EVALUATION OF SEISMIC DIAGNOSIS OF AQUEDUCT LINES USING NON-LINEAR DYNAMIC ANALYSIS

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SUMMARY

The surrounding bridge and utility networks were greatly damaged due to the South Hyogo Earthquake, which occurred in January, 1995. As a result of these events various seismic design codes were revised in Japan. The seismic design code for water facilities was consequently revised in 1997. The main points of the revision are that, from now on as well as applying the factor of ground motion level 1, where the perceived damage will be low, an additional factor of ground motion level 2, where more extensive damage is perceived, should be applied. A seismic design should be derived for two-stage analysis. The seismic design for aqueducts has been revised based on the updated Road Bridge Design Codes part V Seismic Design, with respect to the extent of perceived damage. But the characteristics of aqueducts are different from that of road bridges specifically with respect to the vertical and lateral stiffness, dead load, and span.

This paper describes the measured values of the damping coefficient and natural period on four actual aqueducts, of truss, langer and two cable stayed types and the results of non-linear dynamic analysis of the truss type and langer

INTRODUCTION

When the South Hyogo Earthquake struck in January 1995, many road bridges and lifeline installations in the affected region were severely damaged. As a result of these occurrences, various seismic design codes were revised, and the Seismic Design Code for Water Facilities (SDWF) [1), 2)] was updated in 1997. The new seismic design code specified in the SDWF for aqueducts was developed on the basis of information gained from aqueducts damaged in previous earthquakes as well as from the Road Bridge Design Code part V Seismic Design (RBSD) [3)] which had been revised previously. The basis for the revision of these codes is summarized below.

1) The main girders which escaped unscathed from the South Hyogo Earthquake are analyzed using the conventional seismic intensity method with Ground Motion Level 1(GML1).
2) Bearings which were damaged by the South Hyogo Earthquake, were particularly vulnerable and are crucial to the entire structure performance. Therefore, they are analyzed using the Ductility Design Method with a larger value of Ground Motion Level 2(GML2).
3) Aqueducts expected to exhibit very complex behavior during an earthquake were subjected to dynamic analysis designs to verify their safety in earthquake situations.

There have been many reports dealing with the dynamic analysis of road bridges, however, aqueducts have received relatively little attention in this respect. There remains some concern as to whether the seismic design code for aqueducts are truly well-established, reliable, and problem-free in their actual application. This paper describes two results. One result is concerning to the measurement of the damping coefficient and the natural period of several types of aqueducts. Another result is concerning to the nonlinear dynamic analysis on two types of aqueduct, the Langer type and the Reverse-triangular truss type, which have been designed according to the

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previous version of the SDWF. Through this analysis, issues requiring solution with regard to the seismic design of water installations were also identified, and these are also noted in this paper.

APPLICATION OF DYNAMIC ANALYSIS

Aqueducts subjected to dynamic analysis

The SDWF lists the following types of aqueducts as requiring dynamic analysis in accordance with the RBSD:

1) Aqueducts with a long natural vibration period (of more than 1.5 seconds)
2) Aqueducts with high pier supports (over about 30 m)
3) Aqueducts that can be expected to exhibit complex behavior during an earthquake, such as cable-stayed and suspension bridges
The RBSD defines bridges with complex behavior during an earthquake as having the following characteristics:

1) A prevailing vibration mode other than the primary or exhibiting two or more modes of vibration.
2) Multiple plastic hinge locations or a plastic hinge location cannot be predicted.
As of today, it remains uncertain which type of aqueduct will exhibit such complex behavior because there is so little dynamic analysis data [4)] available on the behavior of aqueducts.

