OBSERVED EARTHQUAKE RESPONSES OF BRIDGES

by Eiichi Kuribayashi I) and Toshio Iwasaki II)

ABSTRACT

This paper discusses the earthquake response characteristics of bridges on the basis of the result of field observations at sixteen bridges during earthquakes and the result of the response analysis for simply idealized systems subjected to the ground motion recorded at these several bridge sites.

On the basis of the result observed at the fifteen bridges of them, the relation between the observed response on tops of these bridge substructures and the ground acceleration suggests less formulation concerning the response characteristics of bridges. Because every one of them has different vibrational characteristics than others and the fundamental natural period would be from 0.2 to 1.0 second. In almost all of cases the acceleration, however, is greater on tops of them than on the surface of the ground.

On the other hand, according to observation at the Ochiai Bridge during The Matsushiro Earthquake Swarm the relation between the response and the ground motion can be seen as what the rate of an increase of the maximum response tends to decrease in accordance with an increase of the maximum value of ground accelerations, there is a following relation statistically,

$$a_R = 8.33\, a_G^{0.50} \quad , \quad \text{in gal} \qquad (1)$$

where a_R represents response accelerations and a_G is ground accelerations. It can be suggested that such phenomena seem to depend mainly upon two factors, that is, (1) the frequency characteristics of quake motions and (2) the nonlinearity of structures.

In this research work, concerning the second item in the preceding paragraph, several quake records are analyzed in particular to examine the nonlinear property, and a significant relation between the observed response and the ground accelerations is presented. Finally, it is concluded that the response acceleration of such structures subjected to earthquake motions can be analytically evaluated so as to approximate it to the observed response even if the structure is simply idealized as a nonlinear system with appropriate mechanical properties.

In addition, it is available for statistical and mechanical analyses on nonlinear behavior of structures that the theoretical approach for similitudes of bi-linear systems is done in this work.

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SYNOPSIS

This paper discusses the earthquake response characteristics of bridges on the basis of the result of field observations at sixteen bridges during earthquakes and the result of the response analysis for simply idealized systems subjected to the ground motion recorded at these several bridge sites. A significant relation between the observed response and the ground acceleration is presented. And it is concluded that the response acceleration of such structures subjected to earthquake motions can be analytically evaluated so as to approximate it to the observed response even if the structure is simply idealized as a nonlinear system with appropriate mechanical properties.

INTRODUCTION

There are several major current research works, which suggest a great deal of interesting in nonlinear behavior of structural systems.

In 1931, J.P. Den Hartog proposed a unique idea on dynamic response analyses of hysteretic systems with combined Coulomb and viscous friction[1]. In 1956, R. Tanabashi proposed a method of structural analyses considering nonlinear vibrations[2]. In 1957, M.J. Greques and F.T. Mavis presented a theoretical study on inelastic behavior of impulsively loaded beams[3].

In 1959, N.M. Newmark proposed an effective method of analytical computation of structural systems with nonlinearity in consideration of using electronic computers[4]. In 1960, A.S. Veletsos and N.M. Newmark presented a numerical application to examine the effect of inelastic behavior on the response of simple systems to earthquake motions[5], and J. Penzien also presented a numerical application on dynamic responses of idealized elasto-plastic frame structures[6],[7], and G.N. Bycroft proposed a standard form of wave motions being similar to strong earthquakes, represented by a band-limitted random motion on single-degree-of-freedom systems taking into also account of nonlinearity[8].

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In 1962, T. Hisada, K. Nakagawa and M. Izumi presented response properties of nonlinear systems with several restoring force characteristics[9].

In 1964, P.C. Jennings proposed a general nonlinear hysteretic force-deflection relation[10]. In 1966, R.W. Clough proposed effects of stiffness degradation concerning nonlinear response analyses[11], and S. Okamoto and his cooperaters presented dynamic behavior of one earth dam during earthquakes by observation[12].

In 1967, R.W. Clough and K.L. Benuska presented an application to tall buildings concerning nonlinear earthquake responses[13]. On the other hand, since the beginning of 1960 age, nonlinear responses have been applied to examine the structural design of the Mitsui Kasumigaseki Building completed in spring 1968.

Now, we are going to discuss about earthquake responses of bridges. There is a question whether the criteria of analyses for single-degree-of-freedom systems and tall buildings above mentioned are available or not for bridges in consideration of the structural property.

There are some different vibrational characteristics from tall buildings in bridges, where the first mode of vibration in almost all of cases tends to be of rocking motion, not of shearing vibration due to bending deformation of columns, and the modal response during earthquakes would be predominant in the first mode. A couple of reasons would be considered, (1) ground compliance and (2) a great deal of energy dissipation into ground, these two factors affect the mechanical systems of bridges.

In order to find a clue to the problem, observation of strong motions at about fifty bridges and the surfaces of the foundation ground during earthquakes has been carried out since 1958. In almost all of cases the strong motion has been observed by the accelerograph specified as shown in Table 1.

In this paper the available information based on the observed record representing typical motions of bridges and ground motions is presented, and a bi-linear hysteretic property of a particular bridge is formulated through the observation and analysis.

EARTHQUAKE OBSERVATION AT THE FIFTEEN STATIONS OF BRIDGES

The observation has been carried out on tops of substructures of recently constructed highway bridges and ground surfaces beside them, and at least the earthquake record has been obtained at fifteen bridges shown in Table 2. The physical property of the foundation ground is found to be classified to a great extent, from clayey soil to gravel, in other point of view the sedimentation was formed from the alluvial epoch to the Tertiary epoch. There are several types of foundation structures, for instance, caisson foundations, steel pile foundations, concrete pile foundations and so on, and these fifteen substructures are less 10 meters high from ground surfaces and the superstructure is girders or trusses less 100 meters long.

