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Behavior analysis of an integrated column by multiple steel pipes using monitoring measurement

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ABSTRACT: Monitoring measurements have been conducted on an integrated columns by multiple steel pipe applied to actual bridges to verify that the pier behave according to the concept assumed in the design. In this measurement, the response is measured for both ordinary conditions and small earthquake conditions. This study proposes a method for verifying the performance of an integrated column by multiple steel pipe using the measured data, and evaluated the performance of the piers using the measured data obtained so far. For ordinary conditions, the measured data were used to verify that the behavior of the piers was as assumed in the design, and for small earthquake conditions, the validity of the analysis model was verified by reproduction analysis using observed waveforms.

1 INTRODUCTION

In the Hanshin-Awaji Earthquake of 1995, piers collapsed or were severely damaged, and it took a long time to restore them. Therefore, Hanshin Expressway developed an integrated column by multiple steel pipes that have higher earthquake resistance than reinforced concrete piers or steel piers, and can be restored easily and quickly.

An integrated column by multiple steel pipes is a single column composed of four steel pipes connected by shear links that incorporate shear panels with historical damping functions. In this structure, vertical loads such as dead and live loads are supported by steel pipes, and horizontal loads such as seismic forces are resisted by shear links. In the event of Level2 earthquake, which is specified in the Specifications for Highway Bridges, Part V Seismic Design [1], the damage is concentrated in the shear panels so that the steel pipes remain sound, allowing vehicles to pass through quickly after the earthquake. In addition, during emergency inspections after an earthquake, the shear panels are damaged before other members, thus limiting the number of members to be inspected. Furthermore, in the event of damage that requires restoration, performance can be restored simply by replacing the shear panels, thereby contributing to the reduction of seismic life-cycle costs.

These concepts have been verified through analysis and experimentation and applied to actual structures such as the Ebie Junction and Nishi-Senba Junction on the Hanshin Expressway. However, it has not been verified whether the columns behave according to the concepts in the actual structure. In response, a monitoring plan based on the structural characteristics of integrated column by multiple steel pipes was developed, and the behavior of the actual bridge has been measured since April 2021.

In this study, we proposed a method for evaluating the performance of integrated columns by multiple steel pipes using the measured data. Furthermore, an example of the performance evaluation of integrated column by multiple steel pipes is shown using the data measured so far.

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2 TARGET STRUCTURE AND MEASUREMENT

2.1 *Target structure*

The integrated column by multiple steel pipes targeted for evaluation was applied to the PD4 of the D-ramp (1), which is the crossing line from the Kobe Route to the Yodogawa-sagan Route at the Ebie JCT. A plan view of the D-ramp (1) is shown in Figure 1 (processed from an aerial photograph). The D-ramp (1) bridge including PD4 is a 5-span continuous steel box girder bridge with orthotropic steel deck between PD1 and PD5 (92.7 + 60.5 + 50.5 + 49.0 + 78.9 = 331.6 m). The end bearings are movable at PD1 and fixed at PD5, and the piers between them are rigidly connected. The height from the ground surface to the superstructure of PD4 is about 30 m, the highest of all the piers on the D-ramp (1), and is a location where the characteristics of the integrated column by multiple steel pipes can be fully utilized. The piers other than PD4 are conventional rectangular section steel piers.

A structural drawing of the PD4 is shown in Figure 2. PD4 consist of four steel pipes, connected by shear links in four cross-sections. A caisson foundation with a diameter of 7000 mm was adopted due to site constraints, and diameter of steel pipe and shear link dimension were determined from the caisson diameter. From the top of the caisson to a height of 13 m, including the second shear link from the bottom, the steel pipes are filled with concrete filling as in the case of conventional steel piers.

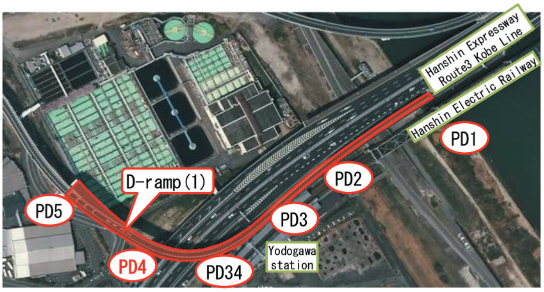


Figure 1. Bridge plan view of D-ramp (1).

