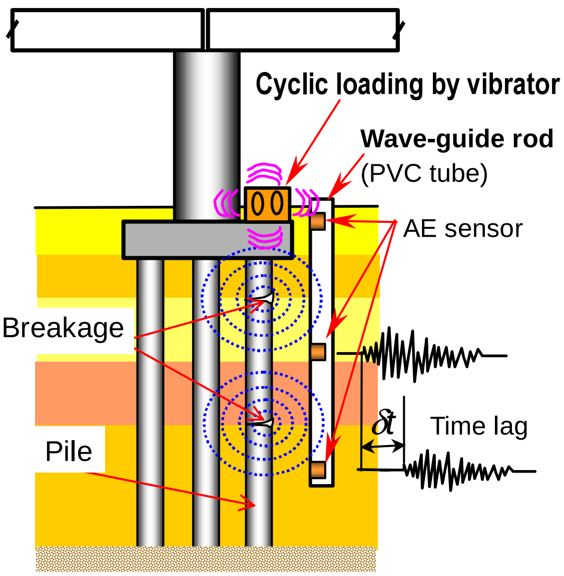


Fig. 1 Conventional AE technique for seismic diagnosis of piles

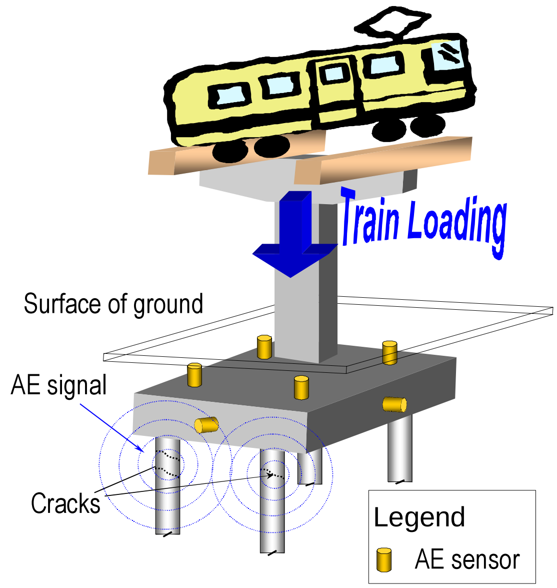


Fig. 2 AE technique proposed for seismic diagnosis of railway structures

In the case of a vertical member like a pier or a pile, the effect of bending deformation would be small even under the train loading. The effect due to shear deformation of the member, instead, could increase. As a result, characteristics of secondary AE might be different from those of the horizontal members. In order to investigate the basic behavior of the train-induced secondary AE activity in vertical members, it is necessary to conduct a model experiment and in situ observation. Based on the results of the experiment/observation, indices for structural integrity assessment are proposed.

AE EXPERIMENT OF MODEL PILES

Outline of experiment

To reproduce the behaviors of actual piles, similarity was taken into account when making a specimen. To confirm the repeatability of pile behaviors, two identical specimens were prepared by using D10 rebars and concrete with strength of 30 N/mm^2. Detailed configuration and rebar arrangement of the specimens are shown in Fig. 3. The diameter of the pile is 300 mm and the size of the footing is 1,300×1,300×500 mm. For the convenience of cyclic loading, the specimens were made as inverted. To fix the specimens stably on the reaction floor, four holes of anchor bolts were made in the footing. To set AE sensors on the surface of the inverted footing, a slot, 500×500×50 mm in size was also created while concrete was cast. In addition to AE sensors, a total of 48 strain gauges were attached on the main rebars to monitor the strain of the specimens.

Given in Fig. 4 is the arrangement of AE sensors in the vicinity of pile head. Since one of the purposes of the experiment is to examine the possibility to detect the defects in the vicinity of pile head through the 2-D monitoring array, AE sensors CH1-Ch4 were attached on the surface of footing. Other sensors were arranged surrounding the expected fracture zone in the vicinity of pile head. A total of 14 sensors, resonant frequency 60 kHz, were used. To examine the possibility of monitoring secondary AE activity under the simulated train loading, the effects of the soil around the pile is neglected. An experiment setup

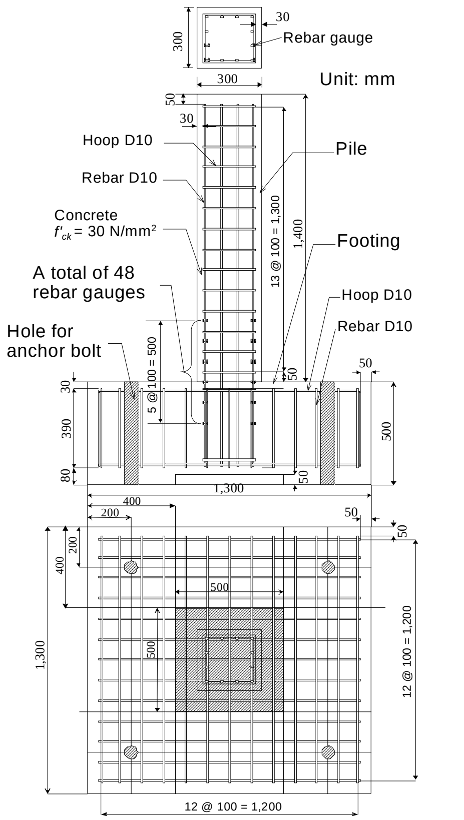


Fig. 3 Configuration and rebar arrangement of inverted model pile (top: elevation view; bottom: plan view)

