Damage Mechanism of the Nakagawa Water-pipe Bridge during the 2011 off the Pacific Coast of Tohoku Earthquake

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SUMMARY:
Since the 1995 Kobe earthquake seismic countermeasures of the water-pipe bridge has been promoted adopting bridge restrainers and lateral moving stopper devices so far in Japan. Several water-pipe bridges, however, had damage during the 2011 off the Pacific coast of Tohoku earthquake in March 2011.This study focuses on one of the damaged bridges, called the Nakagawa water-pipe bridge. This bridge is the large cable-stayed truss bridge of two parallel pipelines with 900 mm in diameter, located in Mito City, Ibaraki Prefecture. The expansion joints between the cable-stayed bridge and side single truss bridge was pulled out and rotated and the bearing were removed. Microtremor test and the three-dimensional FEM analysis were carried out in order to make clear the damage mechanism of the water-pipe bridge.

Keywords: Water-pipe bridge, Tohoku earthquake, microtremor test, eigenvalue analysis

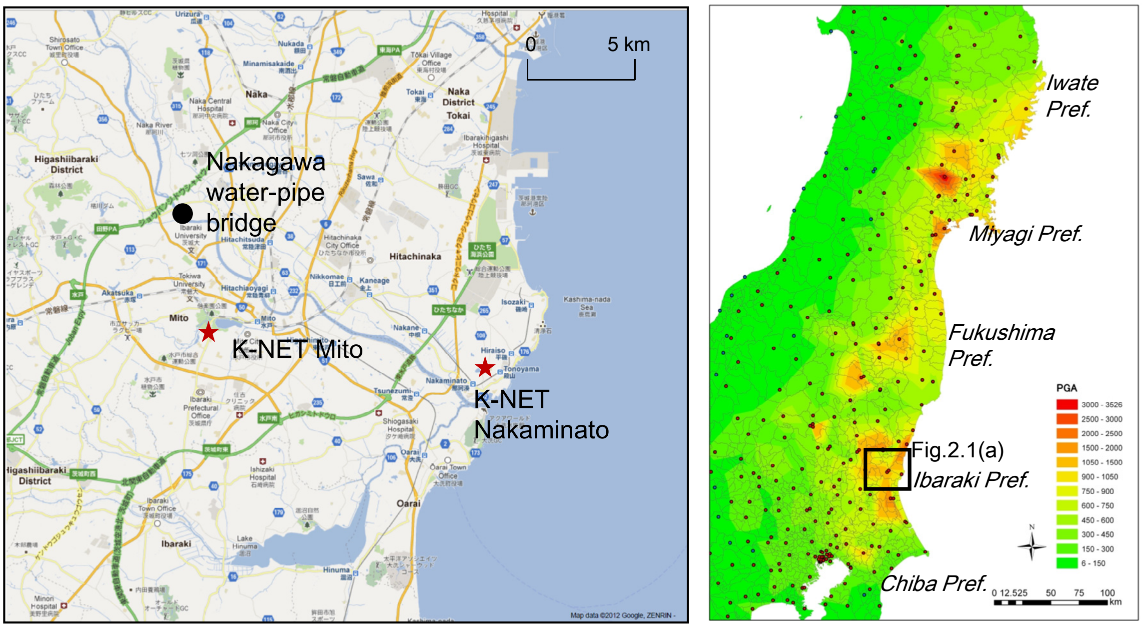
1. INTRODUCTION

Damage to large-diameter water pipeline during an earthquake would induce water-supply cut in the large area. Water-pipe bridge supporting such large-diameter pipeline plays an important role in water-supply facilities. However, the seismic countermeasure of the water-pipe bridge have not been implemented well compared with roadway and railway bridges, and studies on the seismic behavior of water-pipe bridge are also less than the others. While the strong ground motion was experienced during the 1995 Kobe earthquake and the design ground motion was revised to higher level, several large water-pipe bridges had damage during the 2011 off the Pacific coast of Tohoku earthquake. The seismic ground motion induced by this inter-plate earthquake has different characteristics from the design response spectrum. For the better preparation against giant inter-plate earthquake in the future, it is necessary to clarify the damage mechanism of water-pipe bridges in this earthquake. This study focuses on the one of damaged water-pipe bridges, called the Nakagawa water-pipe bridge, and analyzes its damage mechanism based on the microtremor observation and the FEM analysis of a three-dimensional mathematical model.

