Damage Evaluation of Railway Concrete Piers by Means of One-Dimensional AE Source Location

一次元 AE 源を利用した鉄道コンクリート橋脚の損傷評価

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[Summary]

Damage of railway concrete structures has been evaluated using acoustic emission technique. In the technique quantitative assessments of damage can be conducted from 3D AE activity induced by active live load with train passage. To obtain the 3D AE activity, however, it needs multiple AE sensors together with expensive multi-channel AE systems. In order to get the technique into widespread use, in this paper, one-dimensional AE sources which need at least two AE sensors are applied for the damage evaluation. After comparison was made with 3D results it was concluded that the damage estimated by one-dimensional AE sources accorded well with those of 3D, and therefore the damage assessment of railway concrete structures can be reasonably evaluated using one-dimensional AE sources.

[Key words] Railway structures, Damage assessment, Calm ratio, RTRI, 1D AE sources, Practicality

1. Introduction

Among infrastructures railway structures have been constructed earlier than others. At present, a variety of damages in the railway structures due to weathering, earthquake and so forth, are becoming increasingly manifest. The upper part, namely superstructures, of railway structures can be investigated with visual observation while for substructures as foundations, except for general behaviors' evaluation with natural frequency[1)2)], accurate or precise diagnosis, which is necessarily performed for designing repair or reinforcement, is difficult to examine with naked eyes. In order to obtain the damage characteristic of the lower part, the authors have been applied acoustic emission technique, and reported that using train-induced acoustic emission activity the damage of concrete structures can be reasonably evaluated. In this technique existent defects/damages contribute to the AE generation, namely the secondary AE activity. Only identified AE sources with a source location algorithm are considered as damage related AE activity. From the obtained AE sources such damage indices as Calm ratio, RTRI and *b*-value are followed to be calculated. Those damage indices resulted in showing the damage degree reasonably in comparison with actual damage condition. The final goal of this study is to come into wide spread use of the technique and establish the AE database in association with

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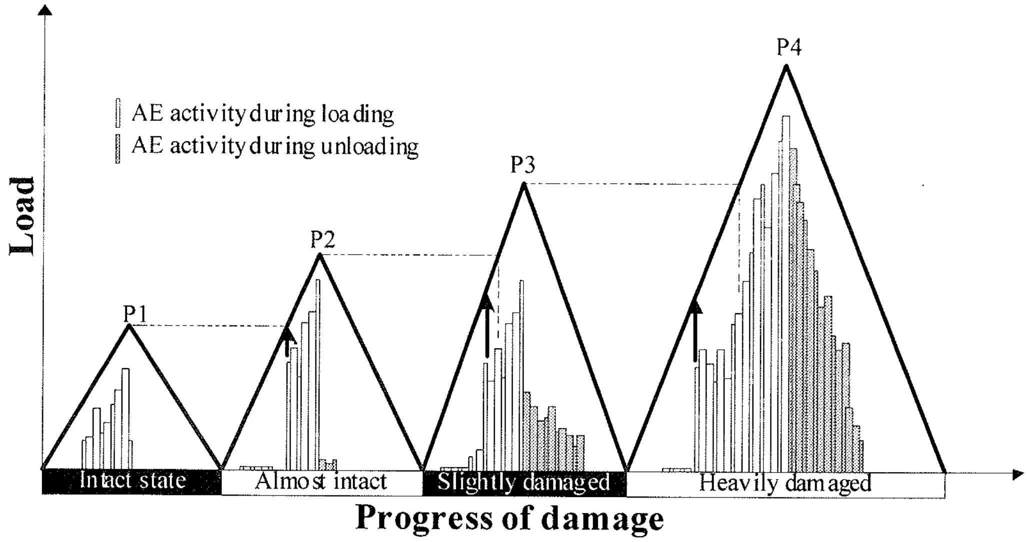


Fig. 1. Schematic representation of AE activity with damage progress.

damage degree. In the paper, a full-scale railway concrete pier is cyclically damaged with AE monitoring. To examine the potential of the simplest way of AE source identification, one-dimensional AE sources are used for determining those damage indices. The resulting damage is followed to be verified with 3D results, and the applicability of one-dimensional AE sources for the damage evaluation of concrete is discussed.

