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Damping Characteristics of Long-Span Suspension Bridges

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Summary

There is uncertainty in damping characteristics in seismic design of long-span bridges. In general, damping ratio of 2% has been employed in practical design. However, smaller damping ratios had been observed according to the results of vibration tests of suspension bridges[1]. A well-instrumented bridge, the Vincent-Thomas bridge, was hit by two major earthquakes, the 1987 Whittier earthquake and the 1994 Northridge earthquake, which generated the most comprehensive data on not only the seismic responses but also support excitations[2),3),4),5)]. Using these data, system identification study was conducted to identify damping characteristics from the half power method, the free vibration decay method, and earthquake response analyses to find out the damping ratio which gives better agreement with the measured data. As the result, identified damping ratios are generally around 2% or more. Smaller damping values were also found in some modes.

1. Vincent-Thomas Bridge and its Observed Data

The Vincent-Thomas suspension bridge was located southwest of Los-Angels, California. Fig. 1 shows the general feature of this bridge. The center, side, and total length of this bridge are 457m, 154m, and 766m respectively. The bridge was designed in 1959. The suspended structure consists of two stiffening trusses, floor trusses and lower chords and the deck was made from non-composite concrete slab. The each main steel tower was connected at 5 locations at mid height by lateral beams. 26 accelerometers were instrumented at the stiffening trusses, the towers, the tower bases, and the ground as shown in Fig. 2. This bridge had suffered two major earthquakes: the Whittier earthquake and the Northridge earthquake. Those acceleration data were very important and very precious to study the damping characteristics and seismic response behavior of long-span bridges. The measured peak displacements are shown in Table 1.

Table-1 Peak displacement amplitude observed during both earthquakes

Location	Whittier earthquake	Northridge earthquake
Center of center span (Transverse direction)	4.6cm (0.00010)*	4.5cm (0.00010)*
Center of center span (Vertical direction)	5.8cm (0.00013)*	17.7cm (0.00039)*
Center of side span (Transverse direction)	3.3cm (0.00007)*	4.7cm (0.00010)*
Center of side span (Vertical direction)	8.7cm (0.00019)*	20.6cm (0.00045)*
Top of tower (Longitudinal direction)	2.8cm (0.00006)*	4.8cm (0.00011)*
Top of tower (Transverse direction)	3.1cm (0.00007)*	4.4cm (0.00010)*

*: (Peak displacement) / (Center span length=457m)

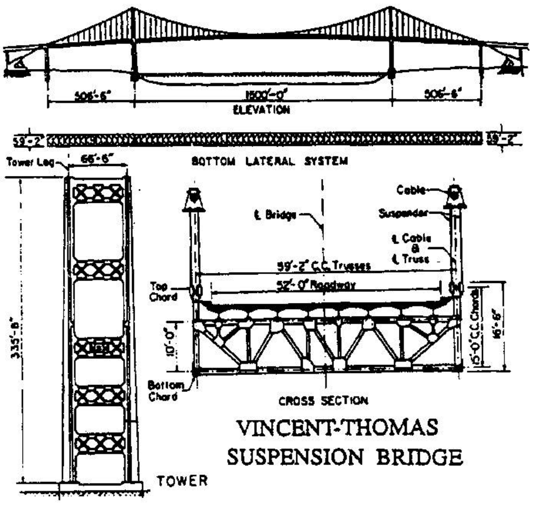


Fig. 1 Vincent-Thomas bridge[7)]

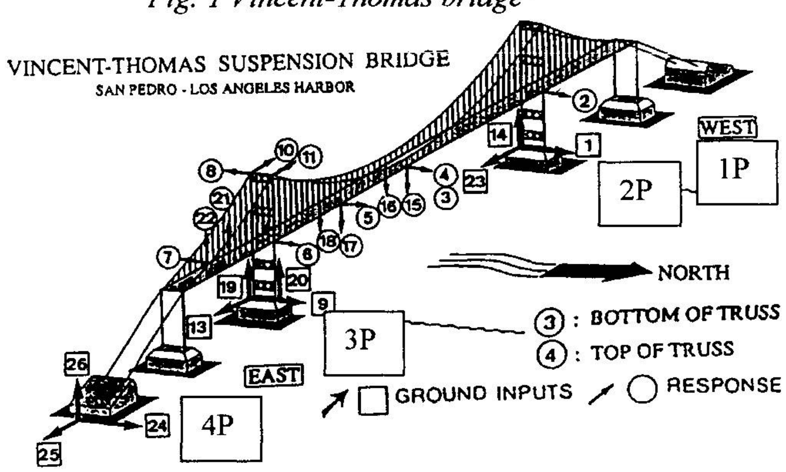


Fig. 2 Instrumentation of the Vincent-Thomas bridge [3)]