Characteristics of Aqueducts

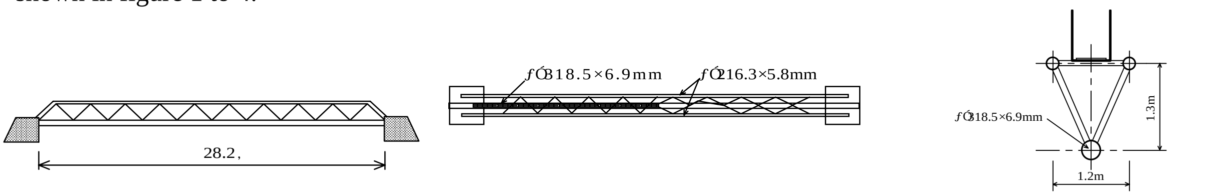
Prior to the discussion of dynamic analysis, it may be useful to differentiate between the structural characteristics of road bridges and aqueducts.

1) The span of an aqueduct is within 100m, generally shorter than that of a road bridge.
2) Large aqueducts are generally of the Langer or Truss structure, while there are fewer examples of cable-stayed or suspension systems.
3) The dead load of an aqueduct is within 150N/m, generally smaller than that of a road bridge.
4) The horizontal loading on an aqueduct was often taken to be the wind load, since the wind load is larger than the seismic load. On the previous SDWF, the seismic design method adopted the static method and seismic horizontal intensity (Kh) was usually used Kh=0.3. The wind load converted into an equivalent Kh exceeds Kh = 0.3.
5) The rigidity of an aqueduct in the horizontal direction is less than that of a road bridge.
6) The performance requirement in the case of GML2 is "the maintenance of traffic functionality" for road bridges, while it is "the maintenance of the water supply function" for aqueducts.

MEASUREMENT OF THE DAMPING COEFFICIENT AND NATURAL PERIOD

As regards damping coefficients, available data for aqueducts was not used because of uncertainties resulting from the scarcity of measurements, and differences in structural characteristics between road bridges and aqueducts. Instead, the damping coefficients of aqueducts selected for this analysis were actually measured. At the same time, the natural period was measured in order to allow verification of the analytical models by comparing the results.

Four aqueducts were investigated with regarding to damping coefficient and natural period. These aqueducts are shown in figure 1 to 4.



(a) Profile **(b) Plan** **(c) Section**

Fig. 1 Truss Type Aqueduct

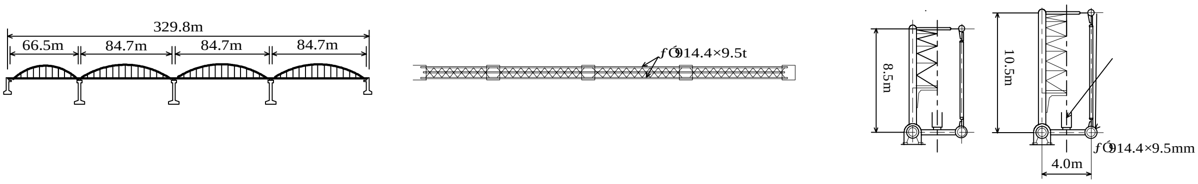


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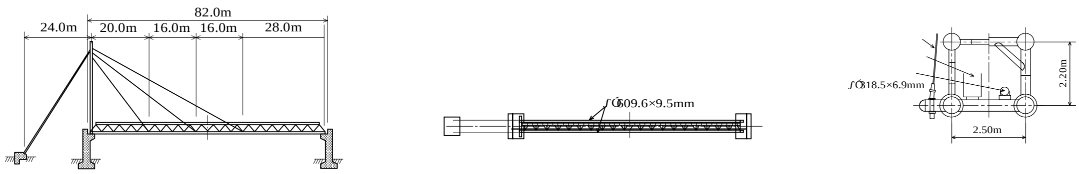
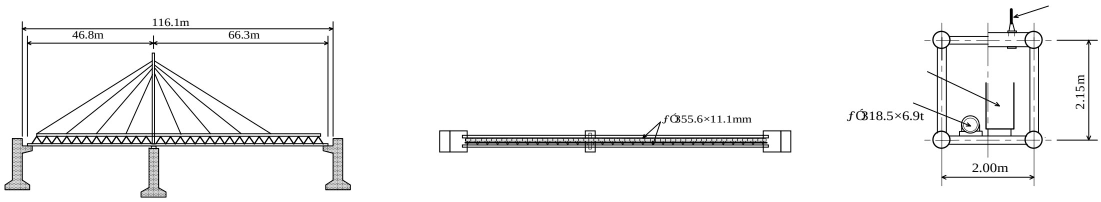
Fig. 2 Langer Type Aqueduct