2.2 *Measurement items*

The measurements based on the monitoring plan have been taken since April 2021. Figure 3 shows the locations of the measurement equipment and the names of the measuring points, and Figure 4 shows the installation status of the equipment.

The measurement cross section of the strain gauges was set at the base of the piers at 100 mm from the protective concrete, and at the top of the piers at a minimum distance of 100 mm from the fillet between the superstructure and the piers to avoid the effect of the stress concentration. Strain gauges were attached to each steel pipe at four points in the longitudinal and transverse direction and at 16 points per cross-section, and the direction of measurement was vertical direction. Accelerometers were set 100 mm below the ground surface and above each shear link of Pipe B, for a total of five locations. The measurement directions were the longitudinal direction, the transverse direction, and the vertical direction regarding the integrated column by multiple steel pipes.

Table 1 shows the frequency and duration of measurements. The effect of live load is measured once a year for about three days in spring, when traffic is average, and the effect of wind load is measured once a year for about one days when strong winds, such as typhoons. The effect of temperature load is affected by atmospheric temperature, so it is measured four times a year for about one week in spring, summer, fall, and winter. In the case of an earthquake, a trigger is determined by an accelerometer installed at the base of the steel pipe, and measurement is started when a certain level of acceleration occurs. In this measurement, the threshold value is set to 1 gal so that data can be obtained even for small seismic motions.

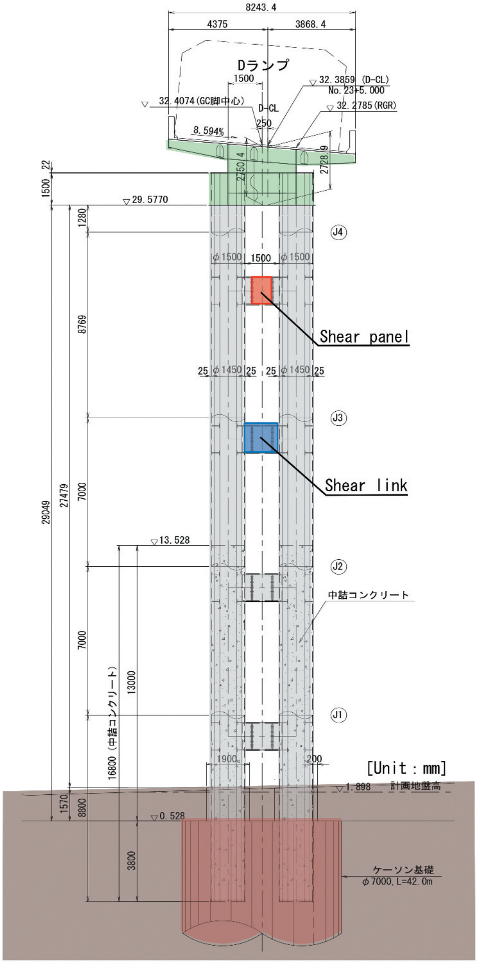


Figure 2. Structural drawing of PD4.