2. Damage Evaluation with AE Activity

In concrete subjected to incremental cyclic loads AE activity can be classified into four different levels with the damage progress as shown in Fig. 1, provided that the damage level can be shown as : intact; almost intact; slightly damage; and heavily damage. As shown in Fig. 1, during the second cyclic load, AEs would be generated at the load level of the maximum prior load. This phenomenon is referred to as Kaiser effect. In the subsequent third cyclic load, in which the material appears slightly damaged, the onset of AE appearance would be at a smaller level than previously. Decrease of effective areas against the external load or accumulation of microcracks within the material appear to play a significant role to show the behavior. Considering the AE activity to the stress level experienced, such damage-indices as Felicity ratio[3], CBI ratio[4], and Load ratio[5] have already been proposed. Also the AE activity during unloading processes is important for the damage characterization[6]. With damage evolution, not only the AE activity during uploading but that during unloading would become more intense. Accumulation of shear type of cracks seems to be attributed to this phenomenon. The ratio of the accumulated number of AE activity during unloading to that during a whole loading process, is refereed to as Calm ratio[5].

For the ratios mentioned previously, they may be difficult to apply for in-situ monitoring since the maximum stress of which the materials have experienced is not readily estimated. Thus, the authors have proposed a RTRI ratio[7] instead. The RTRI ratio is defined as in the following procedure: the onset of AE activity is estimated on the basis of whichever measured parameters as stress/load, strain/deformation and so forth, and the ratio is obtained as the ratio of the parameter's value corresponding to the onset of the AE activity to the maximum value (or peak value) during the whole inspection period, instead of the maximum stress of which the structure has experienced.

In addition to those indices, AE peak amplitudes are known to be closely associated with the fracture scale, namely degree of damage. Accordingly, the peak amplitude might be larger

