A SIMPLE METHOD FOR EVALUATING SEISMIC SAFETY OF EXISTING BRIDGE STRUCTURES

by

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SYNOPSIS

Statistical analysis was made on the effects of various characteristics of bridges on their seismic damage. Based on the results thus obtained, a simple criteria was proposed for the preliminary evaluation of seismic safety (or vulnerability) of existing bridge structures with particular emphasis on the fall of superstructures. The adequacy of the criteria was examined by using past damage data of actual bridges.

METHOD OF STATISTICAL ANALYSIS

Thirty bridges damaged to different degrees by the 1923 Kanto, the 1948 Fukui and the 1964 Niigata earthquake were selected as samples. Fourteen bridges were those collapsed including five bridges which almost collapsed (spans fell off their supports), while the rest were damaged but did not collapse. Degree of damage was evaluated by referring to post-earthquake reconnaissance reports, and a numerical value assigned for each sample. Let the assigned degree of damage of sample i be denoted by A_i. Values of A_i varied from 1.5 to 5 for the collapsed bridges, and from 0.8 to 2 for the rest. Though emphasis was placed on whether or not a bridge collapsed for the evaluation of A_i, the degree of overall damage was also taken into account.

Then, items characterizing the properties of a bridge were identified that were likely to have influenced the degree of damage. After several preliminary analyses, a total of nine items were selected. They are shown in the first column of Table 1. Each item was divided into two or three categories. Selection of categories was inevitably affected by the characteristics of the sample set used for analysis. For example, the samples did not include a damaged bridge built on Type I ground. Since two samples were arch-type and the rest were simple-beam or cantilever-beam-type bridges, there are only two categories in item 3. As shown in Table 1, there are a total of 22 categories for the nine items.

Define a variable x_{ijk} corresponding to category k in item j of sample i. This variable takes a value of 1(one) if the properties of sample i corresponds to category k for item j, and 0(zero) otherwise. In other words, though there are 22 such variables for each sample, only nine of them have values of 1 and the rest are 0. Denote the weighting factor of category k in item j by w_{jk}, and consider

$$\alpha_i = \prod_{j=1}^{9} \prod_{k=1}^{2 \text{ or } 3} w_{jk}^{x_{ijk}} \qquad (1)$$

It is assumed that, if appropriate values were determined for w_{jk}, Eq.(1) gives an estimate of the degree of seismic damage to be sustained by the bridge defined by a set of variables x_{ijk}. Values of w_{jk} are so determined that the calculated degrees of damage α_i's of the thirty samples best agree

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with their assigned degrees of damage A_i's. Replacing α_i by A_i and taking logarithms of both sides of Eq.(1) yield a set of linear simultaneous equations with unknowns log w_{jk}. Therefore, the solution procedure becomes essentially similar to the least-square solution of linear simultaneous equations except for the fact that the variables x_{ijk} are subject to the following relation

$$\sum_{k=1}^{m} x_{ijk} = 1 \qquad (2)$$

where m is the number of categories in item j, namely $m = 2$ or 3 in the present analysis.

RESULTS OF STATISTICAL ANALYSIS

The values of weighting factors determined by the above-mentioned method are shown in Table 1. Since the number of samples was not sufficient and the quality of the sample set seems to be rather biased, the result in Table 1 shows several tendencies which are contradictory to what an ordinary earthquake engineer would expect from experience. Though the ground condition generally becomes worse as it goes from Type II to IV, the weighting factor of Type III (1.86) is greater than that of Type IV (1.60). Such inconsistency is also seen for the categories in item 5. Therefore, if a criteria is to be derived from these results of statistical analysis, it is necessary to modify them by taking account of engineering judgment based on experience.

In the last column of Table 1 are shown the ranges of weighting factors for the nine items. The range of an item is defined as the ratio of the maximum weighting factor to the minimum in the item under consideration. The greater the value of the range of an item is, the more important effect that item has on the degree of seismic damage to bridges. It is seen that type of superstructure, severity of ground shaking, liquefaction and ground condition of the site are the more important factors for the seismic safety of bridge structures.

Fig.1 shows the correlation between the assigned and the calculated degrees of seismic damage. With a few exceptions, the calculated (or estimated) degree of damage is within ±30% of the assigned value.

PROPOSED CRITERIA

In order to derive a criteria for the evaluation of the seismic safety of existing bridges in general, account should be taken of the followings:

(1) A value should be assigned for the weighting factor of Type I ground.

(2) A value should be assigned for the weighting factor of continuous-beam-type bridges.

(3) A value of the weighting factor should be assigned for bridges in which special care is paid for preventing spans from falling off their supports.

(4) Width of substructure's crest should be considered in connection with the length of span. The Specifications for Earthquake-Resistant Design of Highway Bridges (Japan Road Association, 1971) provides the minimum length S (cm) between the end of bearing and

the edge of substructure's crest as

$$S = 20 + 0.5\, l \qquad \text{for } l \le 100$$

$$S = 30 + 0.4\, l \qquad \text{for } l \ge 100$$

where l is the span length in meters.