(a) Profile **(b) Plan** **(c) Section**

Fig. 3 Cable Stayed Aqueduct (A)



(a) Profile **(b) Plan** **(c) Section**

Fig.4 Cable Stayed Aqueduct (B)

The vibration characteristics were obtained by measuring the acceleration and velocity of micro tremors, forced vibrations induced by a walking live load with humans weighing about 60 kgf and free vibrations after synchronized jumping with two humans weighing approximately 60kgf. The natural periods were calculated by both the Fast Fourier Transform method (FFT) and the Maximum Entropy Method (MEM). The half power method was applied to the power spectra obtained using the MEM on micro tremor waveforms to arrive at a damping coefficient. Damping coefficient is also derived from the damping ratio of the free vibration waveforms. Measured values of damping coefficient obtained from micro tremor waveforms, are shown in Table 1. Moreover measured values of damping coefficient obtained from the free vibration waveforms, are shown in Table 2. Damping coefficients gained from two methods are almost the same, so in these cases, magnitude of the waveforms has little influence to the damping coefficients. With regard to the natural period of the truss type and the langer type, measured values were compared with analytical results to demonstrate the validity of the analytical models in Table 3. The analytical conditions of these two types, used in the analysis are given in Table 4. In the case of the langer aqueduct, the measured natural period of the substructure was found to be 0.4 seconds. This indicates that neither aqueduct requires dynamic analysis, either in terms of structural type or natural period according to the revised SDWF.

Table 1 Damping coefficient (Micro tremor waveforms)

	Truss	Langer	Cable stayed (A)	Cable stayed (B)
Damping coefficient	0.002	0.004	0.006	0.006

Table 2 Damping coefficient (Free vibration waveforms)

	Cable stayed (A)	Cable stayed (B)
Damping coefficient	0.008	0.007

Table 3 Natural periods (Unit: Hz)

	Truss		Langer		Cable stayed (A)	Cable stayed (B)
	Measured	Analysis	Measured	Analysis	Measured	Measured
Bridge axial	3.98	4.10	2.55	2.35	1.76	2.10
Horizontal	3.98	3.49	1.16	1.20	1.64	1.77
Comparison (analysis/measured)	88 – 103(%)		92 – 103(%)		-	-

ANALYTICAL CONDITIONS OF NONLINEAR DYNAMIC ANALYSIS

Nonlinear dynamic analysis was applied to the two main types of aqueduct — Reverse-triangular truss and Langer — as built in accordance with the previous version of the SDWF.

In contrast with static analysis, dynamic analysis takes into account the natural period, damping characteristics, and nonlinear hysteresis characteristics of materials. Table 4 shows the specifications of the models, while the analysis models are shown in Figure 5. The nonlinear dynamic analysis program used here was confirmed to be sufficiently precise through a comparison with the calculation examples given in the Civil Engineering Research Center report [5)], namely the 1996 Research Committee's Report on Seismic Design Software**,** as issued in May 1997.