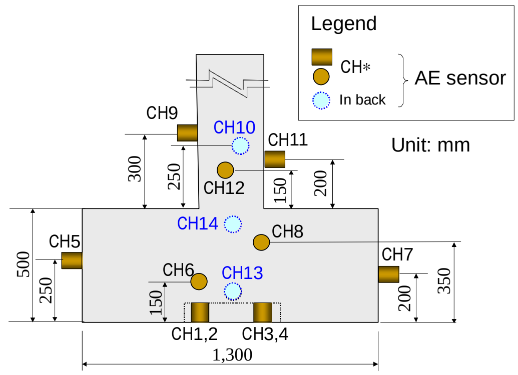


Fig. 4 Arrangement of AE sensors in vicinity of pile head

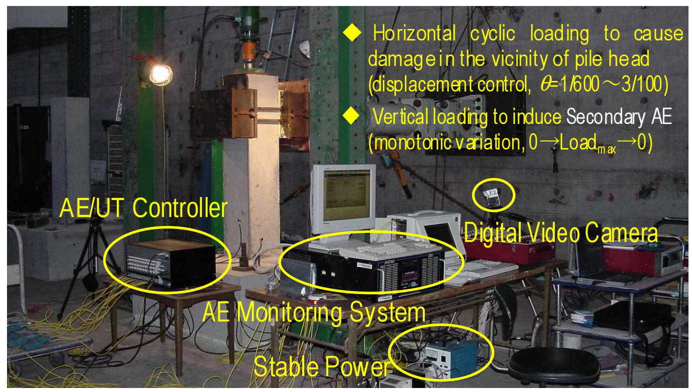


Fig. 5 A set-up for secondary AE monitoring under simulated train loading

of the loading and measuring system is shown in Fig. 5. Three steps of the experiment are illustrated in Fig. 6. Their details are as follows:

Step 1: To simulate generation of cracks in the vicinity of pile head due to earthquakes, a horizontal cyclic load was applied at the tip of the inverted pile. Horizontal loading was conducted under displacement control. In consideration of the damage degree of the member stipulated in seismic design, loading stages were determined to correspond to such deflection angles as 1/600, 1/400, 1/100($1\theta_y$), $2\theta_y$ and $3\theta_y$, respectively.

Step 2: After each cycle of horizontal loading, simulated train loading in the vertical direction was applied at the tip of the pile to generate the secondary AE at crack surfaces. At each horizontal loading stage, vertical loading was conducted three times to vary monotonically from 0 to the maximum.

Step 3: To estimate the damage state in the fracture zone, the secondary AE signals due to the simulated train loading were monitored by the 2-D array consisted of four sensors (CH1-CH4) and the 3-D array of all sensors. To examine the accuracy of 2-D monitoring, it was compared with the results of 3-D monitoring, as illustrated schematically in Fig. 6. In addition to the secondary AE, such characteristics of primary AE as source location and cumulative count of AE hit were also investigated. Moreover, transducers for measuring the horizontal/vertical displacements of the specimens were used to estimate the deformations of the model pile.

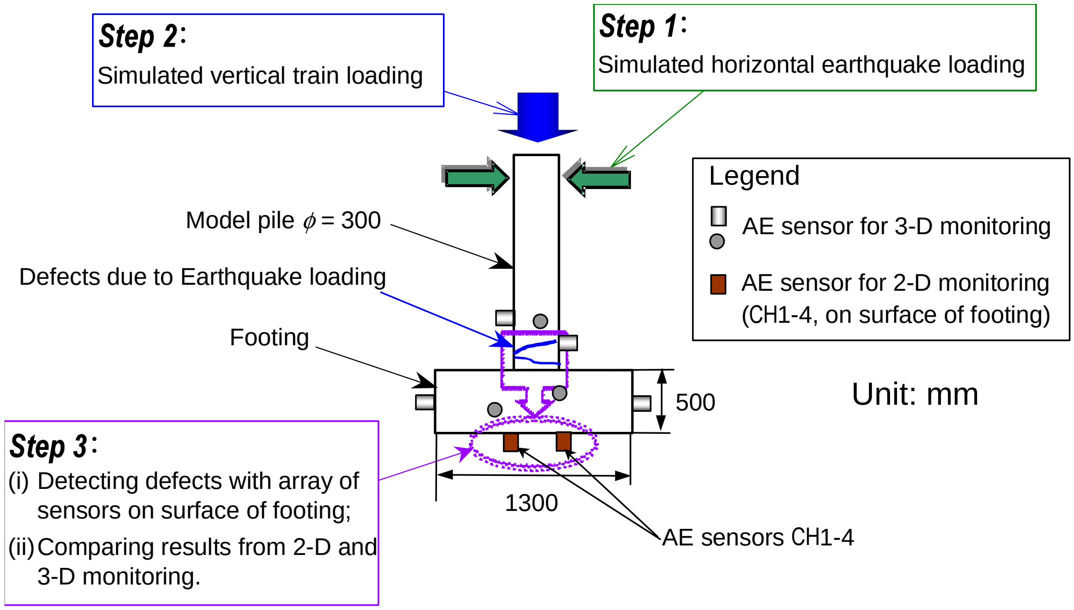
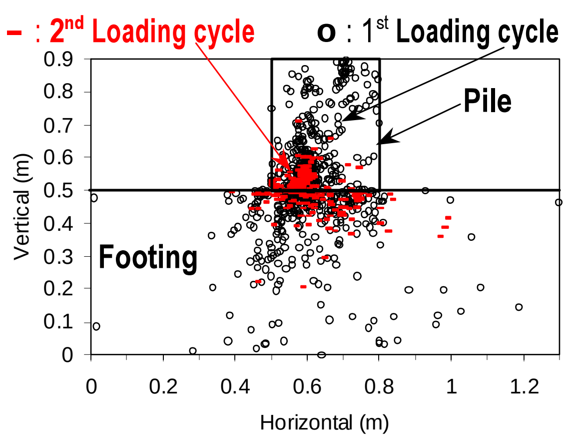


Fig. 6 Schematic illustration of procedure for AE experiment in an inverted model pile