2. OUTLINE OF DAMAGE TO THE NAKAGAWA WATER-PIPE BRIDGE

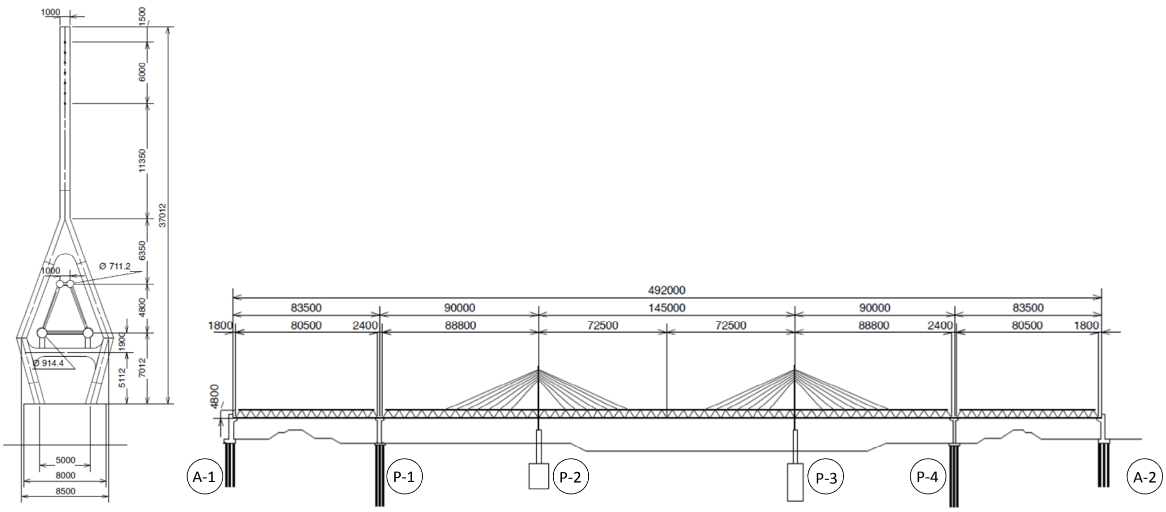
The Nakagawa water-pipe bridge is located in Mito City, Ibaraki Prefecture as shown in Fig. 2.1(a). The bridge crosses over the Naka River. As shown in Fig. 2.1(b), peak ground acceleration recorded in the K-NET strong-motion seismograph networks (NIED) was high in Ibaraki Prefecture. Strong ground motion contains high frequency components besides the fault mechanism of inter-plate earthquake was expected to provoke long-period ground motion. The nearest seismograph was the K-NET Mito, 5 km away from the bridge. Its PGA was recorded 786 cm/s^2 in NS component and 779 cm/s^2 in EW component.

The bridge was constructed in 1994. The main bridge is connected to the side bridges in both sides. The design of main bridge is three-span cable-stayed truss bridge, and the design of both side bridges is single-span truss bridge. The total of bridge length is 492 m and the center span of main bridge is 145 m as shown in Fig. 2.2. Two steel water pipelines of 900 mm in diameter are laid in parallel as the lower chord member of the truss. This water-pipe bridge was designed based on the prior-seismic design specification of the Japan Water Works Association in version 1979 (JWWA, 1979). No seismic countermeasures were adopted at the time of the earthquake.



(a) Mito area (b) PGA distribution of K-NET

Figure 2.1. Location of the Nakagawa water-pipe bridge



(a) Cross-sectional view (b) Side view

Figure 2.2. Schematic view of Nakagawa water-pipe bridge (Unit: mm)

As for the earthquake damage to the Nakagawa water-pipe bride, the expansion joints between the main cable-stayed bridge and the side bridge were pulled out and rotated at Piers 1 and 4 in Fig. 2.3, and water leaked from the joints. The bearings at all the piers of the main bridge were broken by pulling out of bolts and by sliding roller bearing as shown in Fig. 2.4. The damage to expansion joint and bearing is summarized in Table 2.1. The superstructure moved laterally in transverse direction to bridge axis at Piers 1 and 4 (see as Fig. 2.5.). On the other hand, damage to substructures was not observed based on our field survey. The damaged expansion joints of pipeline on the downstream side were fixed and water transmission restarted shortly after the earthquake.