Table 4 Analysis model

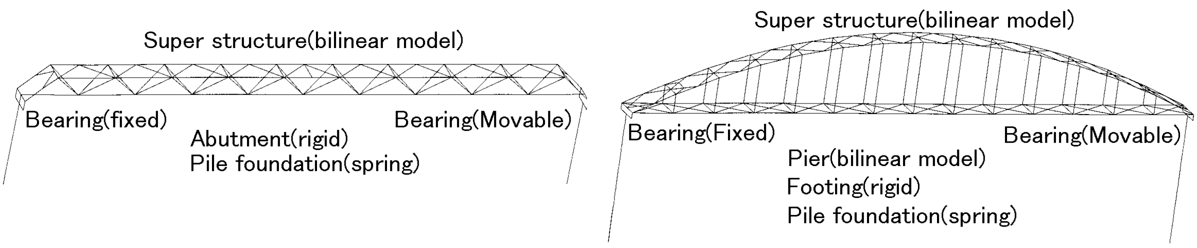
	Langer	Reverse-triangular truss
Super-Structure	Span: 28.2 m, Steel mass: 217 kgf/m Water mass: 73 kgf/m*	Span: 84.7 m, Steel mass: 1,180 kgf/m Water mass: 1,260 kgf/m*
	Steel pipe structure: 3D frame, multiple mass system model	
Sub-Structure	Abutment: rigid (4.0 m high) Pile foundation: spring	Pier: bilinear model (21.0 m high) Footing: rigid, Pile foundation,: spring
Accessories	Bearing (movable, fixed), Flexible expansion joint	

*   For water mass, only the horizontal direction is considered

The structural specifications used in the analysis were taken from structural calculation sheets prepared in accordance with the previous SDWF. The natural period of the ground calculated according to the RBSD is 0.64 seconds (Ground Type III) and 0.21 seconds (Ground Type II).

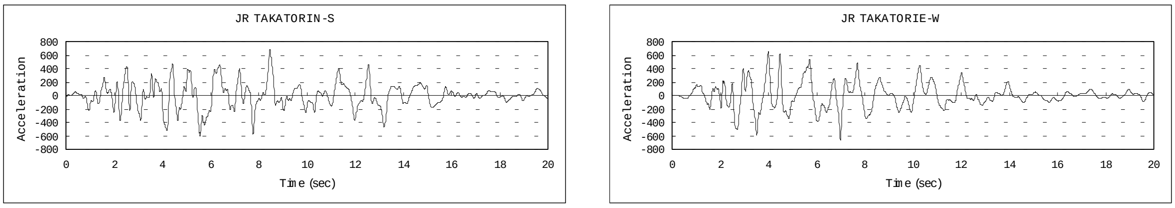
The seismic wave was selected for each ground type and input in the horizontal direction to the bridge axis then right angle to the bridge axis. The seismic waves in the direction of NS and EW were considered while the vertical direction was not considered. The Figure 6 and 7 show the input seismic used this time.

A bilinear model was used to represent the material characteristics of the Langer aqueduct piers, since they are relatively high at 21 m. The abutment of the truss aqueduct were assumed to be rigid, since they are just 4 m high and of embedded foundation as shown in Table 5. A bilinear model was also chosen for the material characteristics of the steel pipe members.



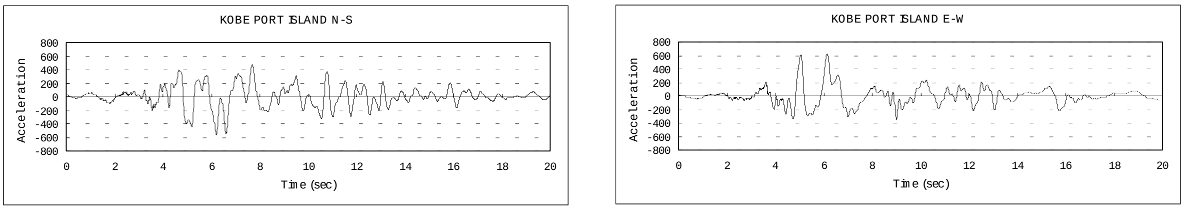
(A) Truss **(B)Langer**

Fig. 5 Analytical Model



(A) N-S **(B) E-W**

Fig. 6 Input seismic wave (JR Takatori Station)