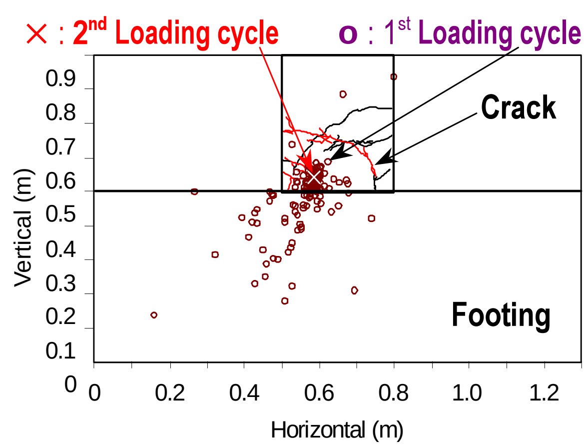
Results and discussion

Primary AE sources are located by 3-D monitoring as shown as an elevation view in Fig. 7 (a). These are observed during two cycles of horizontal loading at the stage corresponding to the deflection angle of 1/100. It is seen that AE sources at the 2nd loading cycle are located inside the cluster of the 1st cycle, especially concentrating at the left area of the pile head. In contrast, an elevation view of the 3-D locations of the secondary AE sources due to the vertical loading is shown in Fig. 7 (b) following the stage of horizontal loading shown in Fig. 7 (a).

It is clearly observed that the secondary AE sources induced by the simulated train loading distribute only within the cluster of AE sources observed in the horizontal loading. This implies that the secondary AE events due to the friction at the pre-existing cracks are successfully detected. Actually, the secondary AE signals detected in this experiment are mostly limited to the area where shear-type cracks visually observed. This phenomenon is in good agreement with that in the previous report by Shiotani [3].



(a) Under horizontal loading



(b) Under vertical loading

Fig. 7 Locations of AE sources due to horizontal and vertical loading (deflection angle of member 1/100)

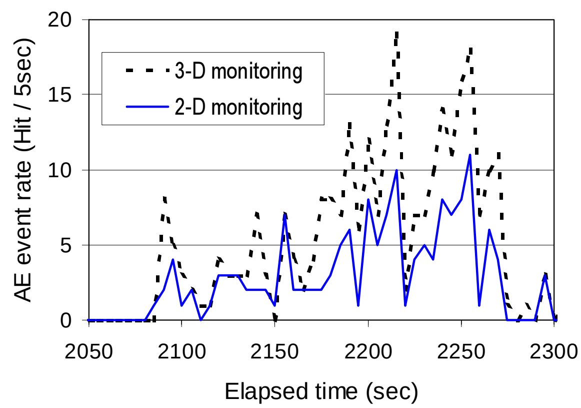


Fig. 8 Comparison of AE event rates between 2-D and 3-D monitoring under vertical loading

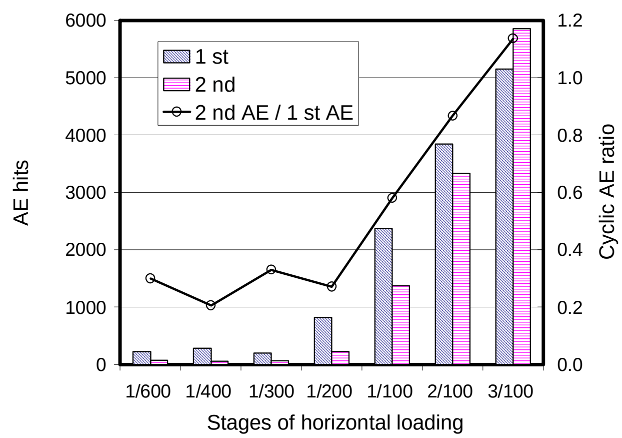


Fig.9 Cumulative counts of AE hits due to horizontal loading

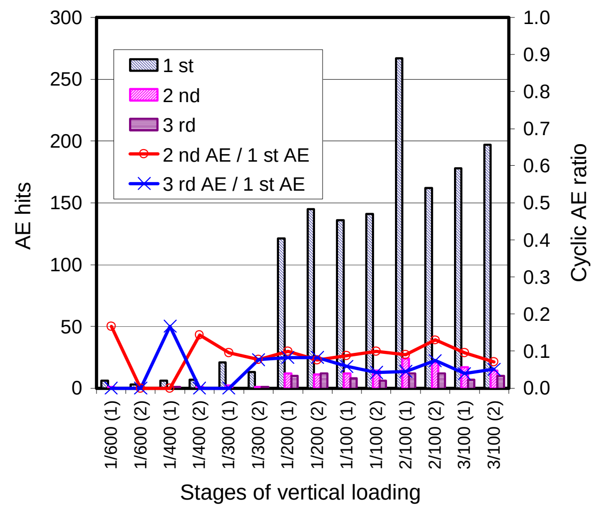


Fig.10 Cumulative counts of AE hits due to vertical loading

Therefore, it is reconfirmed that monitoring the secondary AE is effective to evaluate the damage degree of the existing shear-type cracks.

Fig. 8 is a comparison between event rates of the secondary AE in 3-D (all channels) monitoring and those of 2-D monitoring during the vertical loading at the stage of deflection angle 3/100, where AE events correspond to the number of located AE sources. The number of AE events in 2-D monitoring is less than that of 3-D monitoring, and the tendency of AE generation is still quite similar.

In Fig.9 and Fig.10, the cumulative AE hits and their ratios of the stages of horizontal loading and vertical loading are indicated, respectively. The histograms in the Figures represent AE hits and the lines are their ratios of the 2nd and the 3rd cycles to the 1st cycle. Most of AE hits in Fig.9 are the primary AE under horizontal loading, which reflects crack initiation and crack growth. The number of AE hits is as high as several thousands. In contrast, AE hits in Fig.10 under vertical loading are quite low, because they are mostly the secondary AE generated by fretting at existing crack surfaces. In Fig.10, it is found that the cyclic AE ratios vary gently and thus the secondary AE hits decrease dramatically from the 1st cycle to the cycles thereafter. This phenomenon may be attributed to the limitation of the model experiment, where the horizontal loading is applied without axial force due to the dead load. Therefore, tensile-type cracks