Table 2.1. Damage to expansion joint and bearing of the Nakagawa water-pipe bridge (after Ibaraki Prefecture)

	A1	P1		P2	P3	P4		A2
	MOVE	FIX	MOVE	FIX	MOVE	MOVE	FIX	MOVE
Expansion joint	No damage	—	Damage	—	—	Damage	—	No damage
Bearing	No damage	No damage	Damage	Damage	Damage	Damage	No damage	No damage

Figure 2.3. Damage of expansion joint at Pier 4

Figure 2.4. Damage of bearing at Pier 4

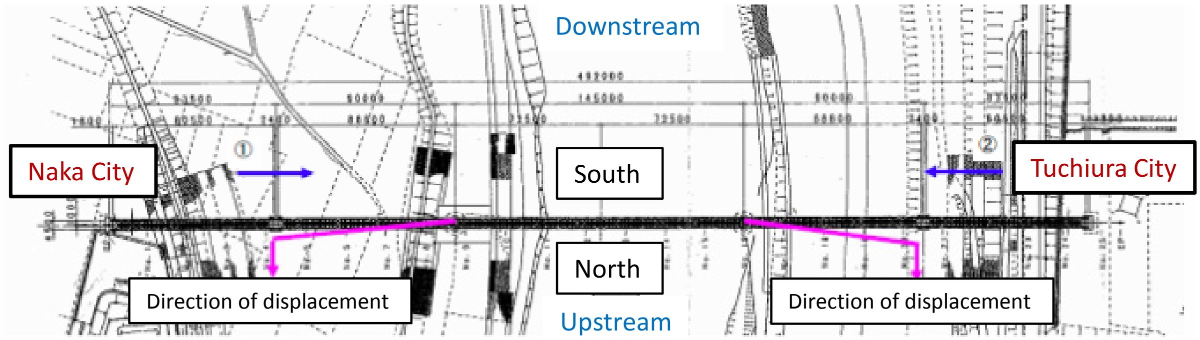


Figure 2.5. Plan view of the Nakagawa water-pipe bridge (after Ibaraki Prefecture)

3. MICROTREMOR OBSERVATION OF THE NAKAGAWA WATER-PIPE BRIDGE

In order to understand the vibration characteristics of the Nakagawa water-pipe bridge and surrounding subsurface ground, the microtremor observation was carried out in December, 2011. One out of two pipelines was not repaired yet and it was not filled with water at that time (see as Fig. 3.1.). The servo-type velocity sensor was used for the observation as shown in Fig. 3.2. Fig.3.3 shows the location of 14 observation points for the bridge and 3 observation points for the ground. The sensor was set on the center of main truss. The microtremor was recorded by 200Hz sampling in three components for a sensor.

As wavelet processing, 10 data sets of 2,048 records are sampled from the observed microtremor at each observation point, and the mean of 10 sets of Fourier amplitude was determined as the Fourier amplitude at the observation point. Since the observation point could not be set under all of the bridge piers at the same time, the transfer function to the microtremor at the bottom of the abutment A1 was calculated and the Fourier spectrum of microtremor at each observation point obtained as shown in Fig. 3.4. Damping ratio was calculated using the half-power method. The vibration modes of the microtremor observation are shown in Table 3.1.

The 1st mode vibration for the entire bridge system is the 1st mode vibration of central span of the main bridge in the transverse direction with 0.59Hz. The 2nd mode vibration for the system is similarly the one in the vertical direction with 0.78Hz. The 3rd mode vibration for the system is the 1st mode vibration of side span of the main bridge in the transverse direction with 1.17Hz. The 1st and 2nd modes of the system have damping of 6 to 8 %. As far as the vibration mode is identified from the predominant frequency of microtremor, the total of first 6 modes is obtained. They are the modes in transverse or vertical direction. Vibration modes estimated by the Fourier amplitude at the predominant frequency of microtremor are shown in Fig. 3.5. The mode of main bridge is symmetric.

