Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

12-1-17

SEISMIC LOAD DETERMINATION OF BRIDGES BY CONSIDERING SYSTEM PERFORMANCE OF HIGHWAY NETWORK

Masaaki NONAKA[1] and Tsuneo KATAYAMA[2]

[1] Earthquake Disaster Mitigation, Japan Engineering Consultants,
Ohkubo 2-2-6, Shinjuku-ku, Tokyo, Japan
[2] Institute of Industrial Science, University of Tokyo,
Roppongi 7-22-1, Minato-ku, Tokyo, Japan

SUMMARY

An evaluation formula is suggested in relation to the optimum seismic load based on cost-benefit analyses which include the three essential seismic loss: 1)the extra cost needed for earthquake-resistant design, 2)the seismic damage cost sustained by bridge(s) and 3)the users' loss due to the highway network malperformance. From the results of this analyses, it can be seen that a higher optimum seismic load is justified for more important bridges and the combination of optimum seismic load for each bridge in the network was obtained by taking the network-performance point of view into account.

INTRODUCTION

A civil engineering structure usually involves a large construction cost and is expected to have a long service life once completed. In an earthquake-prone country like Japan, therefore, it is essential for such structures to have an "economical" earthquake-resistant design. To minimize the total effect of the seismic damage to bridges, it is not only necessary to ensure the structural earthquake-resistant capability but also to account for the aftereffects of the suspension of traffic due to the damaged bridge in the post earthquake period. Although evaluation of the latter type of effect is closely related to the importance factor of the seismic design of highway bridges, quantitative studies on this problem have not been sufficiently investigated to date.

In view of the foregoing, we have attempted to determine the optimum seismic load for highway bridges, taking into account the seismic damage rate of highway bridges in the past and the system performance of highway networks based on the cost-benefit model and the best available knowledge.

COST-BENEFIT ANALYSES

General Concept A typical example of the cost flow of a highway bridge at the end of its service life is shown in Figure 1(a). Firstly, the cost originating at the time of construction may be divided into (A)the original cost and (B)the extra costs needed for an earthquake-resistant design. Next, (C)damage costs, occur at the time of an earthquake and may be divided into the seismic damage cost sustained by the bridge and the users' loss due to the highway network malperformance. The total loss associated with earthquakes is obtained by adding (B) to (C), both of which represents the relation of trade-off to each other. While (B) proportionally increases as the seismic load increases, (C) decreases. If we define the most desirable state achieved as the minimum point of total loss, the optimum seismic load can be determined as shown in Figure 1(b). Using the same approach, finding of the optimum level has been attempted in some studies in various fields: the decision problem of the effective size of industrial equipment, effective countermeasures for flood defense and so on. The most difficult aspects of this type of problem are to determine how to convert the damage into monetary term and what parameters should be used in the analyses.

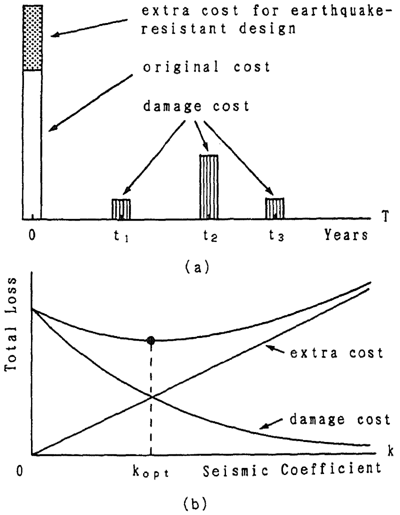


Figure 1 Typical Costs Flow and Optimum Seismic Load on Highway Bridge.

Evaluation of Parameters It was assumed that resistance to earthquakes is represented by the design horizontal seismic coefficient "k" and the severity of earthquake motion is represented by the intensity on the Japan Meteorological Agency's scale "IL". Therefore, the seismic load is generally obtained by "k" times dead load. In the present study, minimization of the total loss was made only in the range between k=0 and 0.3, because the relations given by this study are probably not reliable for values of k greater than 0.3. The extra cost needed for an earthquake-resistant design IC(k) for a design with k=k over the original design with k=0 may be expressed by IC(k)=10ik, where "i" is the cost-increase rate and is considered to be in the range between 0.05 and 0.2. For example, i=0.2 means that 20% extra cost is needed for every 0.1 increase in k over the original cost which does not take into account the seismic loading. The damage rate of highway bridge is defined as the ratio which is given by the damage cost required to restore the damage portion of the bridge divided by the cost of complete reconstruction after the earthquake. The mean damage rate of the highway bridge "MDR" is defined as the mean of DR of all bridges in an area where the ground motion severity may be considered to be constant. By using the damage of highway bridges during four earthquakes, the mean damage rate was obtained as shown in Table 1. A questionaire survey was conducted to generally appraise how an average professional estimates the mean damage rate MDR for all possible combinations of k and IL. Figure 2 shows the mean damage rate surface "CMDR" determined by the experts' opinions together with the mean damage rates listed in Table 1. The mean annual occurrence rate of earthquake motion "SR" was evaluated using the