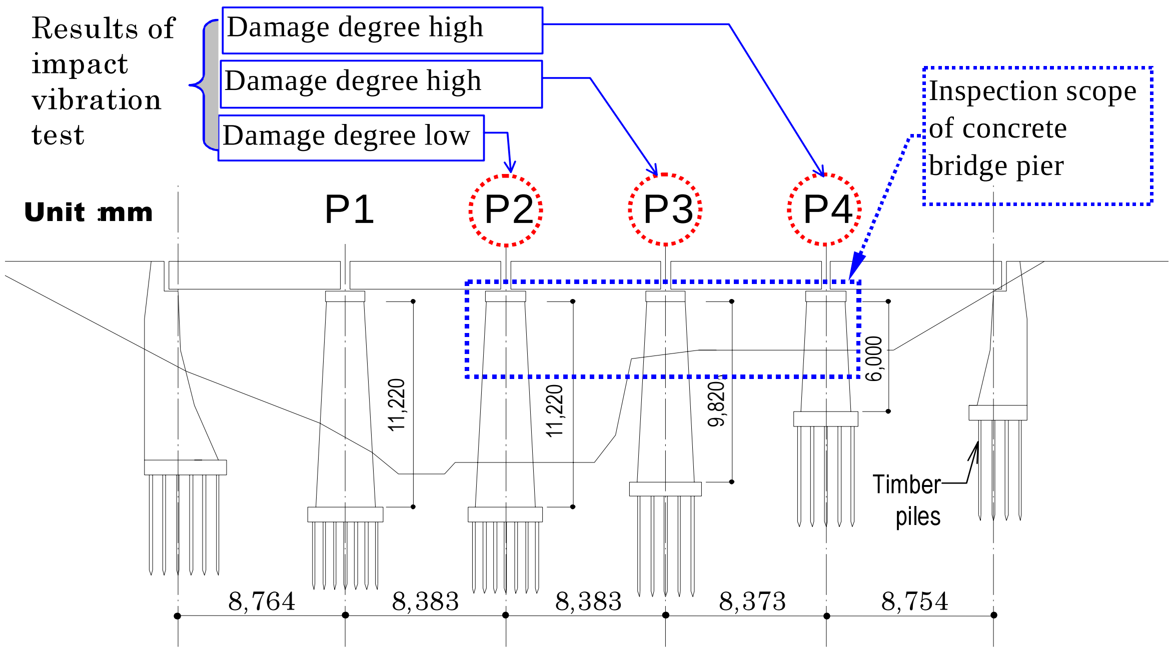


Fig. 11 Whole scheme of the objective bridge with the results of impact vibration test indicated

could occur more predominantly than shear-type cracks. To clarify it, an in situ experiment under real train loading was performed.

IN SITU AE MONITORING UNDER ACTUAL TRAIN LOADING

In situ AE monitoring I

Outline of experiment

To verify the applicability of the proposed method, AE monitoring focusing on the secondary AE activity was carried out in concrete piers of railway bridges. The piers, which are made of plain concrete, were constructed more than 70 years ago. Besides investigating the applicability of the proposed method, the experiment compared the results of AE monitoring to that of impact vibration test and checked the coordination between the two methods. Impact vibration test is a nondestructive inspection method to evaluate the integrity degree of structure by measuring its natural frequency. This inspection method is being used popularly for maintenance of railway structures in Japan. Given in Fig. 11 is a whole scheme of the objective bridge with the results of impact vibration test indicated. According to the inspection results, the piers P3 and P4 had high damage degree, whose rigidity decreased about 80% because of an earthquake occurred before. In contrast with the pier P3 and P4, the P2 had only suffered low degree damage.

In experiment besides the AE monitoring, some other measurements for strain, crack, acceleration and train loading were also conducted to grasp the relationship among AE event, pier deformation and loading action. A schematic illustration of sensor setting for the pier P3 is taken as an example shown in Fig. 12. For AE monitoring 12 sensors (60kHz resonant) were used.

Results and observation

Results of AE sources with regard to the 3 piers are shown in Fig. 13. Under same measurement condition, the AE event number and the counter of AE waves are obviously different between the piers