In Table 3 the maximum acceleration values of all components of earthquake records obtained at these fifteen bridges are shown, and in Fig. 1 the relation between the observed response on tops of bridge substructures and the ground acceleration is shown. Every bridge in the figure has different vibrational characteristics than others, the fundamental natural period would be from 0.2 to 1.0 second, and therefore the figure suggests less formulation concerning the response characteristics of bridges. However, in almost all of cases the acceleration on tops of substructures is greater than that on the surface of the ground.

EARTHQUAKE OBSERVATION AT THE STATION OF THE OCHIAI BRIDGE DURING THE MATSUSHIRO QUAKE SWARM

As well known, The Matsushiro Quake has occurred since the middle of 1965. A peak of it occurred in April 1966. Afterward it has damped out gradually. Since the end of 1965, the response acceleration on the top of the Ochiai Bridge, almost completed on the gravel layer as shown in Fig. 2 and also the ground acceleration have been observed by using a pair of accelerographs. One example of the pair of typical records is shown in Fig. 3. As known through the figure, The Matsushiro Quake seems to show relatively short period characteristics, namely the period from 0.1 to 0.2 seconds. On the other hand, the natural period of the bridge is 0.35 seconds and the damping factor is about 10 percents of critical during the free vibration along the bridge axis. The relation between the response and the ground acceleration can be shown in Fig. 4. There can be seen that the rate of increase of the maximum response acceleration tends to decrease in accordance with the increase of the absolute maximum value of the ground acceleration, and then the above relation can be written statistically as follows,

$$a_R = 8.33\, a_G^{0.50} \quad , \quad \text{in gal} \qquad (1)$$

where a_R represents absolute maximum response accelerations on tops of the substructure, and a_G represents absolute maximum ground accelerations.

As the response acceleration in the above equation can be regarded as that of the gravity center of the whole system of the bridge, which assumption is certainly appropriate to the actual system in this case, the dynamic coefficient, β of the bridge can be written as follows,

$$\beta = 8.33\, a_G^{-0.50} \quad , \quad \text{in gal} \qquad (2)$$

where β represents dynamic coefficients. The above relation given by the observation in the bridge is compared with the case of Sannokai Earth Dam[12], and it is also shown that the rate of increase of the maximum response acceleration of the dam appears to decrease in accordance with the increase of the ground acceleration as same as the case of the bridge.

It can be suggested that such phenomena seem to depend mainly upon two factors, that is, (1) the frequency characteristics of quake motions and (2) the nonlinearities of structures. Concerning the second item, we are going to discuss nonlinear properties in the following chapter.

THE EARTHQUAKE RESPONSE ANALYSIS FOR SIMPLE NONLINEAR SYSTEMS

1. Physical Properties of Bi-linear Systems

Let's consider a single-degree-of-freedom system with bi-linear characteristics as shown in Fig. 5. When the system is subjected to the earthquake ground motion, the differential equation of motion can be written as follows,

$$M \ddot{x} + C \dot{x} + F = - M \ddot{z}_G \quad , \qquad (3)$$

where

M	: Masses,	C	: Damping constants,
F	: Restoring forces of spring (shown in Fig. 5(C)),	K_1	: Initial spring constants,
K_2	: Spring constants after yielding,	p	: Circular frequencies ($= \sqrt{K_1/M}$),
T	: Natural periods ($= 2\pi/p$),	x	: Relative displacements,
$\dot{x}$	: Relative velocities,	$\ddot{x}$	: Relative accelerations,
x_y	: Displacements at yielding points at the virgin curve,	$\ddot{z}_G$	: Ground accelerations.

Eq. (3) can be transformed into the following form by dividing both sides by a term, Mp^2x_y,

$$\frac{\ddot{x}}{p^2 x_y} + \frac{C\dot{x}}{p^2 M x_y} + \frac{F}{p^2 M x_y} = - \frac{\ddot{z}_G}{p^2 x_y} \qquad (4)$$

From this dimensionless equation it can be certainly suggested that the physical similitude will be satisfied. Now let's consider the similitude in this case by using Buckingham Pi theorem. Suppose that nine physical quantities, M, C, p, K_2, $\ddot{z}_G$, x, $\dot{x}$, $\ddot{x}$ and x_y are concerned with this problems. Since the restoring force, F is a dependent function of K_1, K_2, x and x_y, it should be left out. Selecting three fundamental physical quantities which are dimensionally independent to each other, for example, M, p and x_y from these nine quantities, six independent dimensionally products are obtained as follows,

$$\Pi_1 = \frac{C}{pM}, \qquad \Pi_2 = \frac{K_2}{p^2 M}, \qquad \Pi_3 = \frac{\ddot{z}_G}{p^2 x_y},$$
$$\Pi_4 = \frac{x}{x_y}, \qquad \Pi_5 = \frac{\dot{x}}{p\, x_y}, \qquad \Pi_6 = \frac{\ddot{x}}{p^2 x_y}, \tag{5}$$

where Π_1, Π_2, ... , Π_6 are dimensionless products in the theorem, and Π_3, Π_4, Π_5 and Π_6 are the functions of time variables, and furthermore Π_4, Π_5 and Π_6 are the dependent functions on the others.