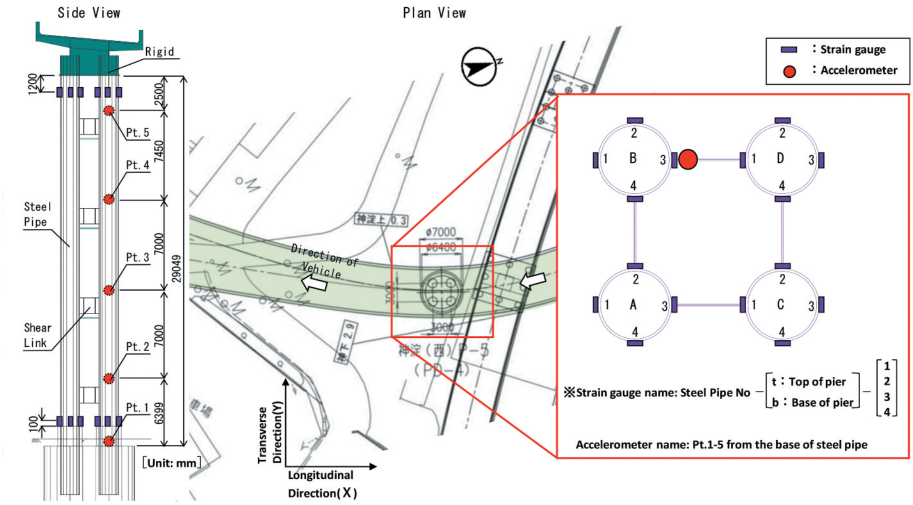
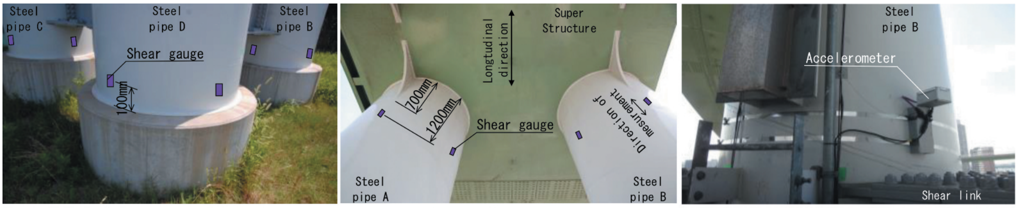


Figure 3. Locations of the measurement equipment and names of the measuring points.



(a) Strain gauge (Base) (b) Strain gauge (Top) (c) Accelerometer

Figure 4. Installation status of the equipment.

Table 1. Interval and duration of measurements.

Situation		Number of times and timing of measurements	Measurement Period
Ordinary Condition	Live Load	Once a year(Spring)	About 3 days
	Wind Load	Once a year(typhoon)	About 1 days
	Temperature Change	Four times a year (Spring・Summer・fall・winter)	About 1 week
Earthquake Condition	Level 1 Earthquake	At the time of earthquake	300 seconds after earthquake
	Level 2 Earthquake		
	Over Level 2 Earthquake		

3 PROPOSAL FOR PERFORMANCE EVALUATION USING MONITORING RESULTS

Figure 5 shows the performance evaluation flow using the measurement results. In this flow, when the performance can be evaluated directly from the measurements, the performance is evaluated by organizing and analyzing the measurement data. On the other hand, when the performance cannot be evaluated directly from the measurements, the performance is evaluated indirectly by reproducing the behavior of the structure through analysis. When using analysis, the reproducibility of the model is first verified by comparing the responses at the measured positions in the analytical model with the measured actions. If there is a discrepancy between the measurements and the analysis results, the analytical model is reviewed after analyzing the factors that may cause the discrepancy, and the performance of the integrated column by multiple steel pipes is evaluated using the analytical model whose reproducibility is verified. Here, we show an example of analysis based on these two evaluation methods.

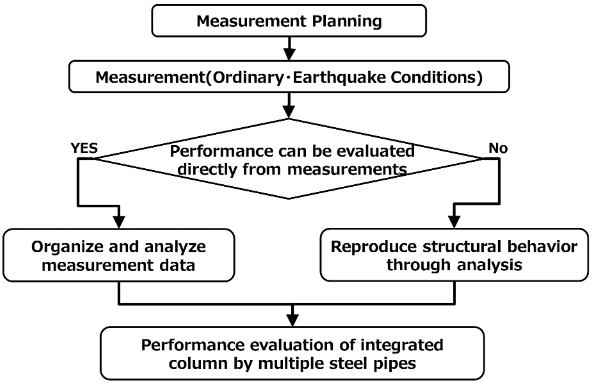


Figure 5. The flow of the proposed performance evaluation.