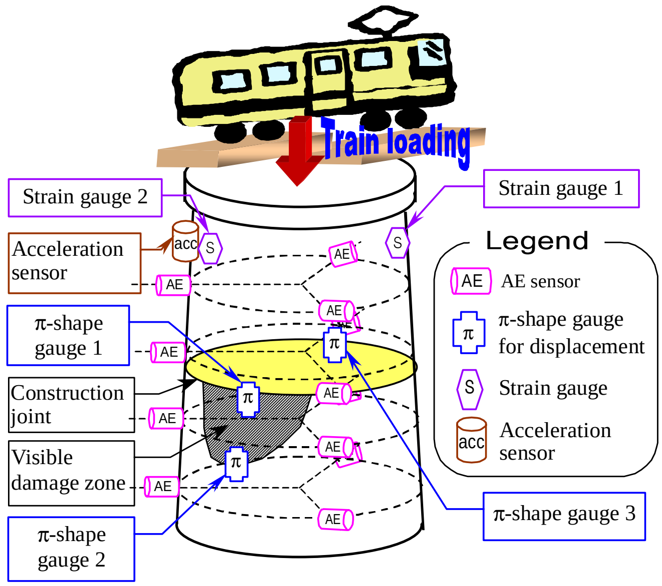


Fig. 12 Schematic illustration of various sensors setting on pier P3

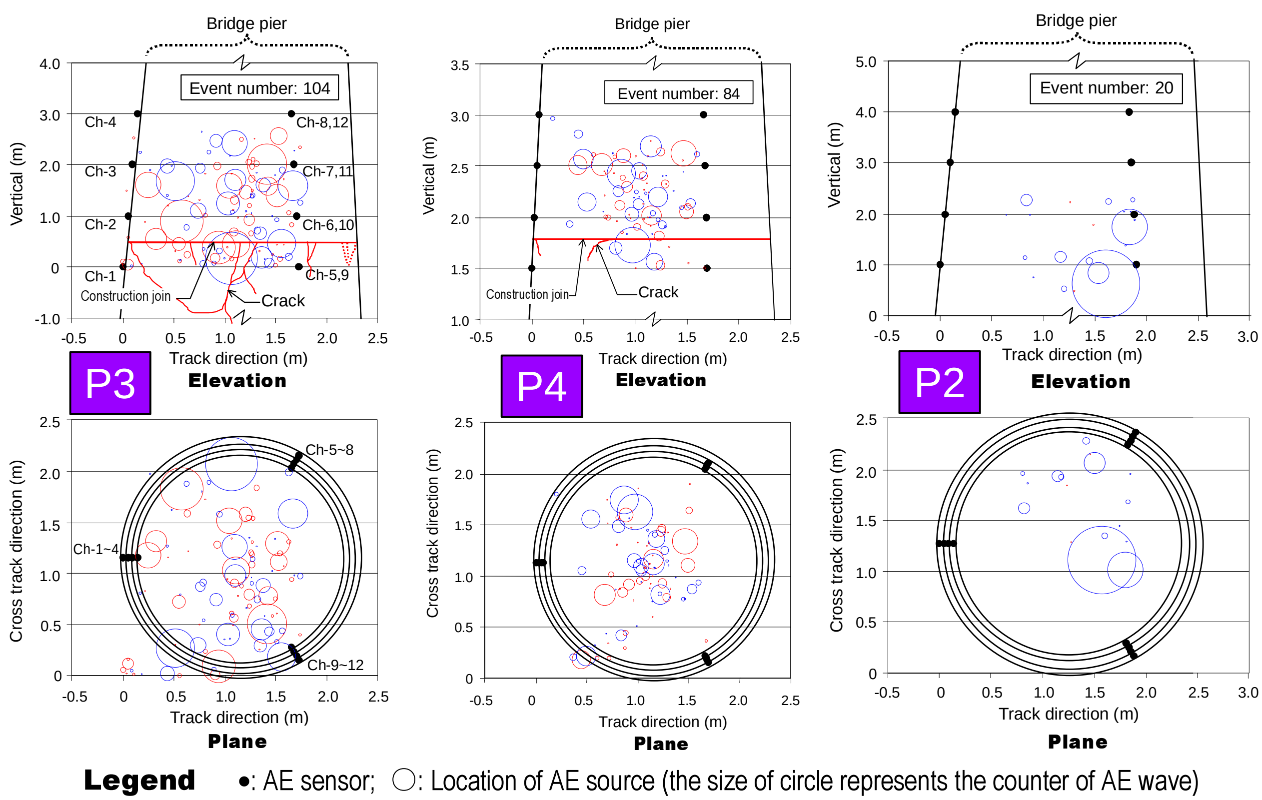


Fig. 13 Secondary AE sources determined by 3D monitoring with regard to each pier

with high damage degree (P3 and P4) and low damage degree (P2). In contrast with the AE event number 104 and 84 corresponding to P3 and P4, there are only 20 AE events for P2. The counters of AE waves for P3 and P4 are larger than the case of P2 in average. As a result, the characteristics of AE event measured are coincident with the integrity evaluation by impact vibration test.

In situ AE monitoring II

Site and measurement

The object for the second in situ AE monitoring was an arch-type pier, which was made of plain concrete and built more than 70 years ago. An illustration of AE monitoring of the pier is shown in Fig. 14 by utilizing the loads due to trains in service.

The surface cracks in the pier, the arrangement of AE sensors and locations of the secondary AE events are shown in Fig. 15 and Fig. 16. With regard to the existed damage, several deep cracks penetrating the pier body at the top left part of the arch were found by conventional inspection. Some cracks and traces of repair also concentrated on the surface of the severely damaged zone.

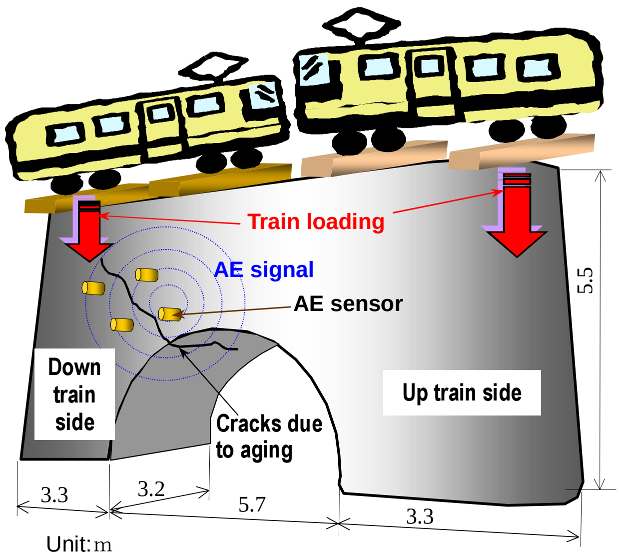


Fig. 14 Schematic illustration of secondary AE monitoring for a pier under loading of train in service

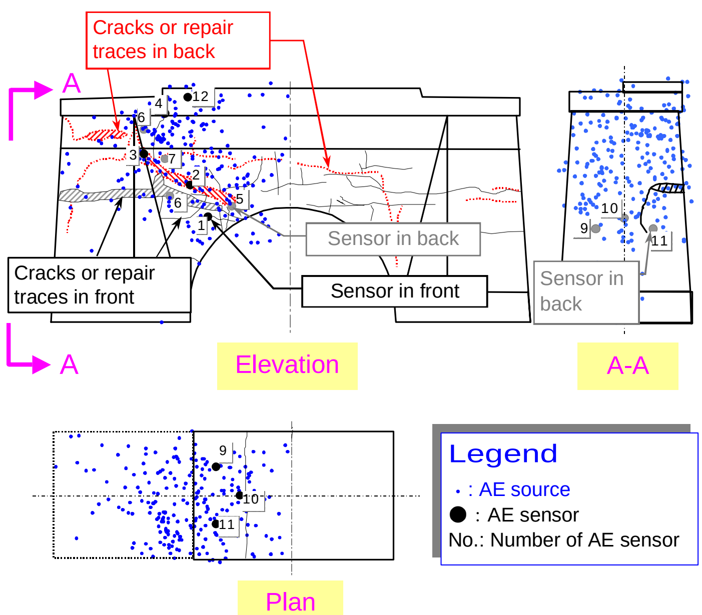


Fig. 15 Secondary AE sources determined by 3-D monitoring (sensor set Pattern A)