Table 1 Mean Damage Rates Obtained from Past Earthquake Damage Data.

Earthquake (Area)	*MDR* (%)
Fukui (Intensity VII)	17.3
Niigata (Intensity V)	5.71
Miyagi-ken-oki (Intensity V)	1.62
Miyagi-ken-oki (Intensity IV)	0.352
San Fernando (Intensity VI)	10.5

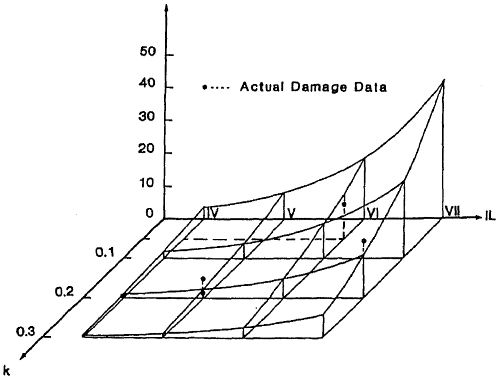
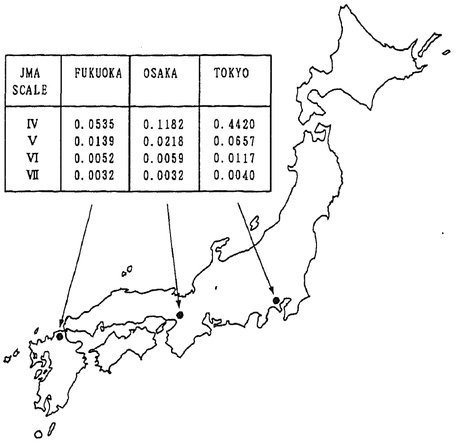


Figure 2 Mean Damage Rate Surface Determined from Experts' Opinions and Past Earthquake Damege Data.

earthquake catalogue of Japan Meteorological Agency (Figure 3). To evaluate the expected loss in the service period, the damage costs per year must be multiplied by a constant δ. The depreciating value of the bridge is considerd a smooth function which approaches the rate of residual value A as the utilized years near the service life T. $\delta=(1-A)/(1-A^{1/T})$. For example, $\delta=20$ is obtained for A=0.1, T=50years.

Optimum Seismic Load of Bridges as a Single Structure Using the parameters discussed above, the amount of the total loss rate is measured by the equation given below.



JMA SCALE	FUKUOKA	OSAKA	TOKYO
IV	0.0535	0.1182	0.4420
V	0.0139	0.0218	0.0657
VI	0.0052	0.0059	0.0117
VII	0.0032	0.0032	0.0040

Figure 3 Mean Annual Occurrence Rates SR(IL)'s at Three Sites Investigated.

$$TLR = IC(k) + \alpha\,\delta\,\{1+IC(k)\}\sum_{IL=4}^{7}\frac{CMDR(k,IL)}{100}SR(IL) \qquad (1)$$

The first term represents the extra cost for an earthquake-resistant design and the second term represents the cost associated with seismic damage. From the result of putting the parameters' value (i=0.15, α=1, δ=20, for example) into the equation, the optimum seismic coefficient and the total loss rate as such state of a highway bridge can be obtained as shown in Figure 4. It can be seen that the optimum seismic coefficient in Tokyo is 0.1 while indicate that non-earthquake-resistant designs are found to be optimum in Osaka and Fukuoka. In this case, the expected damage cost in Tokyo represents about 50% of the original cost while those in Osaka and Fukuoka represent about 18% and 12% of original cost respectively. In considering the indirect loss regarded as the same amount as the direct costs caused by seismic damage to highway bridges (α=2), it can be seen that the optimum seismic coefficient in Tokyo is 0.26 while it is only 0.01 in Osaka, and Fukuoka indicating that non-earthquake-resistant designs are optimum. Comparison of the results of both cases indicates the indirect loss of bridge in the area with the greater seismic hazards is the greater part of the total loss.