3.1 *Performance evaluation using measured data*

The following is an example of performance evaluation based on measured data for behavior under temperature change. The Integrated column by multiple steel pipes is assumed to “Four steel pipes resist horizontal loads as a single column”. In contrast, since it is suspected that each steel pipe resists discretely, the behavior was analyzed using measured data during temperature change.

Among the measured data, the lowest outside temperature was 3.6°C at 5:38 on January 23, 2022, and the highest outside temperature was 39.1°C at 16:04 on July 23, 2022. Figure 6 shows the amount of change in pipe strain resulting from this temperature change (+35.5°C). Focusing on the strain at the base of steel pipes, the strain at the outer transverse direction of pipes B and D (B-b-2 and D-b-2) changed by +617 με and +649 με, respectively, and the strain at the outer transverse direction of pipes A and C (A-b-4 and C-b-4) changed by -350 με and -524 με, respectively. This is considered to capture the behavior of PD4 being pushed outward out of the curve due to the extension of the superstructure caused by the +35.5°C temperature change. And the strain at the outermost edge in the direction of extrusion is the maximum and minimum, respectively. In this manner the strain distribution behaves like a single column, so it was confirmed that the four steel pipes resist as a single column. On the other hand, the strain at the top of the steel pipes did not show the same tendency as that at the base of the pipes. This is because the strain at the top of the steel pipes includes not only the strain caused by the horizontal behavior due to temperature change but also the vertical strain caused by the live load.

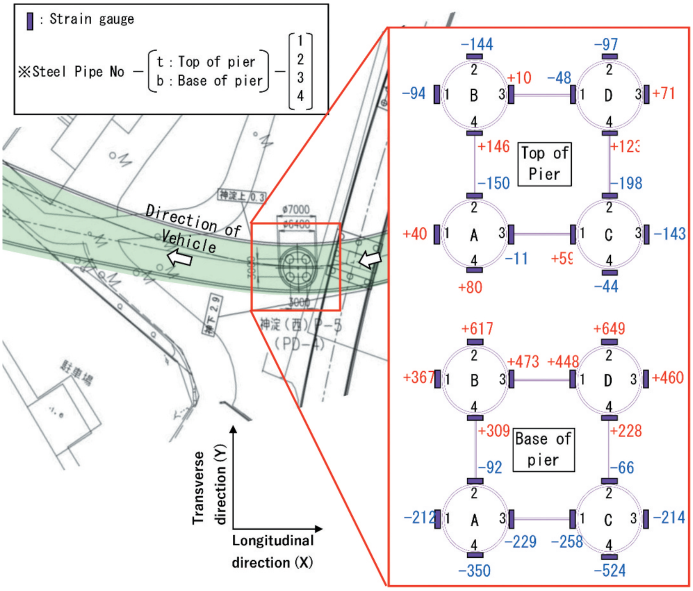


Figure 6. Change in steel pipe strain with temperature change (+35.5°C).

3.2 *Performance evaluation using analysis*

At 23:34 on March 31, 2022, a magnitude M4.3 earthquake occurred with its epicenter in the southern part of Kyoto Prefecture, recording a maximum intensity of 4 near Kameoka City, Fushimi-ku, Kyoto Prefecture. The seismic intensity of 2 was observed in Fukushima-ku, Osaka City, where Ebie JCT is located, and seismic observation data was obtained with the installed measurement equipment.