If the six dimensionless products are to be made the same for a couple of vibrating systems, both systems are undoubtly similar in physical meanings. If furthermore, Π_1, Π_2 and Π_3 are equal for both systems, Π_4, Π_5 and Π_6 are also equal, and both vibrating systems become physically similar, where the values of three fundamental physical quantities can be selected arbitrarily. It is evident from the similarity above mentioned that the scale factor of time must be equal to the square root of that of length, so that the coordinate of time must be reduced according to the scale factor of time. Now suppose a particular problem that two different vibrating systems constructed on the same ground are subjected to the same earthquake ground motion and excited into vibration. In order to exist the physical similitude in them, the both coordinates of time must be equal to each other undoubtedly, therefore Π_1, Π_2, Π_3 and one time constant must be equal in both systems.

In Eq. (5) six dimensionless products have the following physical meanings,

$$\Pi_1 = \frac{C}{p\,M} = \frac{C}{\sqrt{MK_1}} = 2h \qquad (\ h : \text{damping factors}\ ),$$

$$\Pi_2 = \frac{K_2}{p^2 M} = \frac{K_2}{K_1} = 1-\eta \qquad (\ \eta : \text{stiffness factors}),$$

$$\Pi_3 = \frac{\ddot{z}_G}{p^2 x_y} = \frac{\ddot{z}_G}{\gamma\, \ddot{z}_{G\,max}} \qquad (\ \gamma : \text{coefficients of yielding displacements}),$$

$$\Pi_4 = \frac{x}{x_y} = \xi \qquad \text{(dimensionless relative displacements),}$$

$$\Pi_5 = \frac{\dot{x}}{p\,x_y} = \frac{\dot{\xi}}{p} \qquad \text{(dimensionless relative velocities),}$$

$$\Pi_6 = \frac{\ddot{x}}{p^2 x_y} = \frac{\ddot{\xi}}{p^2} \qquad \text{(dimensionless relative accelerations),}$$

where $\ddot{z}_{G\,max}$ is the absolute maximum value of ground motions, $\ddot{z}_G$, $\dot{\xi} = \frac{d\xi}{dt}$, and $\ddot{\xi} = \frac{d^2\xi}{dt^2}$. Substituting these relations for Eq. (4), the following expression can be obtained,

$$\frac{1}{p^2}\ddot{\xi} + \frac{2h}{p}\dot{\xi} + f(\xi, \eta) = -\frac{1}{\gamma}\frac{\ddot{z}_G}{\ddot{z}_{G\,max}} , \qquad (6)$$

where $f(\xi, \eta)$ is a dimensionless restoring force as shown in Fig. 5 (D).

2. The Result of the Response Analysis and the Observation

On the Linear Analysis and the Observation

In the preceding article, the basic idea of earthquake response analyses for bi-linear systems are discussed. If the factor η is taken as zero ($\because K_2/K_1 = 1$), the mechanical model becomes a linear system.

The maximum earthquake acceleration of the fifteen bridges is shown in Table 3 as mentioned already, and about four bridges of them, which vibrational characteristics are known, the earthquake response analyses have been carried out as linear systems. In Table 4 and Fig. 6, the results of analyses are shown in comparison with the observations.

There are available results in which a great deal of potentiality would be shown on the appropriate analysis method of responses of structures subjected to relatively weak ground motions.

On the Bi-linear Analysis and the Observation

Earthquake records over hundreds have been obtained during the period of The Matsushiro Quake Swarm, and above all, on the six particularly strong earthquakes which are within the range of the maximum accelerations from 30 to 300 gal, response analyses have been carried out, and some parts of the results of the analysis are shown in Fig. 7 and 8. Fig. 7 shows an example of one ground motion record and shows observed and analyzed response wave forms. It can be seen from the figure that the result of the bi-linear analysis relatively coincides with the observation. And Fig. 8 shows the response spectrum curves of the typical ground motion shown in Fig. 7, as a typical example. In Table 5 the values of the analyzed response and the observed response are shown. Here we can find a better approximation in bi-linear response than linear response in this bridge.

CONCLUSIONS

According to the observation during earthquakes at sixteen bridges and the response analyses based on the observed results, the following conclusion can be made. The conclusion will be general for other structures qualitatively.

(1) In view of actual problems in earthquake response analyses, acceleration responses of a bridge during a relatively weak ground motion can be evaluated by analytical responses for a linear system taking into account appropriate vibrational characteristics of natural periods and damping factors.

(2) There is much difference between actual acceleration responses during a relatively strong ground motion and analytical responses for a linear system, and in almost all of cases the formers are not greater than the latters.

(3) It is stressed that acceleration responses of a bridge during a relatively strong motion can be evaluated by analytical responses for non-linear systems, even assuming the appropriate restoring force with bi-linear characteristics. In order to obtain the most appropriate mechanical system, it will be recommended to make clear the restoring force characteristics of structures by experimental works and to observe not only response accelerations but also response velocities and displacements of structures during strong motion earthquakes.

(4) It is completely general that the response acceleration is not proportional to the maximum ground acceleration during a relatively strong earthquake, and the dynamic coefficient intends to decrease in accordance with increasing of the ground acceleration.

(5) It is theoretically proved that physical similitude exists in the earthquake response analysis for the bi-linear system.