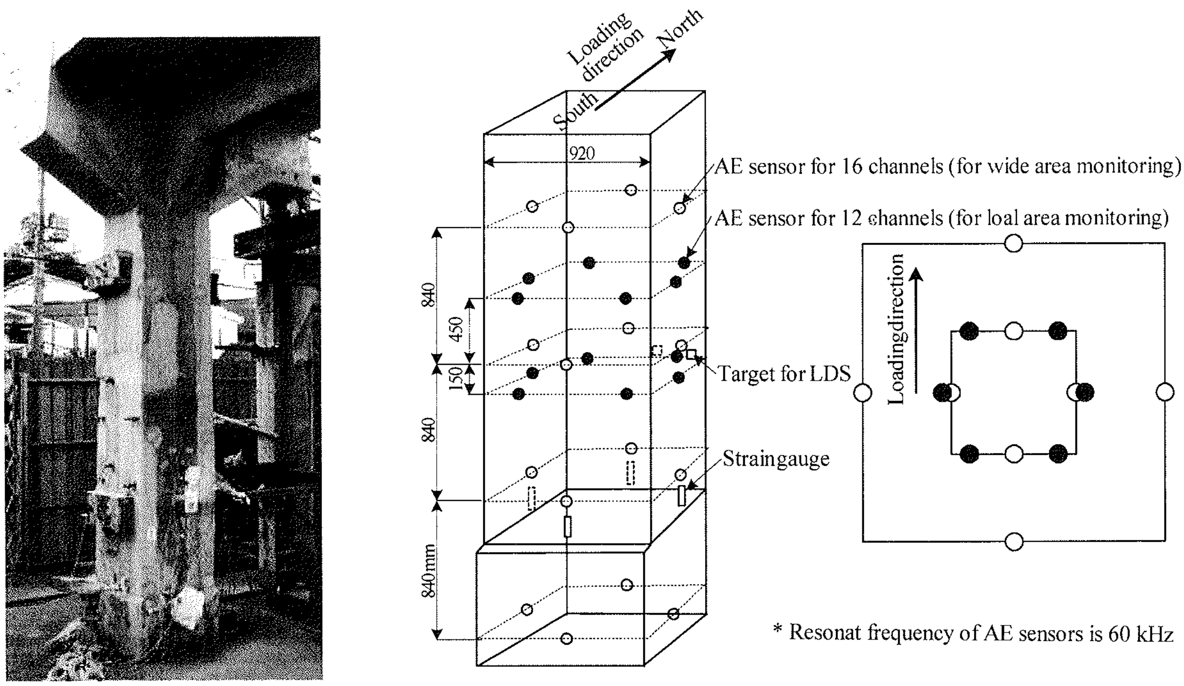


Fig. 2 Photo of measured railway RC pier (left) and sensor configuration (right).

with damage progress of fracture. It was found, however, that the damage evaluation was difficult from only the peak amplitude i.e., as fracture develops an apparent mechanical property of the structure would be worse as well, this causes a high attenuation rate of propagation medium, resulting in smaller energy of AE signals at the sensor even if the AE signals of large energy were produced at the source. Thus, in our study the peak amplitudes have been studied as their distributions, namely improved *b*-value (I*b*-value)[8)9)].

3. Cyclic fatigue test of a full-scale concrete pier

3.1 Experimental condition

To characterize the AE activity corresponding to damage evolution, a railway RC pier (5.87 m high), that was subsequently demolished after the test to alter underground structures (subways), was subjected to incremental cyclic loads. The cyclic test was controlled by lateral displacements from the north direction with such step-wise increments as 1, 2, 4, 8, 16, 32, 64, and 128 mm, where the load was applied by means of two hydraulic jacks (max cap. 392 kN). The pier tested and the sensor configuration are shown in Fig. 2. 16 AE sensors (60 kHz resonance) covered the whole area of the pier, while 12 AE sensors (60 kHz resonance) placed locally onto the area in which stress concentration was expected. The former detected was processed and recorded with DiSP AE system and the latter was led to Mistras AE system (both by Physical Acoustics Corp.). For other measurements, four strain gauges were attached to the lower four sides, and displacements on two sides, namely the north and the east side, are measured with laser displacement meter. To obtain the internal stress condition, strain gauges were also attached to rebars located in the four corners. A set of four strain gauges was each placed at three different heights: 400, 1800 and 3200 mm from the ground.

3.2 Results

Fig. 3 shows the applied load and the lateral displacement as a function of elapsed time where onset, peak, and the termination of each step are indicated with solid lines, broken lines, and solid lines, in turn. The load variation corresponded well to the response of lateral displacement up to 15k s, however from 16k s showing the step of 128 mm in lateral displacement; the load decreased slightly whereas the displacement was kept constant, implyig the fracture either in the pier or

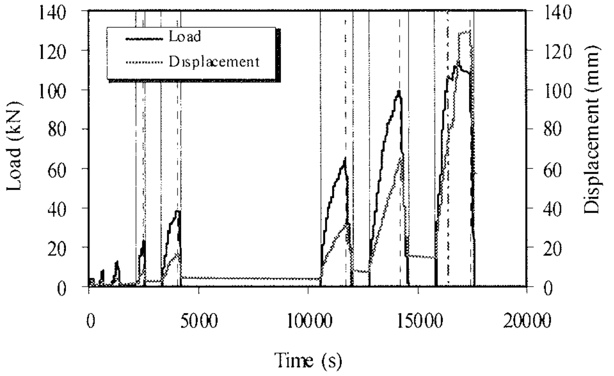


Fig. 3 Load applied and lateral displacement.

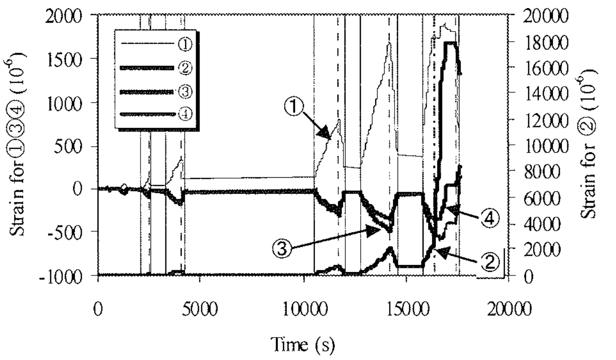


Fig. 4 Rebar strains at 400 mm high.