Figure 3.1. State of the restoration work

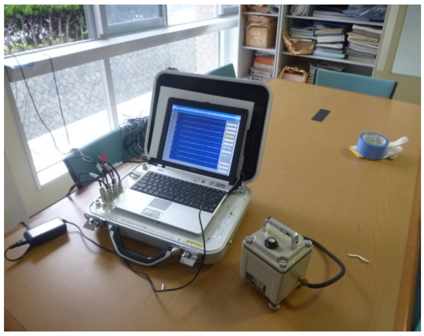


Figure 3.2. Measurement instruments

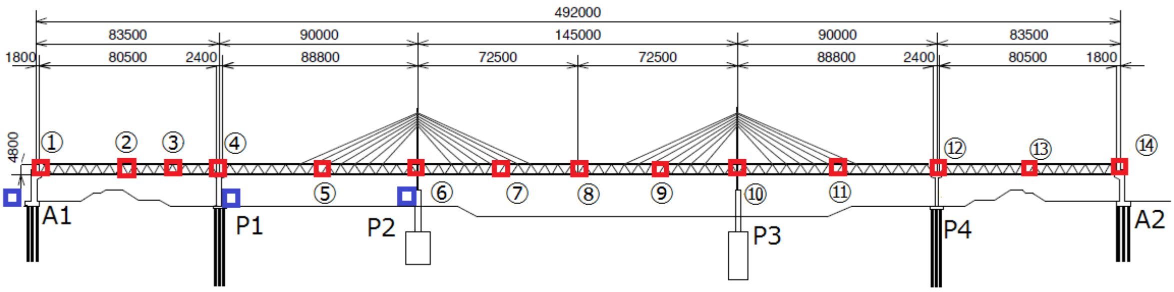
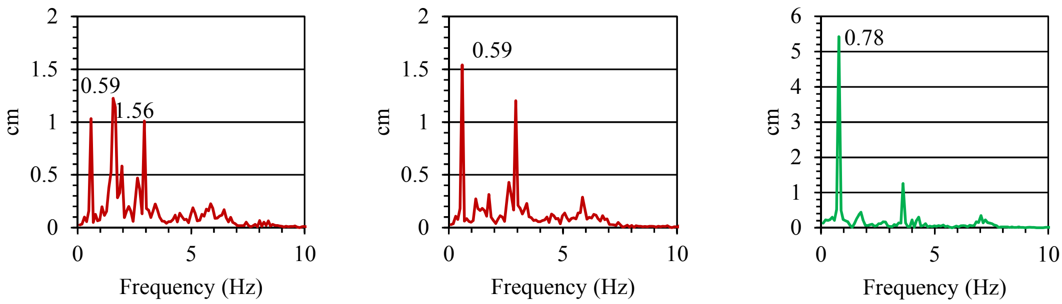