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Table 1 Strong Motion Accelerograph, SMAC – B2

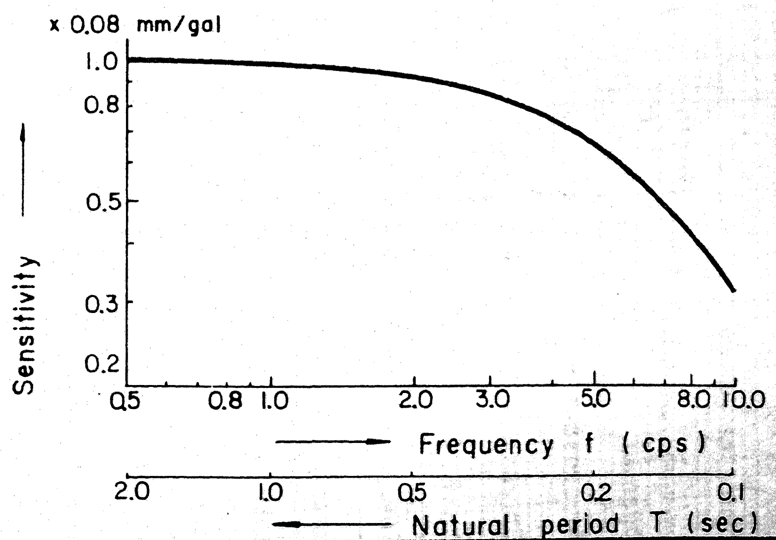
Parts	Specifications and Characteristics
Pendulum	3 – Component accelerometer Natural period : 0.14 sec Sensitivity : 12.5 gal per mm on the paper Damping : critical damping (h = 1) Recording range : 6 ~ 500 gal Magnitication : x 16 (mechanical)
Recording system	Recording paper : scratching stylus roll – paper Recording speed : 10 mm per sec Recording pen : sapphire point
Driving part	Spring motor Operating for about 3 min.
Electric self – starter	Vertical component accelerometer Natural period : 0.3 sec Sensitivity at starting : from 5 to 15 gal
Mechanical Self Starter	Sensitivity at starting : about 100 gal horizontal
Time marking	Interval : 1 sec
Checking device	Pilot lamp and buzzer
Electric power supply	Dry cell 3V x 4 (JIS No FM 5)
Console	Aluminum alloy
Dimension	540 (width) x 540 (length) x 370 (height) mm
Net weight	Approximately 100 kg
Frequency Characteristics	

Table 2 Outline of Fifteen Bridges

Name of Bridge	Structural Feature					No. of Accelerograph *			Vibrational Property **		Index of Location
	Total Length (m)	Width (m)	Superstructure	Substructure	Soil	G	Bridge P	Bridge A	Period T (sec)	Damping Ratio, h	
Ajigawa	1,368	33	Box Girder	Caisson	Silt	1	1		0.5	0.1	1 − 1
							1		0.8	0.1	1 − 2
Amagasaki	280	28.3	Plate Girder	Caisson	Silt	1	1		0.6	0.1	2
Chiyoda	706	6	Warren Truss RC Girder	Caisson	Sand	1	1				3 − 1
				Footing				1			3 − 2
Date	288	7	Warren Truss	Caisson	Gravel	1	1		0.5	0.1	4
Fumimaki	144	7.56	RC Girder	Caisson	Sand	1	1				5
Hirai	622	20	Gerber Box Girder	Caisson	Silt	1	1				6 − 1
							1				6 − 2
Horoman	140	7.5	RC Girder	Caisson	Gravel	1	1				7
Ishiseto	82	6	Howe Truss	Footing	Sand	1	1				8
Itajima	125.16	6	Plate Girder	Caisson	Silt	1	1				9
Nishiarai	444.6	15	Gerber Plate Girder	Caisson	Sand	1	1				10 − 1
				Steel Pile			1				10 − 2
Otanoshike	220.8	11.75	Composite Girder	Steel Pile	Sand	1	1				11
Otome	275	6	Plate Girder	Caisson	Gravel	1	1				12
Shinkatsushika	442	17.7	Box Girder	Caisson	Sand	1	1		0.36	0.07	13
Uonuma	205.6	7	Plate Girder	Caisson	Gravel	1	1				14
Yoshida	270.2	22	Box Girder	Caisson	Sand	1	1		0.2	0.1	15 − 1
							1		0.3	0.1	15 − 2

Note) * G : Ground, P : Pier, A : Abutment, ** in the longitudinal direction of bridge