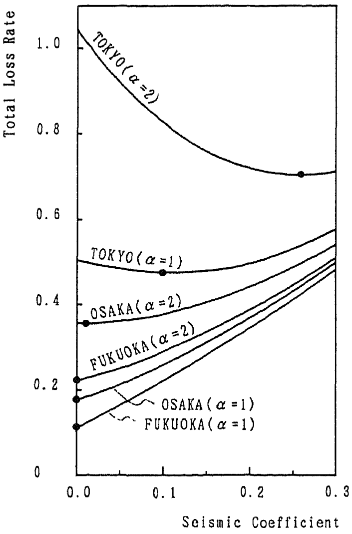


Figure 4 Total Loss Rates for Three Sites.

USERS' LOSS IN AN EXAMPLE NETWORK

The malperformance of the traffic system caused by highway bridge damage has often be seen during the post earthquake period, frequently putting road users to much inconvenience which is described as "users' loss" and is considered to account for a large part of incident loss. All traffic conditions in the whole highway network can be obtained by changing the trip time function parameters of the network analyses, including the pertinent highway bridges. Users' loss was evaluated by considering the number of affected users and the increase of their trip time within the whole network from the results of network analyses. Figure 5 shows the relation between traffic flow and trip time in a certain OD (Origin-Destination) pair. Generally, even if there is no traffic flow, it takes some trip time between OD and the trip time increases with the flow. The demand curve was assumed as a straight line which passes through both coordinates (F, T) and (0, nT) in this figure, where "F" and "T" are the flow value and the trip time in ordinary traffic condition. "n" denotes a size of trip demand such that it is a real number more than 1 and is named as "slope index" in this study. When traffic is restricted along a bridge, the intercept of the trip time function become high because detour vehicles originate and the slope become steep on account of traffic jams around the damaged bridge. The traffic condition in this OD after the bridge traffic restriction is indicated by the coordinates of the intersection of both lines (F', T') which denotes "the equilibrium of demand and supply" in economics. Users' loss in this OD is obtained by the shaded area and is equal to the "the loss of consumers' surplus" in economics. Users' loss in the whole network is given by summation of all ODs'.

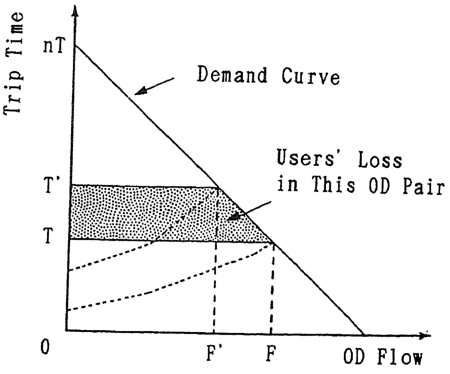


Figure 5 Traffic Demand, Trip Time Function, and Users' Loss.

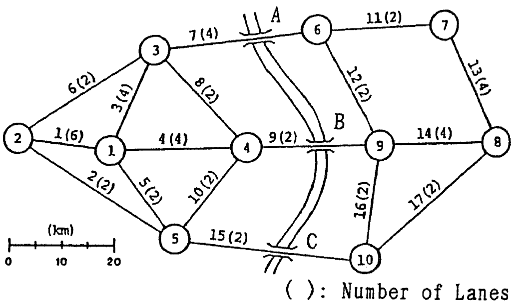


Figure 6 Example Highway Network.

In the case of the example highway network consisting of 17 links, 10 nodes and 3 bridges shown in Figure 6, a flow of 333,370 vehicles/day flow was counted in the whole network of which a 60,010 vehicles/day flow passed over three bridges (Bridge A; 35,335 veh./day, Bridge B; 17,038 veh./day, Bridge C; 7,637 veh./day). The trip time function parameter of links which can be assumed with respect to their number of lanes and length is shown in Table 2. The trip time in each OD was obtained by network analyses based on the OD flow (Table 3).

Table 2 Trip Time Function Parameters of the Links.