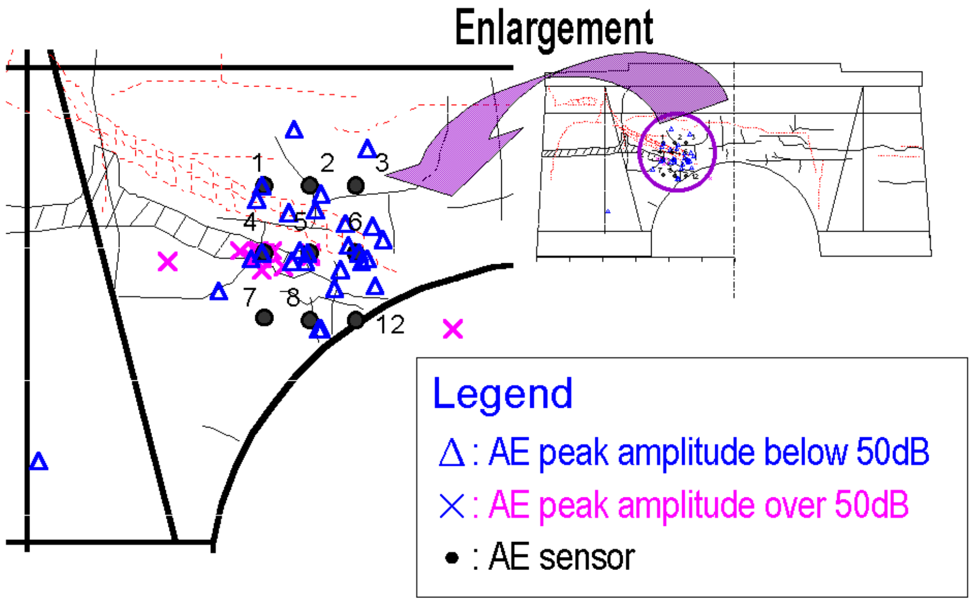


Fig. 16 Secondary AE sources determined by 3-D monitoring (sensor set Pattern B)

As for AE source locations, five patterns of sensor arrangements were attempted. Given in Fig. 15 and Fig. 16 are AE sources obtained from sensor arrangements of Pattern A and Pattern B, respectively. In Pattern A 12 sensors (60 kHz resonant) were set surrounding the damaged zone three-dimensionally. Results of AE source show that most of the AE signals are generated inside the zone. In the case of Pattern B, the sensors were arranged to concentrate on one surface of the pier to investigate the characteristics of AE waves. As a result, it was found that large AE events of peak amplitudes over 50 dB were generated within the damaged zone, whereas AE events of small amplitudes below 50 dB were observed within the zone lightly damaged. This implies the possibility to evaluate the damage degree of structure from the peak amplitudes of AE signals. Thus, the amplitude of AE signal could be an important index for assessing the structural integrity.

Evaluation of damage degree

According to previous studies [7], indices called the "Load ratio" (Ratio of **l**oad at the **o**nset of **A**E activity to previous loa**d**) and "Calm ratio" (Ratio of **c**umulative **A**E activity under un**l**oading to that of previous **m**aximum loading cycle) were applied to evaluate the damage of structure, which are based on the concept of the Kaiser effect. In the case of the secondary AE, however, the concept is not readily applicable. Furthermore, since it is difficult to estimate the maximum load that has been ever experienced by the pier, and the live loads due to trains in service, the calculation of "Load ratio" is impractical. Therefore, a new index called the "RTRI ratio" (ratio of **R**epeated **T**rain load at the onset of AE activity to **R**elative maximum load for **I**nspection period) is proposed. This modifies the definition of "Load ratio" by introducing the relative maximum load instead of the previous maximum one. If the load due to train passage is difficult to measure in situ, the concept of load can be replaced by deformation of structure, which reflects the variation of the load and is ready to be measured in situ.

In the experiment, the RTRI ratio was determined by using the train-induced displacement at Crack 3 shown in Fig. 17. The displacement was confirmed to have a close relation with the train loading by