Table 3 Maximum Accelerations Observed at Fifteen Bridges

Name of Bridge	Date	Magnitude	J.M.A. Intensity	Observed Max. Acc. (gal) Longitudinal Ground	Longitudinal Bridge	Transverse Ground	Transverse Bridge	Vertical Ground	Vertical Bridge	Index of Location	Data No.
Ajigawa	Mar. 27,'63	6.9	4	21.9	67.0	34.0	25.0	14.0	6	1 - 1	1
					28.0		25.0		—	1 - 2	2
Amagasaki	Mar. 27,'63	6.9	4	28.0	46.0	37.6	50.0	13.5	9.0	2	3
Chiyoda	Mar. 12,'67		3	32.5	31.3	25.0	41.3	5.3	7.5	3 - 1	4
					33.8		23.8		10.6	3 - 2	5
	Jul. 5,'67	4.1	3	33.8	58.8	28.8	27.5	5.3	13.8	3 - 1	6
					42.5		25.0		15.0	3 - 2	7
	Sep. 19,'67		3	23.8	36.5	26.3	33.8	5.3	6.3	3 - 1	8
					20.0		27.5		6.3	3 - 2	9
	May 16,'68	7.8	4	87.5	131.3	72.5	112.5	25.0	25.0	3 - 1	10
					91.3		75.0		31.3	3 - 2	11
	May 16,'68	7.5	3	37.5	77.5	31.3	50.0	18.8	17.5	3 - 1	12
					43.8		36.3		18.8	3 - 2	13
Date	Jan. 17,'67	6.3	3	22.1	43.8	19.1	28.8	—	8.8	4	14
Fumimaki	Dec. 24,'63			37.0	43.9	27.5	22.4	—	—	5	15
Hirai	Mar. 19,'67		3	15.6	25.0	17.5	16.3	10.0	—	6 - 1	16
Horoman	May 16,'68	7.8	5	68.8	72.5	51.3	90.0	23.8	36.3	7	17
	May 16,'68	7.5	5	56.3	68.8	43.8	87.5	18.8	25.0	7	18
Ishiseto	Feb. 21,'68	6.1	4	22.5	50.0	20.0	25.0	10.0	5.0	8	19
	Mar. 25,'68	5.6	3	22.5	55.0	22.5	35.0	10.0	5.0	8	20
	Apr. 1,'68	7.5	4	25.0	70.0	30.0	35.0	15.0	10.0	8	21
Itajima	Jan. 1,'67	4.6	2	17.5	28.8	27.5	18.8	—	—	9	22
	Apr. 1,'68	7.5	4	185.0	310.0	170.0	210.0	42.5	55.0	9	23
	Apr. 1,'68	6.2	3	42.5	62.5	35.0	35.0	10.0	10.0	9	24
Nishiarai	May 31,'65		3	21.3	28.0	15.0	16.0	—	—	10 - 2	25
	Nov. 10,'67		3	15.0	16.2	11.3	12.5	—	—	10 - 2	26
Otanoshike	May 16,'68	7.8	4	31.3	45.0	41.3	43.8	12.5	12.5	11	27
Otome	Nov. 28,'67		2	16.1	23.7	10.0	8.7	—	—	12	28
Shinkatsushika	Mar. 2,'67		3	15.0	38.8	21.3	28.7	—	—	13	29
	Nov. 10,'67		3	20.1	43.8	13.8	48.8	—	6.0	13	30
Uonuma	Jan. 9,'66	5.2	3	28.0	65.0	32.5	27.5	—	—	14	31
	Sep. 8,'66	5.1	3	50.0	63.0	44.0	63.0	14.0	13.0	14	32
Yoshida	Aug. 19,'61	7.0	3	15.8	38.0	19.0	—	—	—	15 - 1	33
					43.2		—	—	—	15 - 2	34

Table 4 Observed Accelerations and Linear Responses of Four Bridges

Name of Bridge	Date	Magnitude	J. M. A. Intensity	Observed Max. Acc. (gal)		Linear Response Analysis			Data No.
				Ground	Top of Pier	Max. Acc.(gal)	Idealized System T (sec)	Idealized System h	
Ajigawa	Mar. 27,'63	6.9	4	21.9	67.0	65.8	0.5	0.1	1
					28.0	39.5	0.8	0.1	2
Amagasaki	Mar. 27,'63	6.9	4	28.0	46.0	53.1	0.6	0.1	3
Date	Jan. 17,'67	6.3	3	22.1	43.8	31.0	0.5	0.1	14
Yoshida	Aug.19,'61	7.0	3	15.8	38.0	31.6	0.2	0.1	33
					43.2	41.0	0.3	0.1	34

Table 5 Observed Accelerations and Analyzed Responses of the Ochiai Bridge

Earthquake No.	Date Time	Observed Max. Acc. Ground a_G (gal)	Observed Max. Acc. Top of Pier a_R (gal)	Analyzed Response Acc. Linear a_R^L (gal)	Analyzed Response Acc. Nonlinear Case 1 a_R^{N1} (gal)	Analyzed Response Acc. Nonlinear Case 2 a_R^{N2} (gal)	Percentages of Analyzed Acc. to Observed Acc. $\frac{a_R^L}{a_R}\times100$ (%)	$\frac{a_R^{N1}}{a_R}\times100$ (%)	$\frac{a_R^{N2}}{a_R}\times100$ (%)
I	Apr. 5,'66 17:52	30.0	51.3	43.7	43.7	43.7	85.2	85.2	85.2
II	Feb. 12,'66 04:05	60.0	43.8	55.1	55.1	54.0	125.8	125.8	123.3
III	May 6,'66 19:08	70.0	100.0	97.1	97.1	80.5	97.1	97.1	80.5
IV	May 28,'66 14:21	102.5	107.5	156.4	128.1	106.6	145.5	119.2	99.2
V	Apr. 5,'66 17:51	212.5	190.0	325.8	187.0	195.5	171.5	98.4	102.9
VI	Apr. 17,'66 10:21	302.5	145.0	303.4	202.7	211.8	209.2	139.8	146.1

Note) Linear : Linear System ; $T = 0.35^{sec}$, $h = 0.1$

Nonlinear Case 1 : Bi - linear System ; $T=0.35^{sec}$, $h=0.1$, $\eta=0.6$, $X_y=0.3^{cm}$

Nonlinear Case 2 : Bi - linear System ; $T=0.35^{sec}$, $h=0.1$, $\eta=0.4$, $X_y=0.15^{cm}$

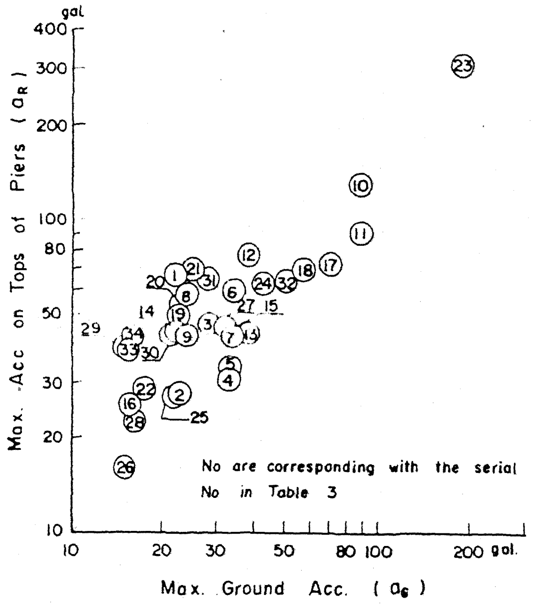


Fig. 1 Observed Results at Fifteen Bridges
(in the longitudinal direction of bridges)