Figure 3.3. Observation points of microtremor

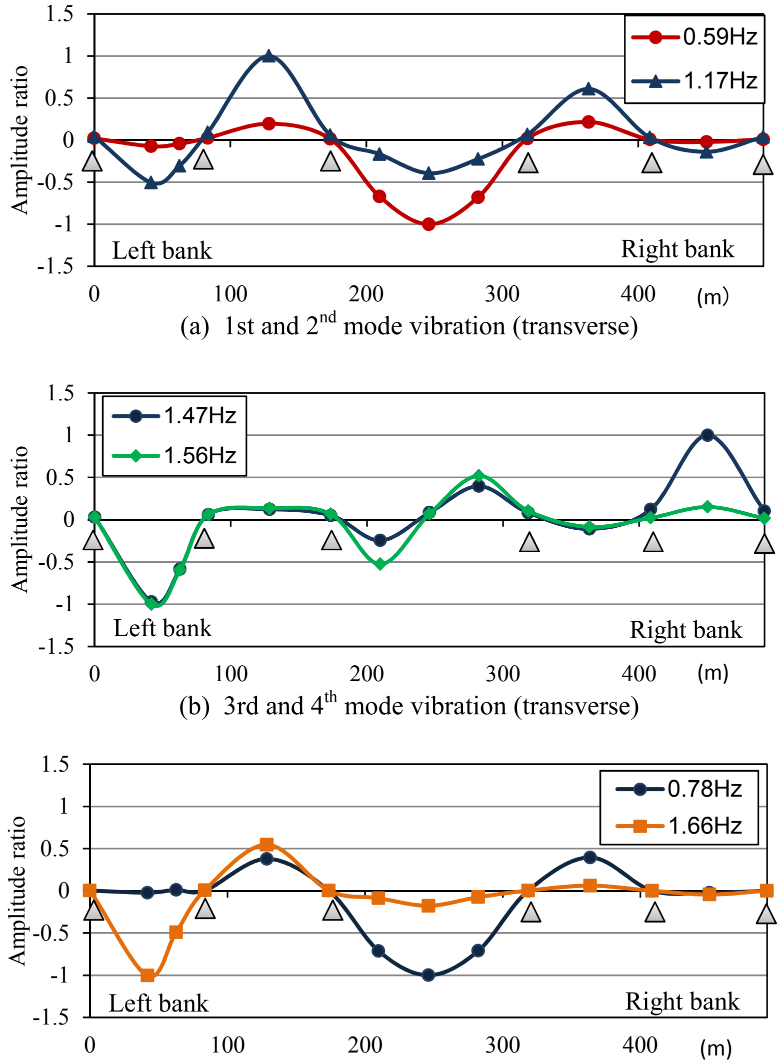


(a) Point 7 (transverse) (b) Point 8 (transverse) (c) Point 8 (vertical)

Figure 3.4. Fourier spectrum of microtremor at observation point

Table 3.1. Result of microtremor observation

Mode	Frequency (Hz)	Damping (%)	Direction of vibration	Remark
1st	0.59	8.5	Transverse	1^{st} mode of center span of main bridge
2nd	0.78	6.4	Vertical	1^{st} mode of center span of main bridge
3rd	1.17	—	Transverse	1^{st} mode of side span of main bridge
4th	1.47	3.4	Transverse	1^{st} mode of right side bridge
5th	1.56	—	Transverse	1^{st} mode of left side bridge & 2^{nd} mode of center span of main bridge
6th	1.66	4.2	Vertical	1^{st} mode of left side bridge



(a) 1st and 2nd mode vibration (transverse)

(b) 3rd and 4th mode vibration (transverse)

(c) 1st and 2nd mode vibration (vertical)

Figure 3.5. Vibration modes based on microtremor observation. Vertical axis is the normalized amplitude, obtained by the ratio of Fourier amplitude to its peak amplitude of the system.

4. NUMERICAL ANALYSIS

4.1. Analytical Model

In this study, the FEM analysis was carried out by using open source code of the OpenSees. As the analytical model is shown in Fig. 4.1, the water-pipe bridge system is modeled with three-dimensional frame structure composed of 312 nodes and 748 elements. Degrees of freedom for an element are given in six directions. Superstructure and substructures are made with beam element, cables with truss element, and bearings with spring element. Expansion joints are not modeled by spring, but free to move. Mass is given as a lumped mass for each node. The bridge system does not include the interaction of the ground and the bottom of substructures is fixed.

The eigenvalue analysis is carried out as the first step of this study, in order to verify the vibration mode of the bridge system obtained by the microtremor observation. In this step, the weight of the water in the water pipeline has been considered to only one side pipeline because of simulating the same condition at the observation. In the next step, the mode of vibration is numerically confirmed by the condition of water-filled pipeline on the both side.

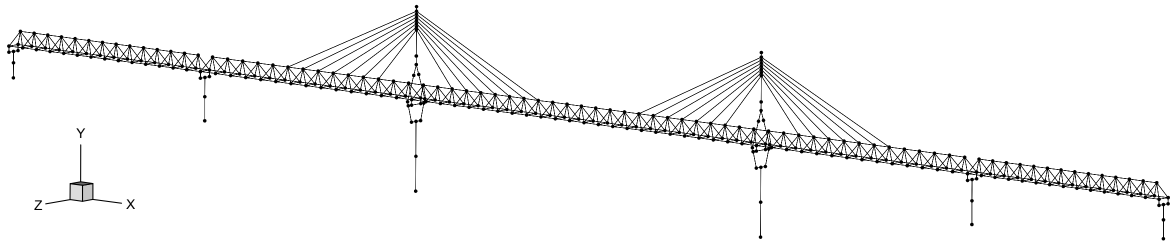


Figure 4.1. Analytical model

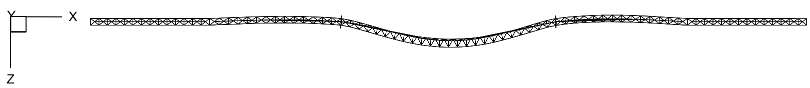
4.2 Analysis Result

At first, the eigenvalue analysis is carried out in the model with single water-filled pipeline. The result of eigenvalue analysis is listed in Table 4.1. It confirmed that vibration mode and its frequency obtained by the eigenvalue analysis are almost same as those measured by the microtremor. The order of vibration mode also agrees with the measured ones.