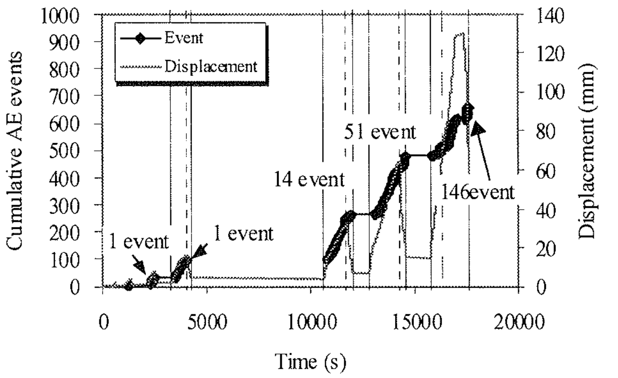
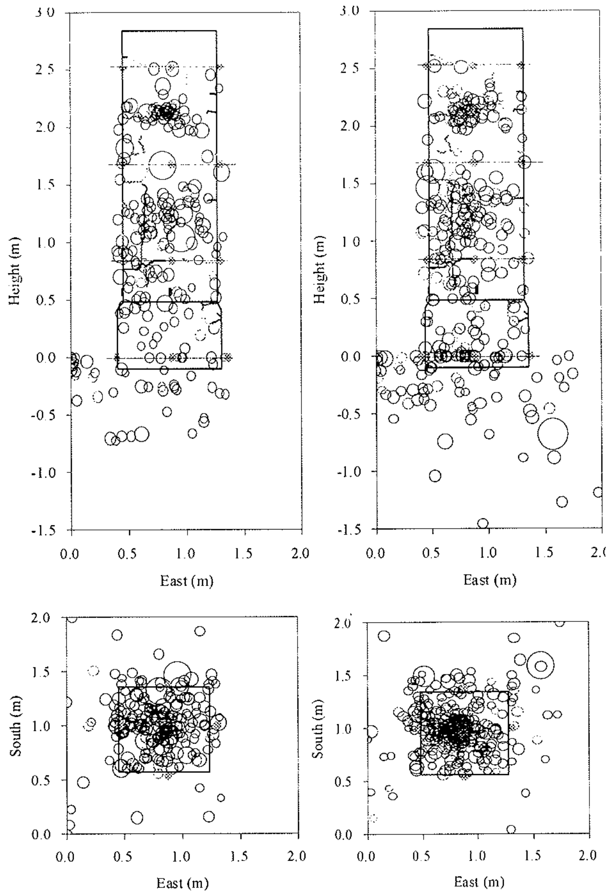


Fig. 5 Cumulative AE and lateral displacement. The number of event shows one obtained during the reduction of displacement.

the supporting ground.

Fig. 4 shows measured strains in the rebar at a height of 400 mm, where the strains named 1 and 2 were installed in the south and those named 3 and 4 were in the north. Again the displacement was given from the north. As shown in the figure, both strains of 3 and 4 showed negative values suggesting compression status, whereas the strains of 1 and 2 appeared positive values showing tensile status. These trends agreed well to the expected stress condition. In especial for strain 2 showing the value corresponding to the right vertical axis, a sudden jump is found at 16350s denoted by a chain line. Strength tests of rebar, additionally conducted, showed the yield point of 1500-1600 μ and the tensile strength of 2200-2300 μ. The strain at 16350s stood at 2274 μ already, suggesting that the rebar attached by strain 2 had yielded during the previous step namely 64 mm in the displacement, and the sudden jump emerged at 16350s demonstrated the time when the stress had reached the maximum tensile strength.



(a) 32 mm (b) 64 mm

Fig. 6 Three-dimensional source locations.