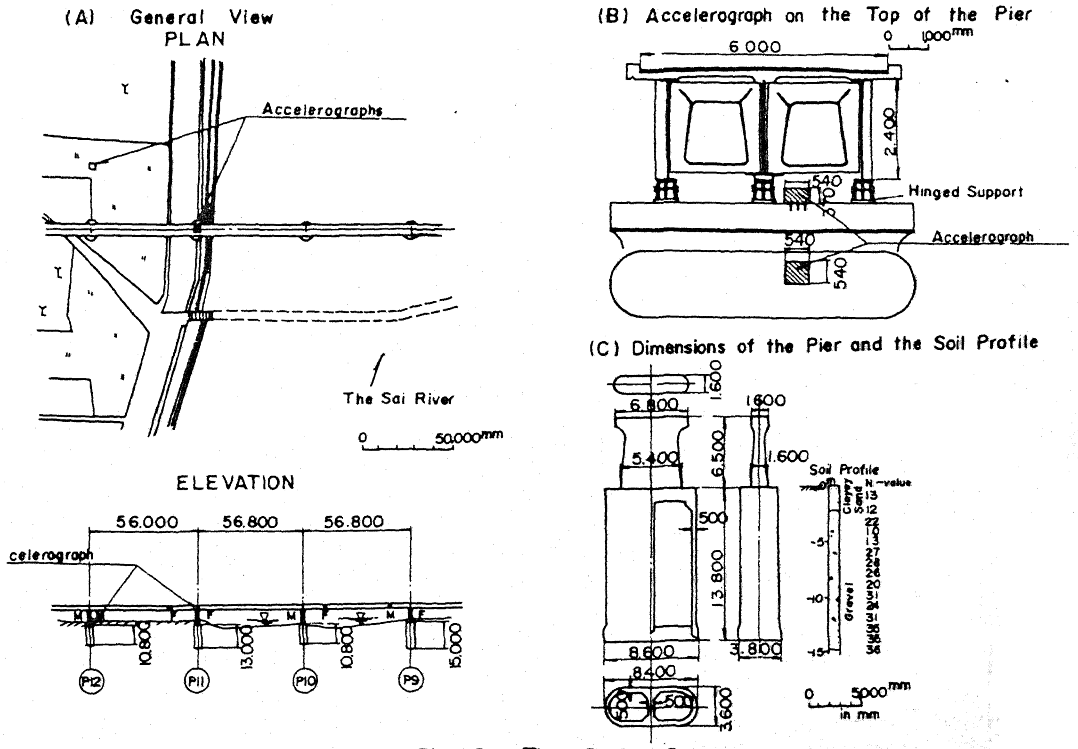


Fig. 2 The Ochiai Bridge

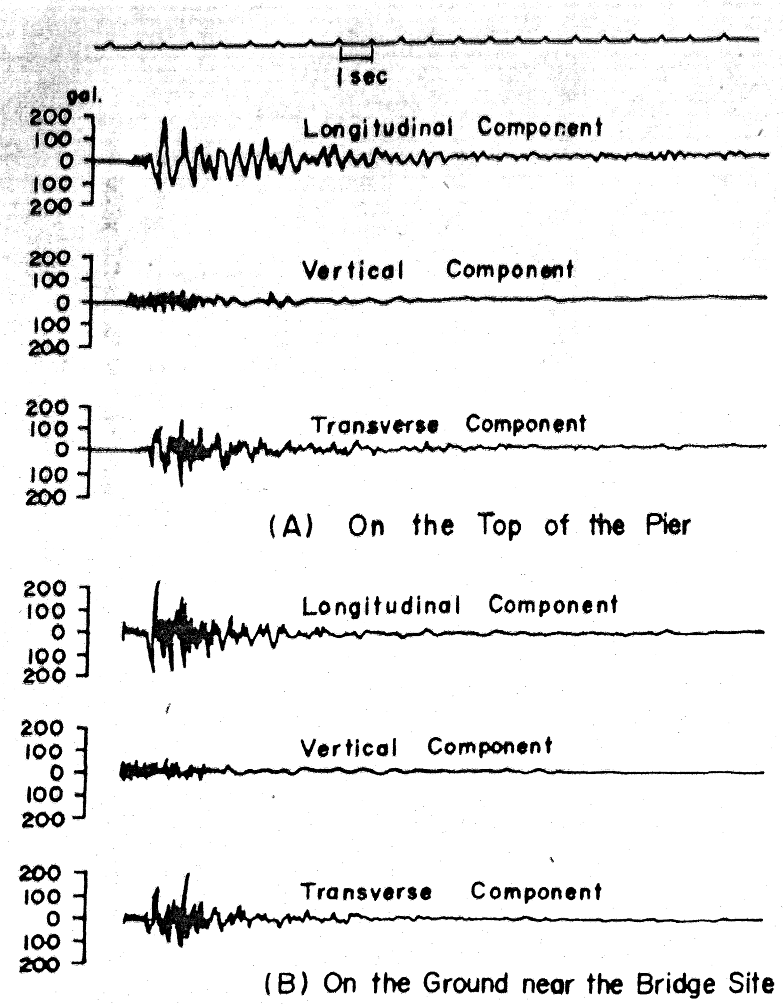


Fig. 3 A Pair of Example of Acceleration Records Observed at The Ochiai Bridge Station