Link No.	a	b
1	1.74×10^{-4}	15.00
2	2.33×10^{-3}	42.00
3	2.60×10^{-4}	15.00
4	3.26×10^{-4}	18.75
5	1.33×10^{-3}	24.00
6	2.00×10^{-3}	36.00
7	3.91×10^{-4}	22.50
8	1.67×10^{-3}	30.00
9	1.67×10^{-3}	30.00
10	1.67×10^{-3}	30.00
11	1.67×10^{-3}	30.00
12	1.67×10^{-3}	30.00
13	3.26×10^{-4}	18.75
14	3.26×10^{-4}	18.75
15	2.33×10^{-3}	42.00
16	1.67×10^{-3}	30.00
17	2.33×10^{-3}	42.00

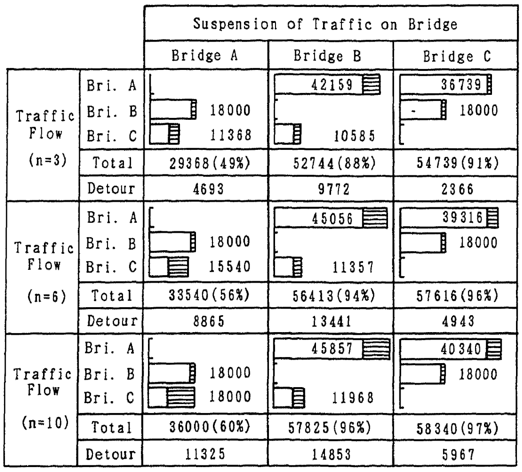
Table 3 OD Flow and Trip Times in Ordinary State.

OD Flow (Vehicles / Day)

	1	2	3	4	5	6	7	8	9	10
1		80000	44000	37000	14100	7700	1300	4200	3000	80
2	29		1400	2000	1100	1040	460	1450	500	120
3	29	44		9300	390	20000	470	850	1150	200
4	34	63	47		2350	600	120	280	6500	300
5	44	46	73	38		270	130	390	5400	3500
6	65	80	36	83	109		2500	1200	1900	120
7	103	119	74	121	140	38		45000	2900	110
8	123	152	108	89	105	72	34		26800	290
9	92	121	77	58	97	41	65	31		900
10	104	106	114	95	60	78	80	46	37	

Trip Time (Minutes)

In the analyses, three traffic conditions were assumed for each bridge during the post earthquake period: intact, half lanes passable, suspension. Therefore, there are 27 kinds of traffic restrictions in the whole network and users' loss due to all traffic restrictions in the highway network was obtained. Assuming that the slope indexes of the demand curve are given by 3, 6 and 10, the variations of traffic flow with each bridge suspended independently from the network are as shown in Figure 7. Since the traffic flow over bridge B in the case of ordinary functioning is nearly equal to its capacity, suspension of traffic on bridges A and C leads traffic to bridge B easily reaching its capacity. In the case of Bridge A being suspended with demand index 10, the traffic flow on both bridge B and C reach the volume. Even if the traffic demand is much larger than this case, both bridges cannot meet an increased flow any longer. This type of traffic state has often been seen in past earthquake disasters.



		Suspension of Traffic on Bridge		
		Bridge A	Bridge B	Bridge C
Traffic Flow (n=3)	Bri. A		42159	36739
	Bri. B	18000		- 18000
	Bri. C	11368	10585	
	Total	29368(49%)	52744(88%)	54739(91%)
	Detour	4693	9772	2366
Traffic Flow (n=6)	Bri. A		45056	39316
	Bri. B	18000		18000
	Bri. C	15540	11357	
	Total	33540(56%)	56413(94%)	57616(96%)
	Detour	8865	13441	4943
Traffic Flow (n=10)	Bri. A		45857	40340
	Bri. B	18000		18000
	Bri. C	18000	11968	
	Total	36000(60%)	57825(96%)	58340(97%)
	Detour	11325	14853	5967

Figure 7 Variation of Traffic Flow of the Links after the Suspension of Traffic Caused by Each One Bridge's Damage.

In order to introduce the effect of users' loss into the seismic load of bridges, the occurrence probabilities must be evaluated. The distribution of highway bridges' damage rate was investigated using past earthquake data and the relationship between the mean value and variance of damage rate was found. It was assumed that events of half lanes passable and suspension on bridges occurred with bridge damage rates of more than 5% and 70% respectively. Finally, the occurrence probabilities of traffic restrictions of bridges was obtained for all possible combinations of seismic coefficients k and seismic intensity IL as shown in Figure 8.