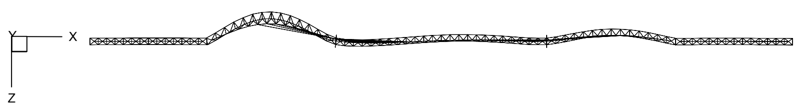
Table 4.1. Result of eigenvalue analysis

Mode degree	Frequency (Hz)		Ratio (Analytic / Measured)	Direction
	Analytic value	Measured value		
1	0.63	0.59	107%	Transverse
2	0.85	0.78	108%	Vertical

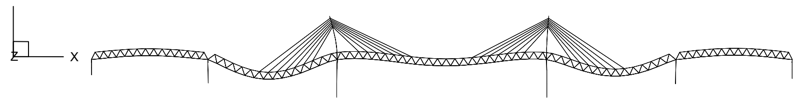
Secondly, in order to simulate the seismic behavior of the bridge at the time of the earthquake, the eigenvalue analysis was carried out in the model with two water-filled pipelines. The vibration mode and the result of eigenvalue analysis are shown in Fig.4.2 and Table 4.2. The first mode of the entire bridge system is 0.54 Hz and the secondary mode is 0.71 Hz. The natural frequency has gets slightly lower from 0.63 to 0.54 Hz due to the increase of mass in pipeline. Effective mass ratio is large in the 4th mode of vibration in the transverse direction and the 11th and 14th mode of vibration in the vertical direction.



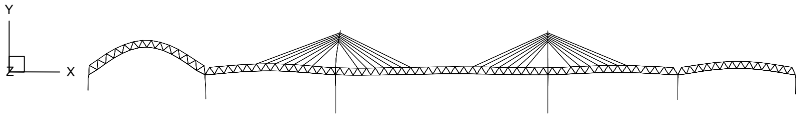
(a) 1st mode of vibration



(b) 4th mode of vibration



(c) 11th mode of vibration



(d) 14th mode of vibration

Figure 4.2. Vibration mode

Table 4.2. Result of eigenvalue analysis

Degree of mode	Frequency (Hz)	Periods (sec)	Effective mass ratio		
			Axis	Transverse	Vertical
1	0.54	1.85	0.000	0.055	0.000
2	0.74	1.35	0.000	0.000	0.042
3	0.99	1.01	0.000	0.025	0.000
4	1.02	0.98	0.000	0.096	0.000
5	1.21	0.83	0.000	0.042	0.000
6	1.21	0.83	0.000	0.043	0.000
7	1.29	0.78	0.000	0.000	0.000
8	1.29	0.78	0.036	0.000	0.000
9	1.35	0.74	0.002	0.000	0.001
10	1.49	0.67	0.000	0.000	0.001
11	1.60	0.63	0.000	0.000	0.082
12	1.63	0.61	0.000	0.003	0.000
13	1.67	0.60	0.001	0.000	0.039
14	1.68	0.60	0.000	0.000	0.095
15	1.91	0.52	0.000	0.013	0.000

Hata et al. (2012) have predicted the strong ground motion at the Nakagawa water-pipe bridge and they have revealed that characteristics of site amplification are different between protected inland and waterside land. The acceleration response spectra of the estimated strong ground motion near the water-pipe bridge is higher than the design Level 2 ground motion in the period of 0.1-0.2 s as well as 0.6-0.8s. Especially the response spectrum at waterside land is higher than that at the embankment side due to amplification of the subsurface ground. Thus, it is considerable that the vibration modes less than 15th mode meet well with the strong ground motion. As the ground motion are different between the waterside and embankment side, the more detail analysis is necessary to solve the damage mechanism of the water-pipe bridge.

5. CONCLUSION

In this study, towards the elucidation of damage mechanism of the Nakagawa water-pipe bridge, microtremor test and eigenvalue analysis were carried out. The 1st vibration mode of the bridge system was turned out to be 1.85 s at the time of the earthquake. Although the recorded and estimated ground motion near the bridge does not have strong motion over 1s, the vibration modes less than 15th mode meet well with the strong ground motion. As the ground motion are different between the waterside and embankment side, the more detail analysis is necessary to solve the damage mechanism of the water-pipe bridge.

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