2. Damping Characteristics Identification by the Half-Power Method and the Free Vibration Decay Method

The analytical methods to estimate the damping ratio have not been firmly established. The first try of identifying the damping ratio of each mode is employing the half power method and free vibration decay method applying to the measured acceleration data. When identifying the damping ratio by half power method, the transfer function and the power spectrum were employed in the frequency domain. The general idea of identifying the damping is shown in Fig. 3. No smoothing work was conducted to the observed data. Table 2 shows the average value of the each identified damping ratio calculated from the power spectrum and the transfer function with input data record of 2P or 3P tower base. According to the results from the transfer function of the Northridge earthquake, the damping ratios are identified as 1-3 % for the lower vertical vibration mode, 1-4% for the lateral vibration mode, and only 1% for the torsion mode of the girder. The estimated damping ratios using power spectrum from the Northridge earthquake data are 1-4% for the vertical and lateral vibration mode. According to the results from the both methods, the damping values estimated by power spectrum were estimated rather greater compared to the result using transfer function. The damping ratios identified for the Whittier earthquake are generally greater whereas the displacement amplitude of the earthquake were smaller. And also, in general, it seems that the damping values are estimated greater in the lower modes and smaller in the higher mode.

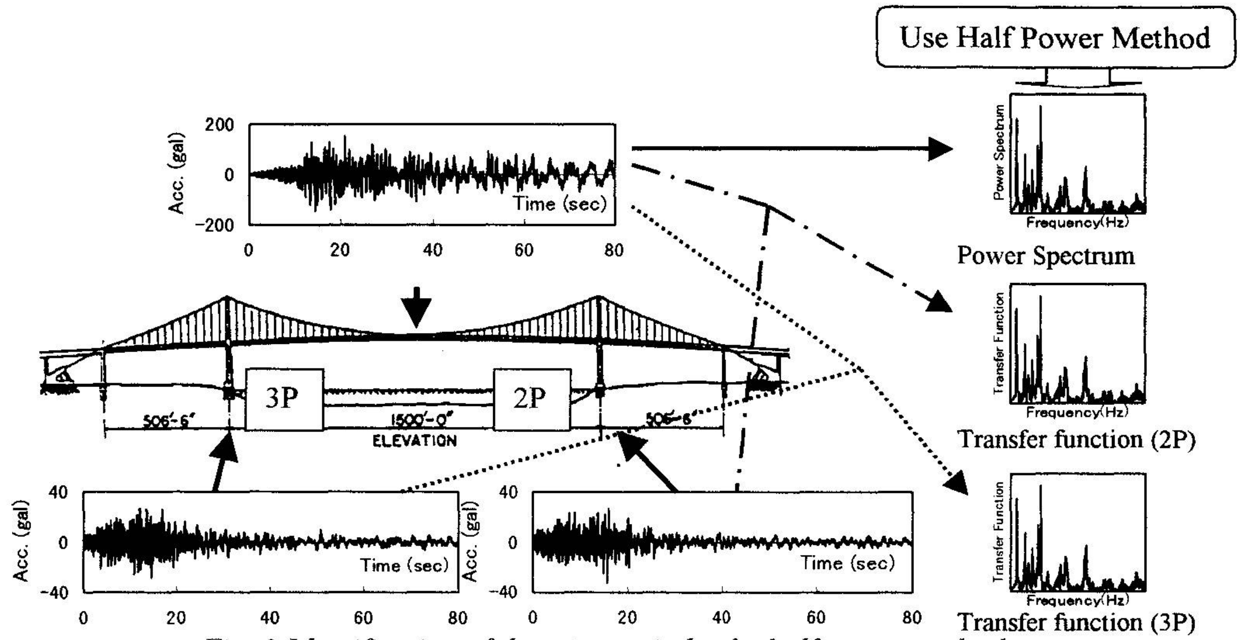
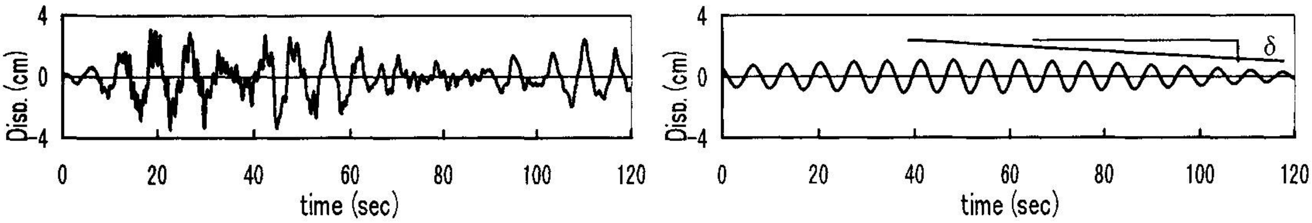