(A) N-S **(B) E-W**

Fig. 7 Input seismic wave (Port Island)

Table 5 Analysis conditions

	Reverse-triangular truss	Langer
Ground	Ground type II ,T_G = 0.21 sec	Ground type III,T_G = 0.64 sec
Input Seismic Wave	JR Takatori Station N-S (max: 687 gal) JR Takatori Station E-W (max: 672 gal)	Port Island N-S (max: 557 gal) Port Island E-W(max: 619 gal)
Damping coefficient	Superstructure:0.002 Substructure :0.002, Ground: 0.2	Superstructure: 0.004 Substructure: 0.002 Ground: 0.2

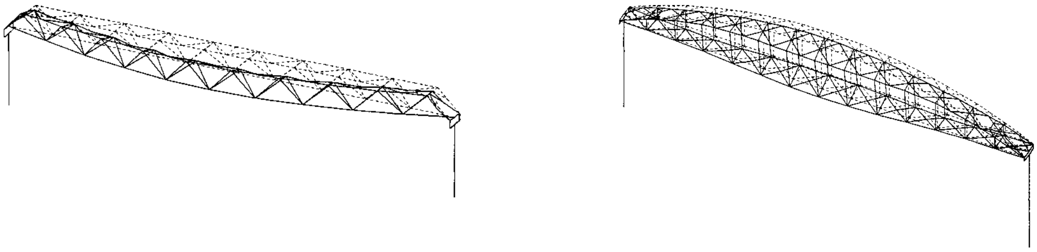
Underlined figures indicate measured values

ANALYSIS RESULTS

Vibration characteristics

The analytical models were verified by comparing the natural period measured as above. Measurements and analysis results are both shown in Table 3, clearly indicating that there is no major discrepancy between them. Therefore we can conclusively say that the analysis models are appropriate for the designed purpose.

The prevailing vibration modes of both aqueduct types turned out to be the symmetrical primary mode. Figure 8 shows these vibration modes in the horizontal direction to the bridge axis.



(A) Truss (B) Langer

Fig. 8 Vibration Mode (Bridge Axis)

Sectional force

The results of nonlinear dynamic analysis are shown in Table 6. This table results in the following findings:

1) When the seismic wave is input in the axial direction, neither type exhibits a plastic hinge.
2) The response magnification is smaller for the truss aqueduct than for the langer aqueduct.
3) A plastic hinge occurred in the langer aqueduct when the seismic wave motion was input in the horizontal direction. This plastic hinge occurred in one of the latticing members connecting the lower chord members on the fixed bearing side, as shown in Figure 9. Figure 10 shows the time record of maximum sectional force by inputting the Port Island E-W wave in the horizontal direction.