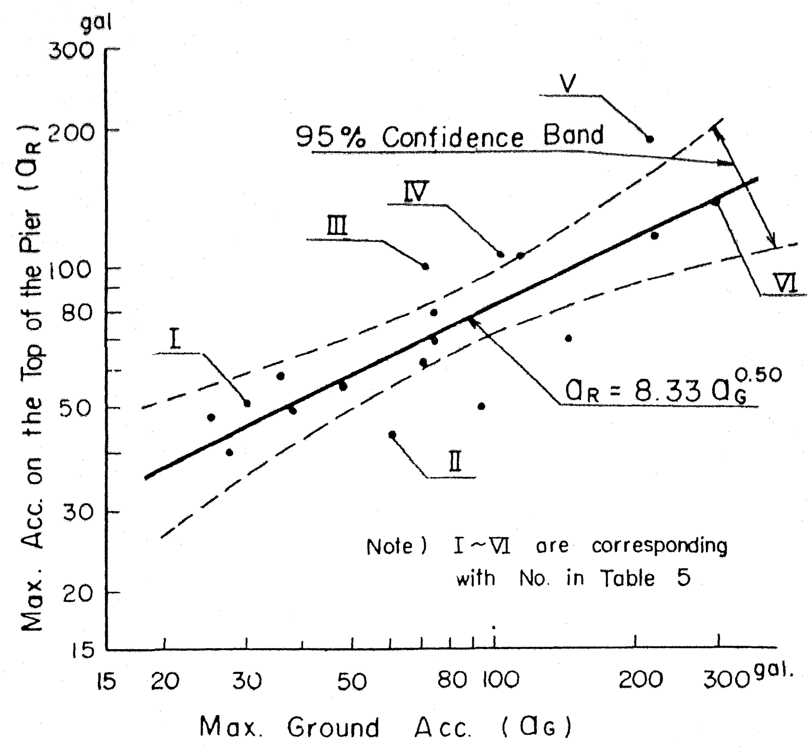


Fig. 4 Relation Between Ground Accelerations and Response Accelerations Observed at the Ochiai Bridge (Longitudinal Direction)