Fig. 3 Identification of damping ratio by the half power method

Table 2 Damping ratios estimated by the half power method

Vibration Mode	Power spectrum		Transfer function			
			Use 2P ground motion data		Use 3P ground motion data	
	Frequency (Hz)	Damping Ratio(%)	Frequency (Hz)	Damping Ratio(%)	Frequency (Hz)	Damping Ratio(%)
Whittier earthquake						
Vertical symmetric #1	0.226	5.3	0.226	2.3	0.232	2.1
Vertical symmetric #2	0.372	2.8	0.371	1.5	0.386	1.4
Vertical asymmetric #1	0.183	3.9	0.177	1.5	0.177	1.2
Lateral symmetric #1	0.134	7.9	0.134	5.4	0.140	3.5
Lateral asymmetric #1	0.427	2.1	0.421	0.8	0.421	0.9
Sway	0.232	4.3	-	-	0.232	4.8
Torsion #1	0.510	1.9	0.507	0.5	0.507	1.0
Northridge earthquake						
Vertical symmetric #1	0.226	2.0	0.226	2.5	0.226	1.3
Vertical symmetric #2	0.342	1.1	0.336	2.1	0.340	2.2
Vertical asymmetric #1	0.159	3.5	0.165	3.5	0.165	2.7
Lateral symmetric #1	0.134	5.8	0.140	4.1	0.110	4.5
Lateral asymmetric #1	0.419	1.7	0.421	0.7	0.417	1.9
Sway	0.244	5.9	-	-	0.238	4.0
Torsion #1	0.530	1.7	0.531	0.4	0.525	0.9

The measured data has long damped free vibration part after principal excitation so that damping ratio can be identified using the free vibration decay. Fig. 4(a) shows the lateral displacement time history at the center of the center span during the Northridge earthquake. According to this figure, it is recognized that the principal excitation was almost ceased 20 second or so but a long free vibration was followed and continued until 80-120 second. The identification work was carried out by extracting the target frequency component of the target vibration mode by band-pass filtering in the frequency domain and the damping ratio was identified the free vibration decay in the time domain using extracted data. The band pass filtering width was determined by trial and error basis. Fig. 4(b) shows the extracted displacement response of the lateral #1 mode of the main girder in the time domain. Table 5 shows the list of the identified damping ratios of each vibration mode. Star mark (*) was put if beating was not clearly removed when extracting the target frequency component. According to the results of the Whittier earthquake, the damping ratio of lateral #1 vibration mode was identified as 5.5% but the rest shows smaller values. On the other hand, the larger damping ratio of vertical #1 and sway vibration mode were identified in case of the Northridge earthquake. The identified damping ratios using free vibration decays are relatively smaller compared to the result by the half power method.