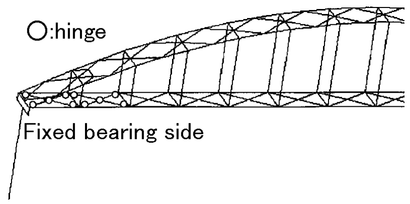


Fig.9 Location of plastic hinge

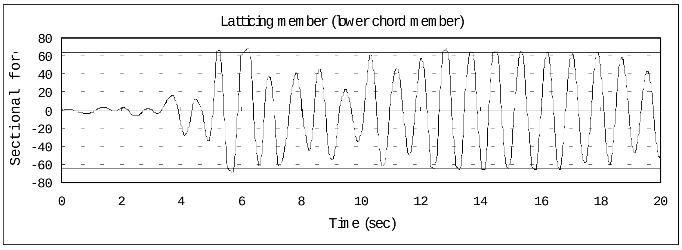


Fig. 10 Time Record of Sectional Force

Table 6 Analysis results

		Input direction of seismic wave	Truss	Langer
Superstructure Member Force		Axial	Elasticity: within tolerance	Elasticity: within tolerance
		Horizontal	Elasticity: within tolerance	Plastic hinge: in diagonal lattice member
Bearing Reaction Force	Vertical Reaction (Lift)	Axial	F: 0.4 tf, M: 0.4 tf<2.1 tf*	F: 6.8tf, M: 7.9 tf<16.0 tf*
		Horizontal	F: 2.2 tf, M: 1.6 tf>2.1 tf*	F: 79.5 tf, M: 76.0 tf<16.0 tf*
	Axial reaction	Axial	F: 2.5 tf>0.6 tf*	F: 49.5 tf>24.0 tf*
		Horizontal	F: 12.2 tf>0.6 tf*	F: 586.2tf>24.0 tf*
	Horizontal reaction	Axial	F: 0.0 tf, M: 0.0 tf<0.5tf*	F: 2.1 tf, M: 0.7tf<12.0 tf*
		Horizontal	F: 2.4 tf, M: 2.5tf>0.5tf*	F: 67.6 tf, M: 55.3tf<12.0 tf*
Displace-ment	Expansion Bearing / Flexible expansion joint	Axial	10.1 mm <16 mm (B)* 10.1 mm <50 mm (FEJ)*	43 mm <132 mm (B)* 43 mm <155mm (FEJ)*
		Horizontal	1.3 mm <16 mm (B)* 1.3 mm <50 mm (FEJ)*	27 mm <132 mm (B)* 27 mm <155 mm (FEJ)*
Response acceleration (response multiplication)		Axial	1144 gal (1.7 times)	1339 gal (2.2 times)
		Horizontal	2341 gal (3.4 times)	3580 gal (5.8 times)

Underlined figures indicate maximum response values, while those marked * show tolerable or design values.
B indicates bearing, and FEJ indicates flexible expansion joint.

Displacement and reaction force

The analysis of displacement and reaction force as shown in Table 6, yielded the following results:

1) The maximum dynamic response displacement of the bearings was within the tolerance for both aqueduct types.
2) The maximum dynamic response displacement of the flexible expansion joints was also within tolerance. The flexible expansion joint was designed to cope with greater thermal expansion than required by the previous SDWF, and this explains why they did not dislocate and water continued to flow when the earthquake displacement was applied.
3) The reaction force on the bearings exceeded tolerance for both types of aqueduct. The comparison between static and dynamic analysis result is shown in Table 7. In the static analysis, a seismic load equivalent to GML2 as specified in the SDWF was input. When this seismic wave motion was input in the horizontal direction to the bridge axis, dynamic analysis indicated a loading far beyond the static design load. Figure 11 and 12 show the time records of reaction force on the bearings of truss type and langer type.

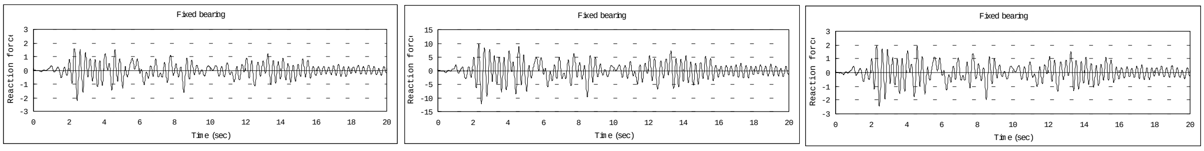
Table 7 Bearing reaction in static and dynamic analysis

	Truss		Langer	
	Static	Dynamic	Static	Dynamic
Vertical (Lift)	0.6 tf	0.4 tf (A), 2.2 tf (H)	15.5 tf	7.9 tf (A), 79.5 tf (H)
Horizontal direction	13 tf	0.0 tf (A), 2.5 tf (H)	27.9 tf	2.1 t f(A), 67.6 tf (H)
Axial direction	1.0 tf	2.5 tf (A), 12.2 tf (H)	13.5 tf	49.5 tf (A), 586.2 tf (H)

(A: Axial) means ground motion was input in the axial direction.