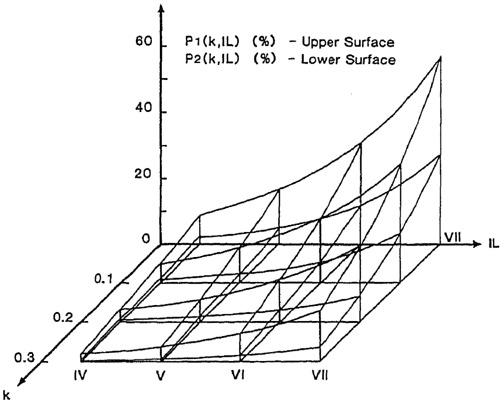


Figure 8 Occurrence Probabilities of Events of Half Lanes Passable and Suspension on Bridges.

OPTIMUM SEISMIC COEFFICIENT

Considering users' loss obtained by the approach mentioned formerly, the amount of total loss rate was measured by the equation given below:

$$TLR(k_A, k_B, k_C) = \sum_{k=k_A}^{k_C} IC(k) + \delta \sum_{IL=4}^{7} \left[\sum_{k=k_A}^{k_C} \{1+IC(k)\} \frac{CMDR(k, IL)}{100} + \frac{\lambda \sum TUL(S_A, S_B, S_C) P_{SA, SB, SC}(k, IL)}{COST} \right] SR(IL) \quad (2)$$

Here, λ: users' time value, S_A, S_B, S_C: traffic restriction state on Bridg A, B, C, respectively, TUL: total users' loss in the whole network, $P_{SA, SB, SC}(k, IL)$: occurrence probability of restriction state(S_A, S_B, S_C) obtained by the product of occurrence probabilities of all bridge, COST: the summation of all bridge's construction costs.

The optimum seismic coefficients and their total loss rates for Bridges A,B and C were obtained as shown in Table 4. Here, this highway network is assumed to be in the Kinki area of Japan and the original construction cost of Bridges A,B and C are considered to be ¥250, ¥200, ¥200 million respectively, the service life as 50 years and the users' time value as ¥25/minute.

The optimum seisimic coefficients of all the bridges in the network is believed as the degree of importance from the network-performance point of view to add to the results of Equation 1. For example, in the case of n=3 and i=15%, the optimum coefficients of Bridge A, B and C were 0.2, 0.14 and 0.07 respectively from the results of Equation 2. It can be seen that the loss associated with Bridge A is greater than that of Bridge B and C. Therefore, a higher seismic coefficient is justified for the design of Bridge A. In the case of n=6, i=15%, the optimum seismic coefficients of Bridges A, B and C were 0.3, 0.21 and 0.12 respectively. Compared with the results of both cases, the increased rate of optimum seismic coefficient was arranged for Bridges A, B and C. The result shows that as the network will have an increased traffic demand in a post-earthquake period, it is reasonable to invest much extra cost for earthquake resistant design for important bridges.

Table 4 Optimum Seismic Coefficients and Total Loss Rate of all Bridge.

	i(%)	n=3				n=6			
		k_{opt}			TLR	k_{opt}			TLR
		A	B	C		A	B	C	
$\delta = \frac{1-A}{1-A^{1/T}}$	5	0.30	0.30	0.27	0.27	0.30	0.30	0.30	0.34
	10	0.27	0.21	0.14	0.40	0.30	0.28	0.20	0.49
A=0.1	15	0.20	0.14	0.07	0.49	0.30	0.21	0.12	0.61
T=50 years	20	0.15	0.08	0.01	0.55	0.27	0.16	0.07	0.72

CLOSING REMARKS

The optimum seismic loads of highway bridges were determined by the formula based on the cost-benefit model. The importance factor of highway bridges which investigated by the network analyses was introduced into the decision of their optimum seismic load. The reliability of a cost-benefit analysis strongly depends on the values of parameters assumed in the model. The conversion of trip time into trip cost is by itself an extremely difficult problem. However, it is hoped that the findings of this study will cast some light on the future improvement of the earthquake-resistant design of bridges by taking into account more rational importance factors from the network-performance point of view.

ACKNOWLEDGMENT

The first author wishes to express his gratitude to research fellows of the Katayama Laboratory in University of Tokyo for their frequent helpful suggestions and assistance.

REFERENCES

Nonaka, M., "Studies on Optimum Design Seismic Coefficient Determination of Highway Bridges", Doctor Thesis Submitted to the Dept. of Civil Engineering, University of Tokyo (1988). (in Japanese)