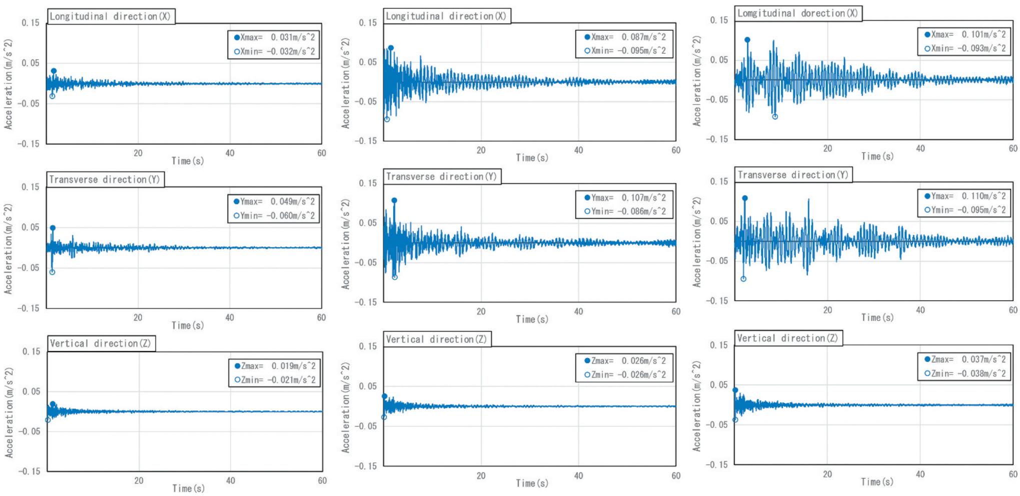
The integrated column by multiple steel pipes is designed to behave elastically in the event of small to medium-sized earthquakes. However, this behavior is difficult to evaluate from the limited number of measurement points shown in Figure 4 and from visual observation, so it is necessary to reproduce the behavior of the integrated column by multiple steel pipes during an earthquake by time history response analysis and to evaluate the behavior using the analytical model. On the other hand, it has been reported that the nonlinear dynamic analysis models generally used in seismic design do not match the behavior of small- and medium-scale earthquakes. Therefore, since the acceleration during the earthquake could be measured, although it was a small earthquake, we first used this observation data to confirm the reproducibility of the behavior using a general nonlinear dynamic analysis model.

3.2.1 *Observation waveform*

The time history waveforms of the acceleration at the measured points and the acceleration response spectra with 5% damping are shown in Figures 7 and 8. The points at the base of the pier (Pt. 1), the second shear link from the base (Pt. 3), and the fourth shear link from the base (Pt. 5) are shown here as representative points among the accelerometers shown in Figure 6.

3.2.2 *Modeling of target bridges*

The analytical model was a fiber model that can account for biaxial bending moments, axial force variation, and geometric nonlinearity for the entire system of D-ramp (1). Figure 9 shows the 3-D frame model of the entire bridge system and the modeling method for the integrated column by multiple steel pipes. The fiber elements of the steel pipe cross section of the PD4 piers were divided into 64 sections in the circumferential direction and 2 sections in the thickness direction.



(a) Pt.1 (b) Pt.3 (c) Pt.5

Figure 7. Observed acceleration response time history waveform.

The function separating type bridge supporting of the PD1 are modeled with linear spring elements in the longitudinal and transverse directions.

Since the purpose of this study is to analyze the behavior of the actual bridge, the yield strength of each member is based on the actual strength. For the PD4 piers, the yield strength was set based on the material tests, σ_y = 377 N/mm^2 for steel pipes (standard value: σ_y = 315 N/mm^2) and σ_y = 229 N/mm^2 for shear panels (standard value: σ_y = 225 N/mm^2). The yield strength of the pier members, except for the PD4 piers, was the average value of the statistical data, based on the results of the statistical data survey.

3.2.3 *Reproducibility of small earthquakes*

A dynamic analysis was conducted using the acceleration measured at Pt.1 as the input earthquake motion to confirm the reproducibility of the acceleration measured at Pt.3, Pt.4, and

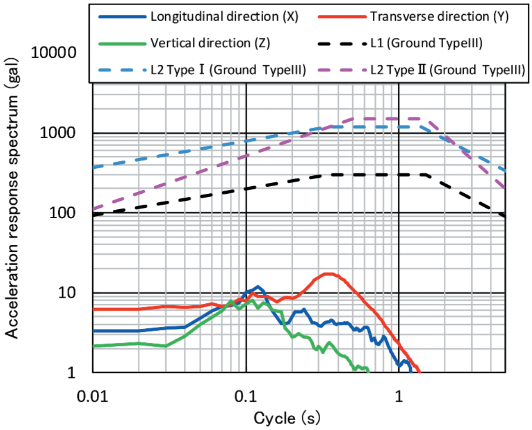


Figure 8. Acceleration response spectra of observed waveform (Pt.1).