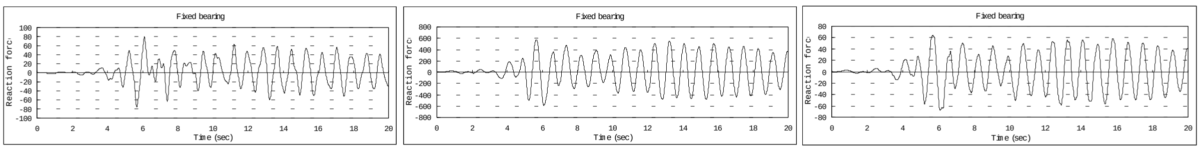
(H: Horizontal) means seismic wave was input in the horizontal direction.

Static means static calculation on the basis of SDWF



(A) Vertical (B) Axial (C) Horizontal

Fig. 11 Time Record of Reaction Force on the Bearing (Truss)



(A) Vertical (B) Axial (C) Horizontal

Fig. 12 Time Record of Reaction Force on the Bearing (Langer)

DISCUSSION

Reverse-triangular truss aqueduct

1) As regards the vibration mode, the symmetrical primary mode prevailed.
The sectional force and displacement remained within tolerance. These results suggest that adequate seismic design of the girder of truss aqueducts may be obtained through static analysis using the seismic intensity method. However, if the aqueduct has higher piers, considerable displacement of the substructure would occur, possibly causing the tolerance of the flexible expansion joints to be exceeded. Therefore, in such cases, the seismic resistance of the aqueduct needs to be verified through dynamic analysis.

2) The bearing reaction force, when checked by dynamic analysis, was found to exceed the static analysis value by a large margin. Since there is very little data available on the dynamic analysis of aqueducts, however, it is

difficult to conclude that such a situation is typical. Therefore, more analysis data on aqueducts should be collected in order to establish a suitable seismic design method for bearings.

Langer aqueduct

1)The vibration mode of the Langer aqueduct was predominantly the symmetrical primary mode. The sectional force exceeded the tolerance in some areas, and plastic hinges developed, but there are no points in an aqueduct of this type that would render the entire system unstable. Thus, the aqueduct would be able to maintain the water supply. Further, the maximum dynamic response displacement also remained within tolerance.
The results of dynamic analysis indicate that the design of main girders may be satisfactorily checked for safety through static analysis. It should be noted, however, that since plastic hinges arose relatively close to the bearings, a reliable seismic design method for this type of aqueduct, as well as for bearings needs to be established.
2)The reaction force at the bearings, as revealed by dynamic analysis, far exceeds the value obtained in static analysis. In practice, aqueducts can maintain a flow of water even if the bearings suffer damage, thanks to devices designed to prevent the girder falling. However, it is extremely important to increase the amount of available dynamic analysis data on langer aqueducts, as in the case of truss aqueducts, so as to establish a reliable design method.

CONCLUSION

This report gives the measured values of the damping coefficient and natural period, the results of nonlinear dynamic analysis by using seismic wave of GML2 on actual aqueducts and discusses the interpretation of the results.

From this study, we can conclude the following items.

(1) The damping coefficient of aqueducts is 0.002 to 0.008, is very small in comparison with that of road bridges.

(2) The seismic resistance of aqueducts of the Reverse-triangular truss can be verified through static analysis, except in the case of the bearings.

(3) On the other hand, langer type should be verified through dynamic analysis.

(4) The reaction force at the bearings, as revealed by dynamic analysis, far exceeds the value obtained in static analysis.

However, since there is a scarcity of nonlinear dynamic analysis data on aqueducts, it cannot be said that these findings definitively reflect the behavior of aqueducts in general. It is therefore very important to increase the amount of nonlinear dynamic analysis data available for aqueducts. It is also important to develop appropriate methods for verifying that seismic-resistance is such that water flows are maintained, and to establish proper design methods for bearings, expansion joints, and nearby areas, which are the most vulnerable when a major earthquake strikes.

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