Fig. 5 shows the cumulative AE events and the lateral displacement with respect to elapsed time. The AE events are defined as located AE sources in three dimensions with a source location algorithm. The AE events started to be active from 16 mm displacement (around 4k s), and the AE activity during unloading (or decrease of displacement) was intensively observed from 32 mm displacement (11k s). Using the onset of

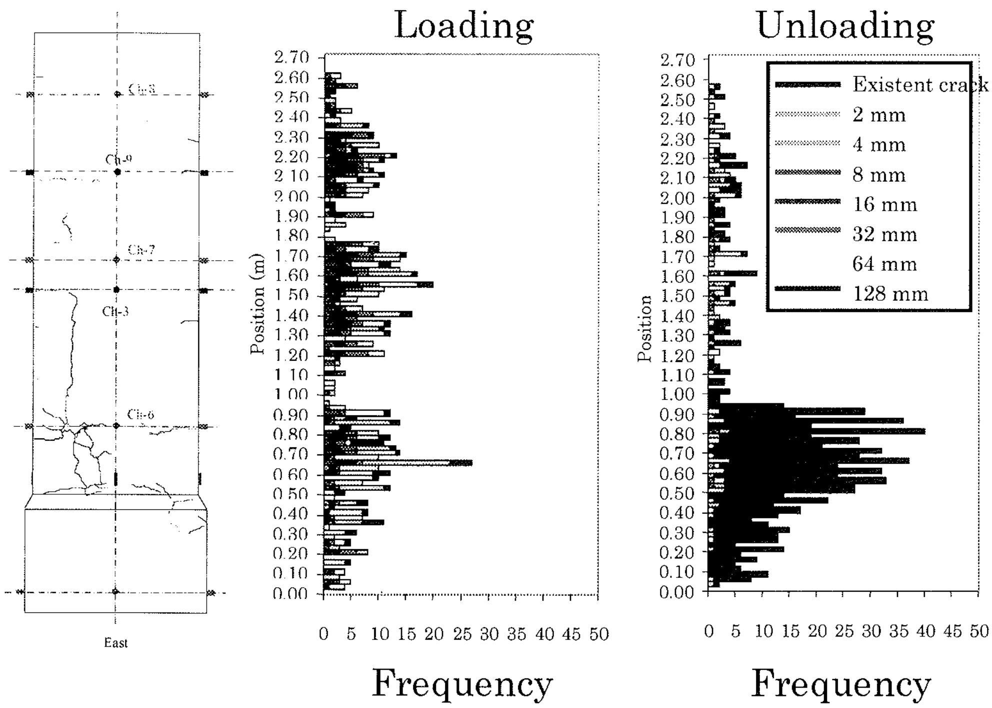


Fig. 7 One-dimensional source locations.

AE activity and the accumulated numbers of AE events during unloading to those during a whole loading process in every stage, RTRI and Calm ratio are calculated, respectively.

Fig. 6 shows 3D AE sources on the eastern surface for 32 mm (a) and 64 mm (b) of lateral displacement. The crack trace is also drawn in the chart. As along the figure, AE sources at around 1.0 m height, corresponding to the vertical crack observed, were started to be active from 32 mm displacement. AE sources can be found in the foundation as well (see below 0.0 m).

Fig. 7 shows 1D AE sources on the eastern surface. The 1D AE sources were obtained using the sensor array for wide area monitoring (see Fig. 1). In the figure, the crack trace and AE events are drawn at every step-wise lateral displacement with different colors. AE sources both in upper and intermediate areas started to appear from 8 mm displacement (see the red). Specifically numerous AE sources were observed during 64 mm lateral displacement. AE sources under unloading are actively generated during 128 mm lateral displacement and the locations of AE sources are well identical to those of observed cracks.

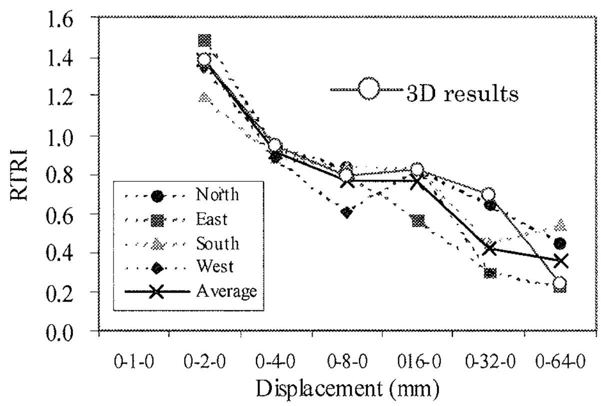


Fig. 8 RTRI obtained both from 1D and 3D AE.