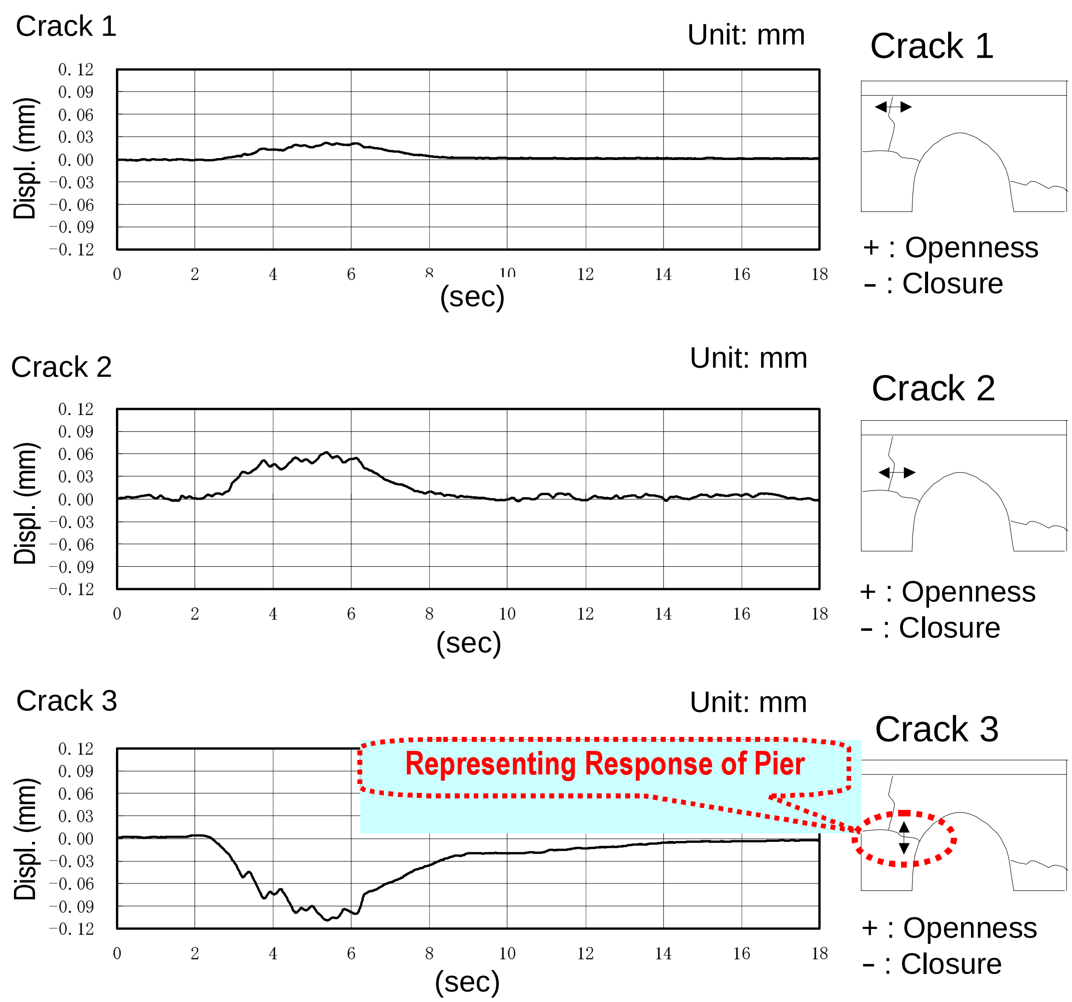


Fig. 17 Histories of displacement corresponding to cracks in a pier under train loading

comparing with riding density of the train passed. Therefore, the histories of displacement were adopted to represent the variation of the train-induced live loads to the pier. Given below are the formulae for calculating the RTRI ratio and Calm ratio based on the variation of AE hits and displacement at Crack 3.

$$RTRI = \frac{Displacement_{onset\ of\ AE\ activity}}{Displacement_{\max load\ during\ inspection\ period}} \tag{1}$$

$$Calm = \frac{Cumulative\ AE\ Activity_{from\ peak\ of\ displacement\ to\ end}}{Cumulative\ AE\ Activity_{from\ beginning\ of\ displacement\ to\ peak}} \tag{2}$$

As an example, Fig. 18 shows the process of calculation of the two ratios. The time histories of cumulative AE hits and displacement measured by a π-shaped gauge at Crack 3 are shown in the Figure. With regarding to the chart of displacement, the stages of displacement increase (from beginning of displacement to peak) and decrease (from peak of displacement to end) represent the loading and unloading stages of the live loads, which are used in Eq.(2). The displacement corresponding to the onset of AE activity is derived as 0.071 mm and the peak value during the inspection period as 0.116 mm from

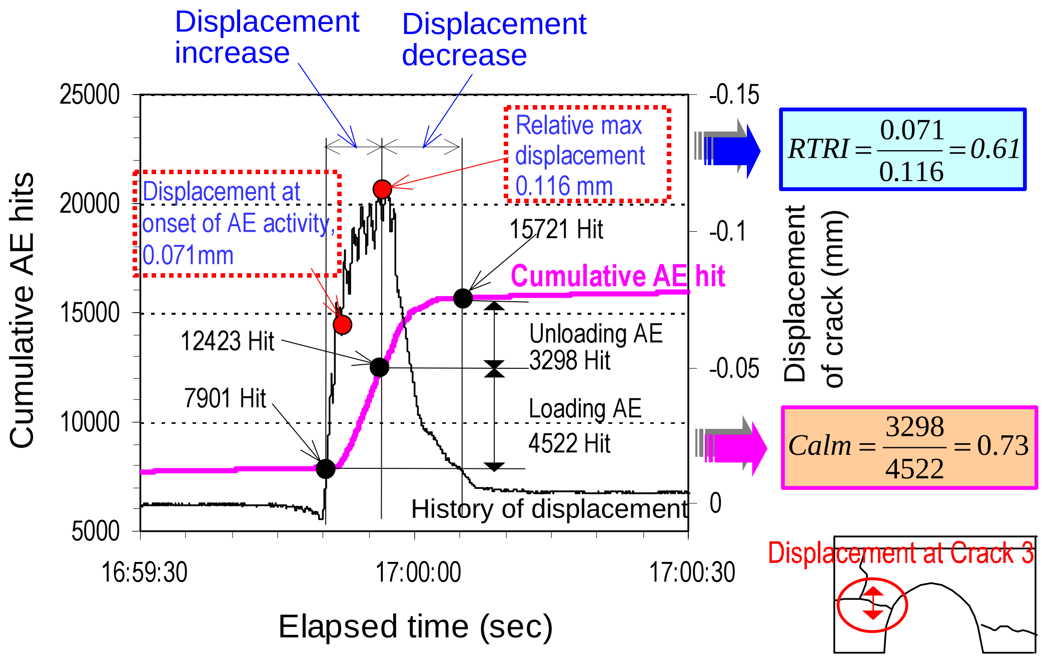


Fig. 18 Calculation of the RTRI ratio and Calm ratio based on variation of displacement at Crack 3