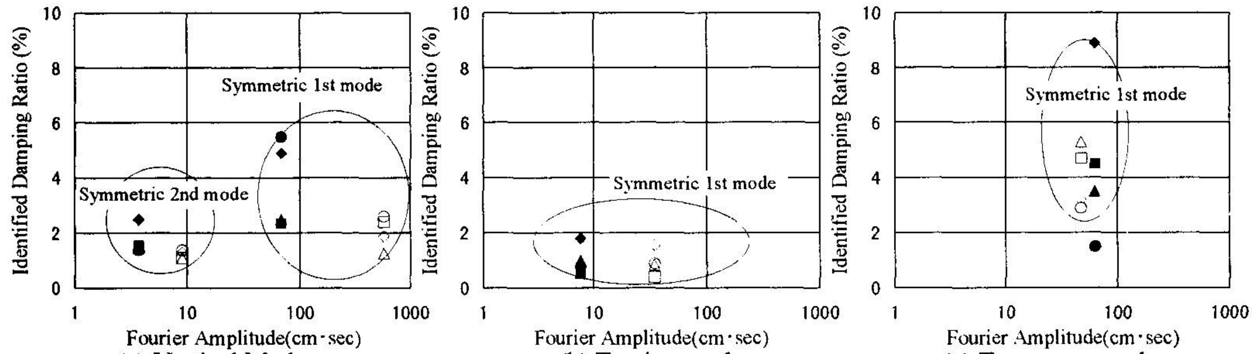
(a) Measured data *(b) Extracted data (Band width 0.20-0.25Hz)*

Fig. 4 Measured displacement history and extracted displacement time history of lateral #1 vibration mode at the center of the center span in the transverse direction (Northridge)

Table 5 Damping ratios identified from the free vibration decay

Vibration Mode	Location	Whittier earthquake(%)	Northridge earthquake(%)
Girder:			
Lateral symmetric #1	Center of the center span	5.5	2.6
Lateral asymmetric #1	1/3 point of the center span	1.4	1.4
Torsion #1	Center of the center span	0.8	0.9
Vertical asymmetric #1	1/3 point of the center span	1.4*	0.9
Vertical symmetric #1	Center of the center span	1.5*	2.9
Vertical symmetric #2	Center of the center span	2.0*	0.6
Sway	Tower point	1.7	3.4
Tower:			
Longitudinal direction	Top of the tower	0.7	1.6
Lateral direction	Top of the tower	0.3	0.6

*: Identification was carried out using beat waves



(a) Vertical Mode (b) Torsion mode (c) Transverse mode

◆◇: Half power method (Power spectrum) ■□: Half power method(Transfer function - 2P input)
▲△: Half power method(Transfer function - 3P input) ●○: Free vibration decay method

(◆■▲● Whittier Earthquake ◇□△○ Northridge Earthquake)

Fig. 5 Amplitude dependencies of damping ratio with Fourier displacement amplitude at the center of the center span

Fig. 5 shows the relation between the Fourier displacement amplitude and damping ratio of major modes identified by the half power method and the free vibration decay method in order to study the amplitude dependency of the damping ratio. The Fourier amplitude was focused at the center of the center span. Here the difference of the two earthquakes is expressed as the difference of the

Fourier amplitude. As for the vertical mode, the identified damping ratios are around 2%. When focusing the each mode, damping ratio decreases as the Fourier amplitude increases. The stiffness contribution of non-composite concrete deck or friction at the bearings may influence the damping characteristics of this bridge in the high Fourier amplitude region. As for the torsion mode of the girder, the damping ratios are around 1% and show no amplitude dependency. As for the lateral vibration mode of the girder, the damping ratios are relatively greater but the amplitude dependency could not be identified.

3. Damping Characteristics Identification by Earthquake Response Analyses

Another identification method of damping characteristics is to search the damping ratio that gives better agreement with measured peak acceleration or displacement data in the earthquake response analyses using a proper bridge model. In order to match the measured peak data and the analyzed data, proper modal damping ratio should be given. However, there is no theoretical and practical technique to set the best or the most proper modal damping ratio for each mode so that unique damping ratio, 0,1,2,3,5%, was set to each mode. The identification of the damping ratio was made by comparing the peak measured acceleration or displacement data the peak calculated data.