Fig. 8 shows RTRI on each surface obtained from 3D AE sources as well as 1D AE sources. It is noted that since the RTRI obtained in each displacement's step evaluated the damage condition in the previous stage, the horizontal axis can only show the damage up to 64 mm i.e., the RTRI obtained on the basis of 128 mm displacement shows the actual damage during 64 mm displacement. In the figure, remarkable decrease can be found during 32 mm displacement. Regarding the trend of 3D and 1D, both showed the same variation as a function of given displacement, irrespective to the direction of surface. This suggests that one-dimensional

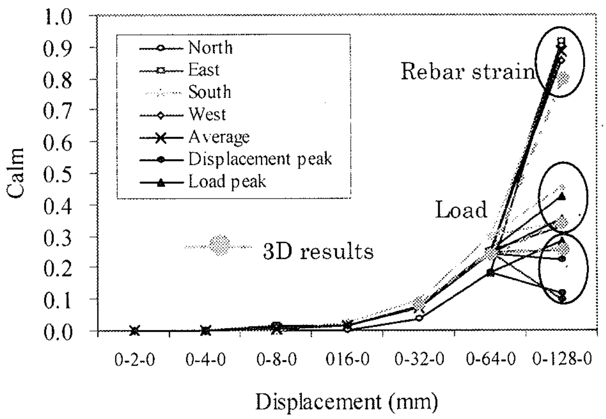


Fig. 9 Calm ratio obtained both from 1D and 3D AE.

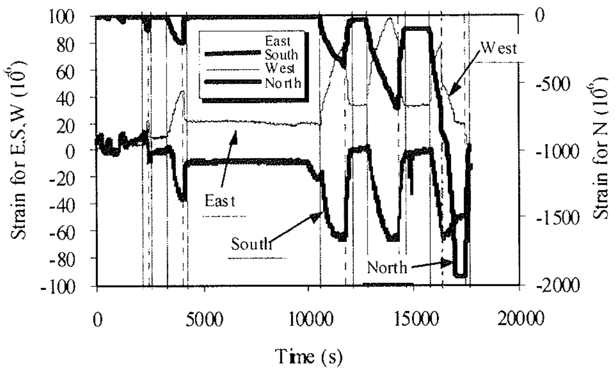


Fig. 10 Concrete strains on different surfaces.

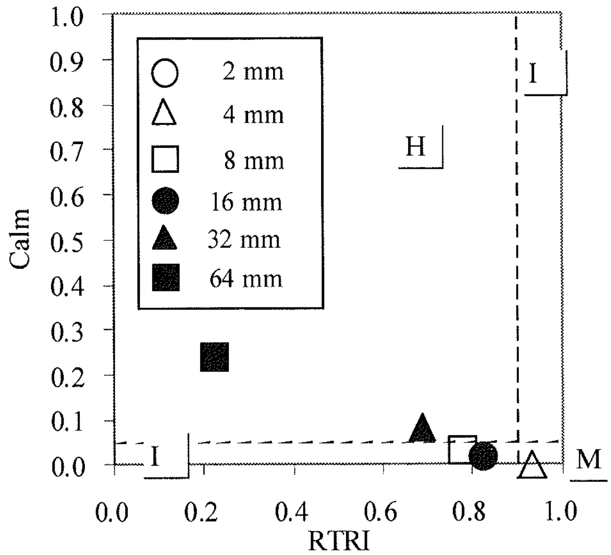


Fig. 11 Relations between Calm ratio and RTR.I

sources can provide the same useful damage information as those of 3D.