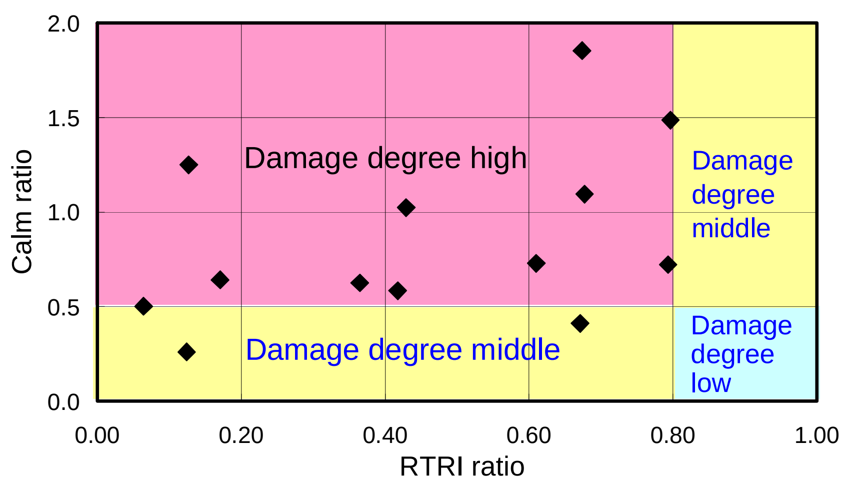


Fig. 19 Damage qualification of pier based on RTRI ratio and Calm ratio

the Figure. Thus, the RTRI ratio is calculated as 0.61 based on Eq.(1). As to the Calm ratio, the numerals of cumulative AE hit corresponding to the loading and unloading stages are 4522 and 3298, respectively. Then, the Calm ratio is obtained as 0.73 according to Eq.(2). Therefore, corresponding to all passage of trains the RTRI and Calm ratios can be achieved in this way.

The qualified damage degree of the pier based on the RTRI ratio and Calm ratio obtained above is demonstrated in Fig. 19. The results show that most of the measured data are plotted within the zone of “Damage degree high” (Calm ratio > 0.5, RTRI ratio < 0.8). This is reasonably in agreement with the actually damaged situation of the pier. Therefore, the proposed index “RTRI ratio” based on the secondary AE activity is proved to be useful and suitable for in situ AE monitoring.

The limits to qualify the damage degree in Fig. 19 are determined after evaluating the real damage of the pier with other NDI methods. Actually, fundamental treatment of the damage qualification is quite similar to Ref. Ohtsu [8]. But, the limit of the Calm ratio, 0.5, in the figure seems too large. The different limits for the Calm ratios in the two studies might attribute to the difference on target structures and experimental conditions. In the previous study, the experiments were conducted in a laboratory under precise loading conditions. The target structures were reinforced concrete beams under lateral cyclic loading. So, AE events in the beams were mainly generated by the bending-type deformation. Unlike the laboratory experiments, the results obtained in this study were based on the in situ AE monitoring, where the absolute maximum load ever being experienced by the structure could not be estimated properly. The target was a plain concrete pier that deformed under the train-induced axial loading. The secondary AE events were generated by fretting at surfaces of existing cracks. Furthermore, there were some uncertainties in situ on noises caused by the train passage, etc. As reported in a recent paper Shiotani [9], efforts to remove such noises are in progress. Results of damage qualification with higher precision are in progress.

CONCLUSIONS

In order to apply the conventional AE technique to seismic diagnosis of railway structures, a new method is proposed to utilize the loads due to in-service trains. To verify its applicability, AE experiments of the model pile and in situ AE measurements under actual train traffic are conducted. The following conclusions are obtained.

1) The secondary AE events generated by fretting at surfaces of existing cracks are detectable due to train loading. AE events of large peak amplitudes are observed within the severely damaged zone.
2) Through a comparison between AE source locations obtained from 2-D and 3-D arrays in a model experiment, it is realized that the tendencies of the two arrays are quite similar. From the viewpoint of engineering practice, AE parameters measured by the 2-D AE sensor array on the footing surface are satisfactory enough.
3) A new index "RTRI ratio" is proposed instead of "Load ratio." By applying the two indices, RTRI ratio and Calm ratio, to in situ AE monitoring, it is demonstrated that the structural integrity of railway structures can be estimated economically.

Thus, the applicability of the new technique is demonstrated. With regard to future studies to upgrade the reliability of the technique, the characteristics of secondary AE in various types of structures will be investigated. Based on the results of these studies, a reference database for the seismic diagnosis of railway structures can be constructed.

REFERENCES

1. Ohtsu M. Simplified moment tensor analysis and unified decomposition of AE source. J. Geophys Res 1991;96:6211-6221.
2. Shiotani T, Sakaino N, Shigeishi M, Ohtsu M, Asai Y, and Hayashi T. AE Characteristics of full-scale concrete-pile under bending and shear load. Proc. 6th International Symposium on Acoustic Emission from Composite Materials, 1998;163-172.
3. Shiotani T, Shigeishi M, and Ohtsu M. Acoustic emission characteristics of concrete-piles. Construction and Buildings Materials. 1999;13:73-85.
4. Luo X, Haya H, INABA T, Shiotani T, Nakanishi Y. Experimental study on evaluation of breakage in foundations using train-induced acoustic emission. Proc. Structural Engineering World Congress 2002, Yokohama, Japan. 2002;T9-1-e-3(CD).

5. Luo X, Haya H, Inaba T, Shiotani T, Nakanishi Y. Study on the applicability of Train-induced secondary AE for nondestructive inspection of structures. Proc. 16th International AE Symposium, Tokushima, Japan. 2002;205-212.
6. Yuyama S, Ohtsu M. Acoustic emission evaluation in concrete. Acoustic Emission – Beyond the Millennium, Elsevier Science Ltd., 2000;187-213.
7. Recommended practice for in situ monitoring of concrete structures by acoustic emission. Japanese Society for Nondestructive Inspection (NDIS), NDIS 2421, 2000; (in Japanese).
8. Ohtsu M, Uchida M, Okamoto T, Yuyama S. Damage assessment of reinforced concrete beams qualified by acoustic emission. ACI Structural Journal 2002; 99(4):411-417.
9. Shiotani T, Nakanishi Y, Luo X, Haya H, Inaba T. Evaluation of structural integrity in railway structures using train-induced acoustic emission. Proc. Structural Faults + Repair 2003, Edinburgh, UK. CD-ROM.