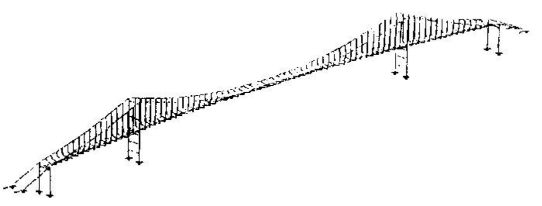
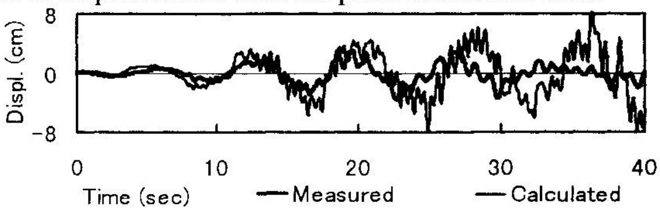
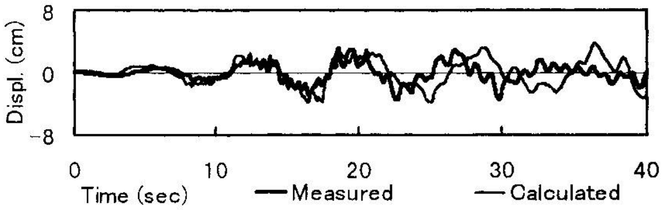


Fig. 6 Fish bone model of the bridge



(a) h=0%



(b) h=5%

Fig. 7 Displacement time history data (Analytical and measured data, Northridge earthquake)

The super structure of the bridge was model by a fish bone model as shown in Fig. 6. The deck was non-composite concrete slab. It is assumed in this study that 40% of the stiffness contribution of the slab is expected for the lateral stiffness of the girder. The accuracy of the model had already been verified by comparing the measured dominant frequencies to the calculated ones obtained by the eigen analysis using this model. Using the verified model, a series of time history analyses were conducted by changing the modal damping ratio. The number of the modes that was considered in this study was 1^{st} to 292^{nd} modes. The total summed equivalent mass of those modes was 95%. Fig. 7 shows an example of an analytical result comparing the observed data. This figure shows the lateral displacement time history at the center of the center span during the Northridge earthquake and the analytical results by changing the damping ratios. According to this figure, the damping ratio can be identified 5% or more by comparing measured and calculated peak data. In this way, the damping ratios were identified if the maximum response of each data were agreed each other in terms of acceleration or displacement. Table 4 shows the identified damping ratios estimated using this method.

Table 4 Damping ratios identified by earthquake response analyses, which gives the same peak acceleration and displacement as the observed data

	Whittier earthquake		Northridge earthquake	
	Displ.	Acc.	Displ.	Acc.
Transverse Mode				
The center point of the center span	Greater than 5%	1%	Greater than 5%	3~5%
The 1/3 point of the center span	Greater than 5%	1%	Greater than 5%	2%
Vertical Mode				
The 1/3 point of the center span	Greater than 5%	1~2%	1~2%	3~5%
The center point of the center span	1~2%	1~2%	0~1%	Greater than 5%
The tower point of the center span	2%	0%	3~5%	0%
Tower				
Transverse, The top of the tower	2%	0~1%	Greater than 5%	Greater than 5%
Longitudinal, The top of the tower	Greater than 5%	5%	3%	Greater than 5%

According to the identification results, following damping ratios were generally identified: 0-2% for vertical direction of the center span of the girder and 2-5% for other vibration mode and the location. The identification results were different whether using acceleration data or displacement data. One possible reason is that some impulses were found in the measured data so that smaller damping ratio was needed when fitting the peak response. This assumption is also verified from the fact that the analytical peak displacements occurs almost at the same time as measured one whereas the analytical peak accelerations does not occur at the same time as measured one.

4. Conclusion

The identified damping ratio varies by estimation methods, modes, and earthquakes. In general, the damping ratio of around 2% is identified. This result shows that the damping ratio of 2% that is generally employed for seismic design of long-span bridges is reasonable enough. However, this result was obtained from the data on a suspension bridge with medium center span length. Therefore, further research is needed to study the damping characteristics of long or super long span suspension bridges.

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