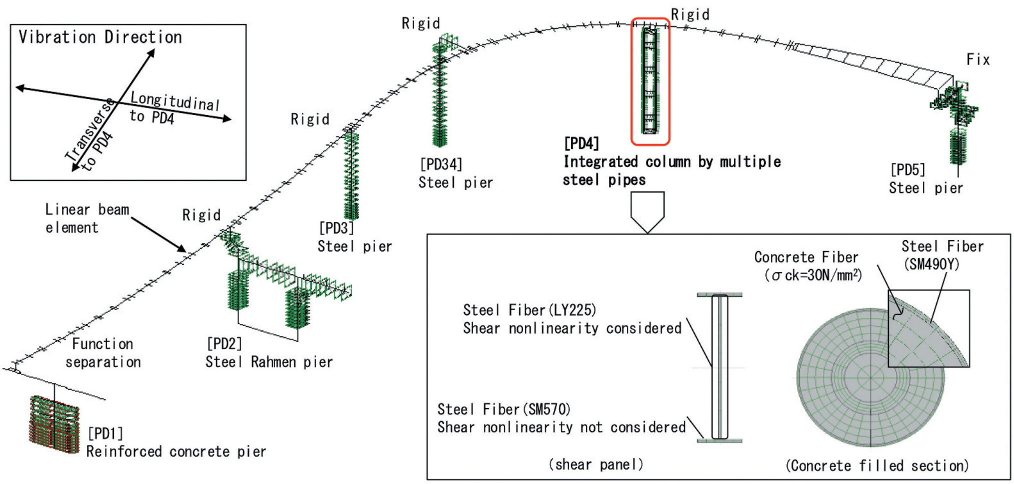
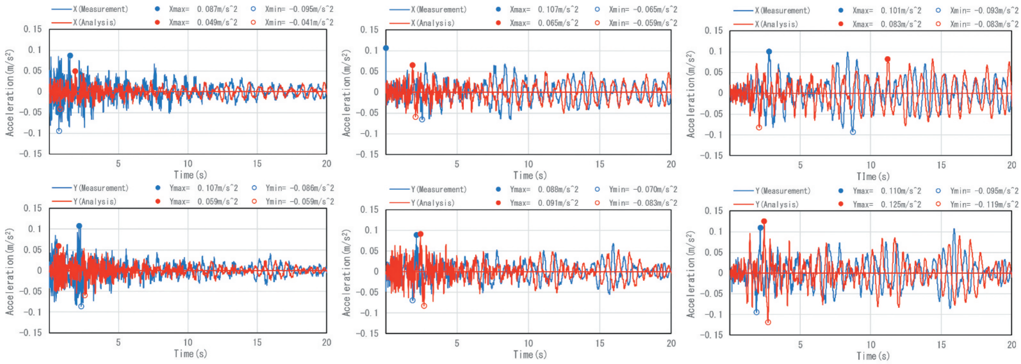


Figure 9. Analytical model of D-ramp (1) and the integrated column by multiple steel pipes.

Pt.5. Pt.1 is an accelerometer installed at the base of the PD4 pier, and this acceleration is the response acceleration waveform affected by the seismic response of the foundation structure and the interaction between the foundation structure and the ground. To use this response acceleration waveform as the input seismic motion, the boundary condition of the analytical model was fixed at the base of the piers, and the seismic motion was applied to the base of the pier. The earthquake motion was applied to the PD4 in three directions simultaneously: longitudinal, transverse, and vertical, in accordance with the direction of measurement. The general-purpose structural analysis program SeanFEM was used for the analysis.