Fig. 9 shows the same result as Fig. 8 but for Calm ratio. Besides the RTRI, the Calm ratio can evaluate the damage up to during 128 mm displacement. It is noted in the chart that the Calm ratios during 128 mm lateral displacement were calculated from three different behaviors: lateral displacement; applied load; and rebar strain. From the figure, the Calm ratio became active from 32 mm lateral displacement and further increase was found in 64 mm. This trend agreed well to that of RTRI. However for 128 mm displacement, the Calm ratio gives different values in accordance with employed structural behavior i.e, considerable increase was found in rebar, a slight increase for load and almost constant for displacement. The parameter which can evaluate the damage condition properly will be followed to discuss.

3.3 Discussion

3.3.1 Effective structural behaviors in association with AE activity

As shown in Figure 4, one of the rebar showed to reach the tensile strength during 128 mm lateral displacement, while for the yield point of the rebar, the rebar was evidently yielded during the previous displacement stage (64 mm). From those findings, the internal damage of the pier appeared to be developed intensively from the lateral displacement of 64 mm. Figure 10 shows the surface concrete strains of the pier on all of the directions. In sound or minor damage condition, the strain's variation would follow that of applied deformation, however, the both surface strains on the east and the west showed decrease even during the up-deformation process (see 64 mm displacement i.e., between 13k s and 15k s), implying that the pier had already lost the bearing capacity. Furthermore from the crack observation, distinct shear type of cracks could not be developed in the pier through the test. Accordingly, the damage evolution of the pier seemed to be terminated during the 64 mm displacement and further development of the damage would not be introduced by the subsequent stage, namely 128 mm lateral displacement. Considering those findings, the Calm ratio on the basis of the rebar-strain thought to overestimate the damage (see Figure 9), and thus the Calm ratio based on either the load or the displacement could reasonably evaluate the actual damage.

3.3.2 Damage quantification of AE damage indices

Fig. 11 shows the chart consisting of Calm ratio and RTRI. In the map, damage criteria reported [10] are overlaid with broken lines. H, I and M in the chart show the damage level: heavily, intermediate; and minor damage, respectively. As mentioned, since the RTRI during 128 mm could not be obtained, the plots up to 64 mm in the lateral displacement are shown. Using the reported criteria, the minor damage was estimated when 4 mm displacement was given, the intermediate damages were both evaluated during 8 and 16 mm, and from 32 mm heavily damage was assumed in the pier. Conclusively, these evaluations were in good accordance with other findings as well as actual damage.

4. Conclusions

A full-scale railway concrete pier was cyclically damaged along with AE monitoring. Main findings obtained through the test are as follows:

1) Damage indices obtained from AE activity in combination with structural behaviors showed a good agreement with actual damage. Among structural behaviors, internal strains attached rebar overestimated the actual damage. The applied load or the deformation would be appropriate when evaluating the general structural integrity quantitatively.

2) Since the aforementioned issue was both found in 3D and 1D AE sources, it can be concluded that structural integrity of railway concrete structures is potentially evaluated by using the simplest array of AE sensors, namely 1D AE sources.

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【要旨】

AE法による鉄道構造物の損傷診断手法に関して，これまで三次元AE源に基づく定量的損傷診断手法を確立してきた。しかし，三次元AE源による損傷診断法は，数多くのAEセンサ，多チャンネル対応のAE計測システム，ならびに三次元AE源標定プログラムなどが必要となり，実用手法としての限界が示唆されていた。そこで本論文では，簡便な一次元AE標定法および，得られる一次元AE源を利用した損傷推定の可能性を検討するため“実鉄道橋脚の繰返し載荷試験”に同手法を適用し，損傷の進行にともなう一次元AE源より，損傷指標を算出，三次元AE源による同結果，目視き裂観察や変形挙動より推定される損傷程度と比較検討し，一次元AE源の実用性を検討した。その結果，一次元AE源より求めた損傷診断結果は三次元AE源より得た同結果と大過なく構造物の損傷程度を定量的に評価可能であることが明らかとなった。これらの成果により，鉄道など交通荷重が見込めるコンクリート構造物にAE法を適用し，一次元AE源より損傷指標を算出することにより定量的に構造物の損傷が評価可能となった。

【キーワード】　鉄道構造物，損傷評価，Calm比，RTRI，一次元AE源，実用化