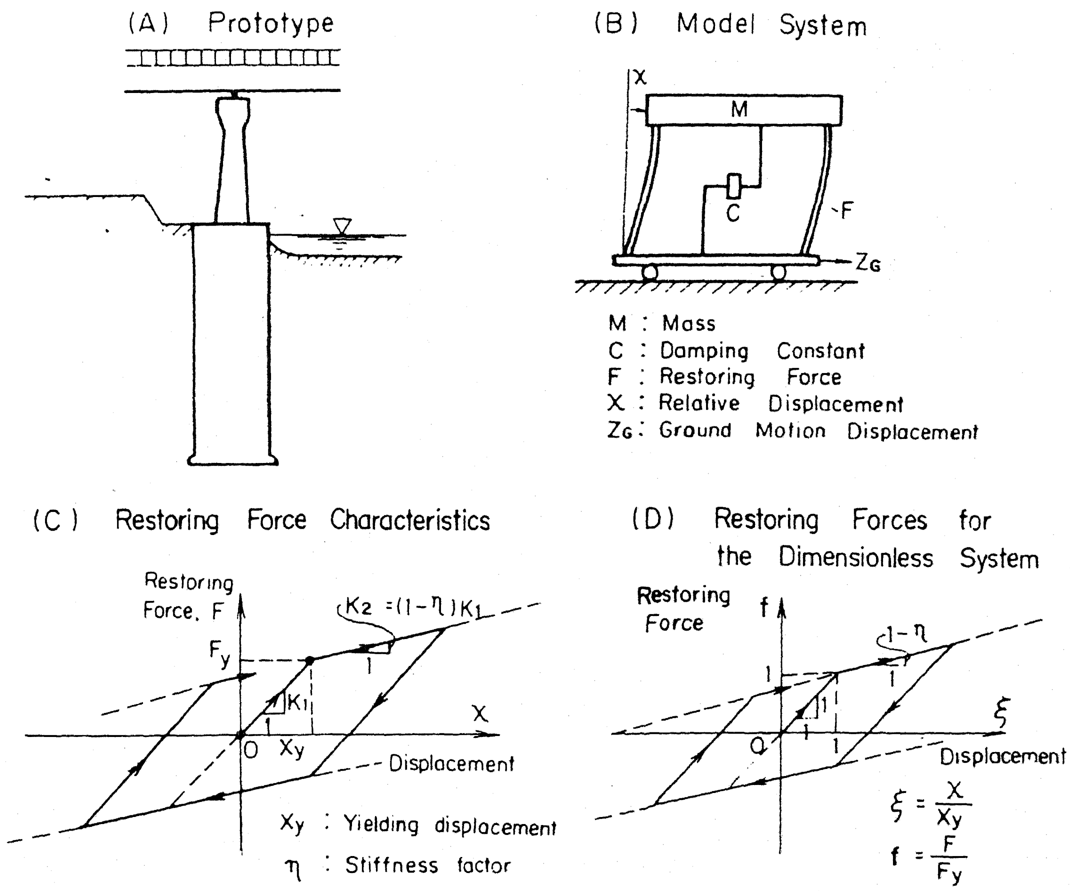


Fig. 5 Mechanical Models in Nonlinear Analyses

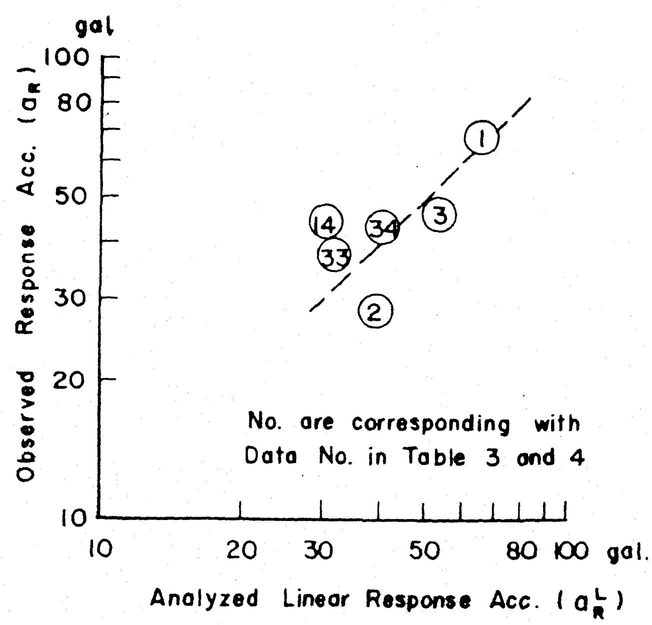
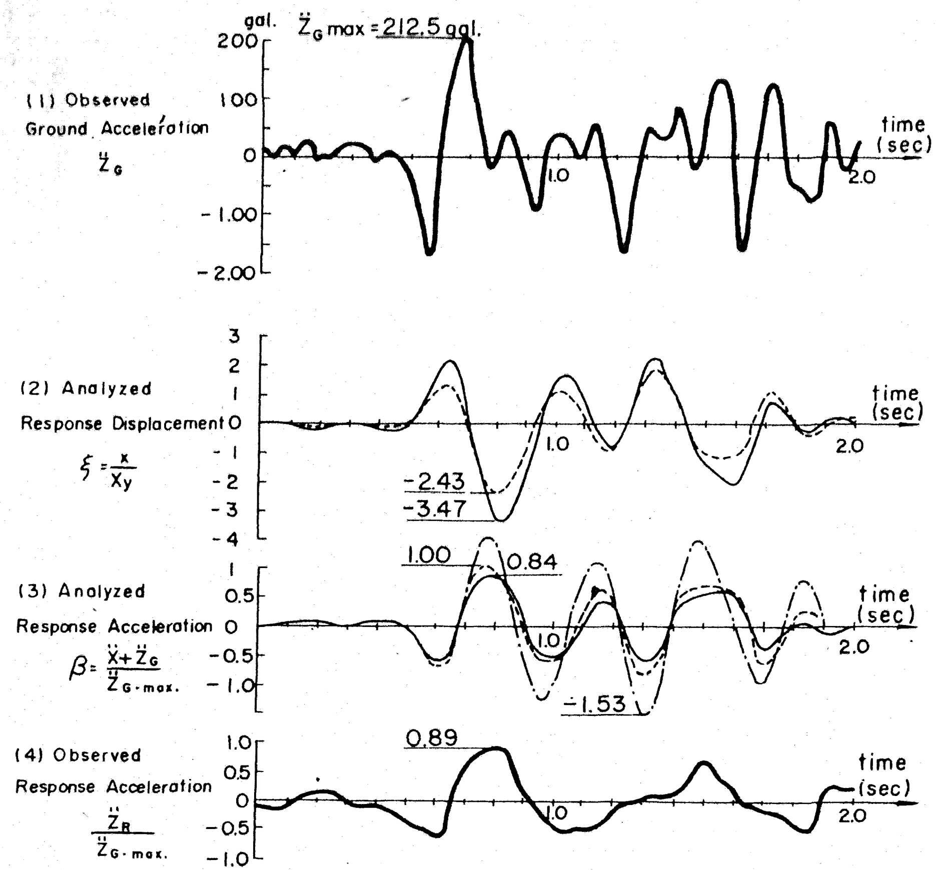


Fig. 6 Comparison between Observed and Analyzed Linear Response Acc. at Four Bridges



—·—·— : Linear System of $T = 0.35^{sec}$, $h = 0.1$

——— : Nonlinear System of $T = 0.35^{sec}$, $h = 0.1$, $\eta = 0.6$, $\gamma = 0.4$ ($X_y = 0.264^{cm}$)

– – – – : Nonlinear System of $T = 0.35^{sec}$, $h = 0.1$, $\eta = 0.6$, $\gamma = 0.6$ ($X_y = 0.395^{cm}$)

━━━ : Observed Accelerograms

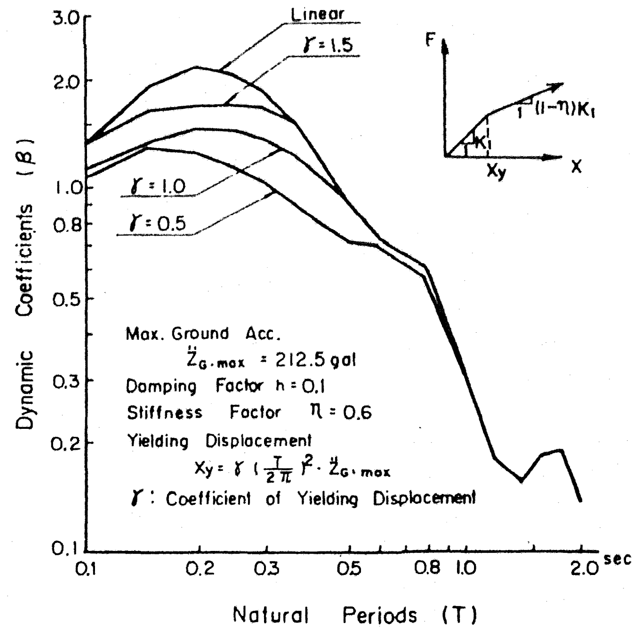


Fig. 8 Examples of Earthquake Response Spectrum Curues for Bi-linear Systems