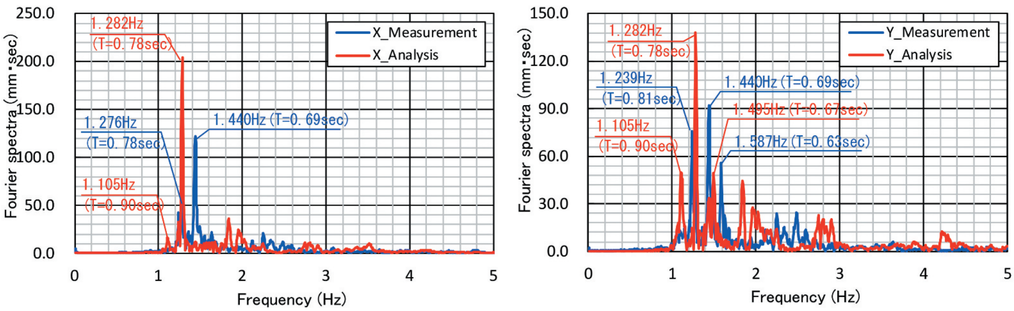
Figure 10 shows a comparison of the observed and analyzed acceleration response time history waveforms in the longitudinal and transverse direction for Pt. 3, Pt. 4, and Pt. 5. In terms of the maximum acceleration, the observed waveform tends to be larger than the analytical result at Pt. 3, while the results at Pt. 4 and Pt. 5 are almost identical. However the acceleration response time history waveforms did not match, and there were some points where they were in opposite phase.

Figure 11 shows the Fourier spectrum of Pt. 5. Focusing on the lowest dominant frequency in the longitudinal direction, the observed waveform is 1.28 Hz, while the analytical result is 1.11 Hz. Similarly, in the transverse direction, the analytical results show a shift to the low frequency side (long period side) compared to the observed waveform. This is because the stiffness of the superstructure of the analytical model does not take into account the stiffness of the concrete balustrade and pavement, and the stiffness of the concrete balustrade, especially when the width is narrow and the girder height is low, as in the case of a ramp bridge, is considered to have a large impact. In addition, because this is a curved bridge, the out-of-plane stiffness of the concrete balustrade is expected to affect both the longitudinal and transverse directions.



(a) Pt.3 (b) Pt.4 (c) Pt.5

Figure 10. Comparison of observed and analyzed acceleration response time history waveforms (Upper row: bridge longitudinal direction, lower row: transverse direction).



(a) Longitudinal direction (b) Transverse direction

Figure 11. Comparison of Fourier spectra of observed and analyzed waveforms (Pt. 5).

Thus, it is necessary to check the reproducibility of the behavior of the measured positions using the analytical model, and if the measured values differ from the analytical values, the analytical model should be updated after analyzing the factors causing the discrepancy. It is effective to evaluate items that are difficult to evaluate from measurement data and visual observation, such as whether the entire steel pipe and all shear panels behave elastically, using an analytical model whose reproducibility has been confirmed.

4 CONCLUSION

This study proposes a method for evaluating the performance of integrated columns by multiple steel pipes using measurement data and an example of performance evaluation using the measurements obtained so far. The findings are as follows.

(1) An evaluation flow was proposed for cases in which the performance can be directly evaluated from the measurements, and for cases in which it cannot.

(2) As an example of the case where direct evaluation is possible from the measurements, the strain at the base of the steel pipe measured when the temperature changes was analyzed, and it was confirmed that the four steel pipes resisted as a single column as assumed in the design.
(3) As an example of a case that cannot be directly evaluated from the measurements, the measured acceleration during a small earthquake was used to verify the reproducibility of a general nonlinear dynamic analysis model. As an example of a case that cannot be directly evaluated from the measurements, the measured acceleration during a small earthquake was used to verify the reproducibility of a general nonlinear dynamic analysis model. The results showed that the analysis tended to be long-period in both the longitudinal and the transverse direction. This is thought to be due to the stiffness of the concrete balustrade, which is not considered in the analytical model.

In the future, it is necessary to analyze the causes of the discrepancy between the actual behavior and the behavior of the analytical model, and to evaluate the performance with a matched model. It is also necessary to evaluate the performance of the integrated column by multiple steel pipes piers when subjected to larger actions, using the measurement data obtained.

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REFERENCES

[1] Japan Road Association: Specifications for Highway Bridges, Part V Seismic Design, 2017.