(5) Though the effect of material used for abutment or pier was not noticeable for the samples used (not included in the final analysis shown in Table 1), this item should be included in the criteria to be used for both older and newer existing bridges.

By taking account of the above-mentioned considerations and by practicing engineering judgment based on experience, a criteria is *tentatively* proposed in Table 2. The degree of seismic safety (or vulnerability) is to be judged by the product of the ten weighting factors, each of which is taken from one of the ten items in Table 2. The larger the product is, the more vulnerable the bridge is to seismic effects and the higher the possibility is for its girders to fall off the supports.

It is seen that some of the important values of weighting factors introduced in the criteria are not based on the results of the statistical analysis. For example, a weighting factor of 2.0 was assigned for continuous-beam-type bridges, 0.6 for the bearing with antiseismic devices, and 0.8 for the width of substructure's crest with $A/S \ge 1$. Adequacy of these values was examined as shown in Fig.2 by comparing the relative order of seismic safety evaluated by the criteria for various types of bridges commonly encountered in practice which are characterized by four of the items in the criteria, i.e. "superstructure's type", "type of bearing (whether or not antiseismic devices are installed)", "number of spans", and "width of substructure's crest". Though there may be found some small inconsistencies in the relative order of seismic safety as shown in Fig.2, it was concluded that this result is reasonable as judged from the general performance expected for different types of bridges in the event of a strong seismic disturbance.

The criteria was then applied to the thirty sample bridges originally used for the statistical analysis mentioned earlier. Since all of the required information of these samples are not known especially for the bridges damaged by older earthquakes, several assumptions had to be made: (i) height of substructure was assumed as 7.5m if it was between 5 and 10m, (ii) width of substructure's crest was assumed to be less than S for all the samples, and (iii) a weighting factor of 1.4 was used for friction pile foundations. The results thus obtained are shown in Fig.3, in which the samples are divided into two groups, i.e. collapsed (including almost collapsed) and not collapsed, and are arranged in each group in the decreasing order of the scores calculated by the proposed criteria. It is observed from Fig.3 that the scatter of the scores is large for the bridges belonging to the former group and that some of the scores in the latter group are higher than those of some collapsed bridges. It should be noted that there were a number of bridges belonging to the latter group which could not be included in the statistical analysis because of the lack of information.

When two of the most heavily damaged bridges in the latter group, which turned out to show the two highest scores in this group by the proposed criteria, were added to the fourteen collapsed samples, the mean of the 16 scores was found to be 39.9 with a standard deviation of 8.16. For the rest (14 bridges) of the samples, the mean and the standard deviation were 24.1 and 5.83. It can be easily shown that the difference between these two sample means is significant at the 0.001 level, indicating that the proposed criteria may be used to evaluate the seismic safety (or vulnerability) of existing bridges with special emphasis on the fall of superstructures from their supports.

For a *very conservative* evaluation, the mean minus 3σ value of the former (collapsed) group may be used to judge whether or not a bridge is likely to be substantially damaged (including the collapse of superstructures) endangering the traffic route to be disrupted during a strong earthquake motion. It should be noted from Fig.3, however, that if this value is used, the bridges judged unsafe by the criteria will include a sizable number of bridges which may be able to maintain their structural integrity in the event of an actual strong seismic motion.

POSSIBLE APPLICATION AND COMMENTS

Fig.4 shows the distribution of the scores as obtained by the proposed criteria for a total of 260 highway bridges located on the main evacuation routes in the metropolitan area of Tokyo for three different assumed levels of the severity of ground shaking, namely M.M. Intensity Ⅸ, Ⅹ, and Ⅺ and greater. The severity of shaking in Tokyo during the 1923 Kanto earthquake is generally considered as M.M. Intensity Ⅸ. When a very conservative bound (mean minus 3σ) is used to evaluate the percentage of bridges which may collapse during a strong earthquake motion, it is seen from Fig.4 that approximately 10% of the bridges are vulnerable when subjected to the ground shaking whose intensity is comparable to that experienced in Tokyo during the Kanto earthquake. As mentioned previously, this value probably overestimates the true number of unsafe bridges. This is understood if one reviews the degree of damage sustained by the highway bridges in the metropolitan Tokyo during the Kanto earthquake. There were about 670 highway bridges in Tokyo, of which about 420 were timber bridges. It is reported that none of them collapsed due to the dynamic effects of ground motion though about 290 were burnt down by the ensuing fire. The quality of the bridges in those days must have been much inferior to their counterparts in today's Tokyo.

In addition to the macroscopic application of the criteria as shown above, it can be used to particularize the specific bridges whose seismic safety is of dubious quality. The criteria can be also used to forecast to what extent the seismic safety of a bridge is improved when particular countermeasures are taken.

However, it is important to note at this point that the criteria proposed in this paper is only a *tentative* one because the number of the samples used for the original statistical analysis was too small to cover the wide variety of actual bridges. This criteria is intended to be used for the preliminary safety examination only. More rigorous and complicated analyses should be made for those bridges whose seismic safety is found dubious by the simplified method presented here.

ACKNOWLEDGMENT

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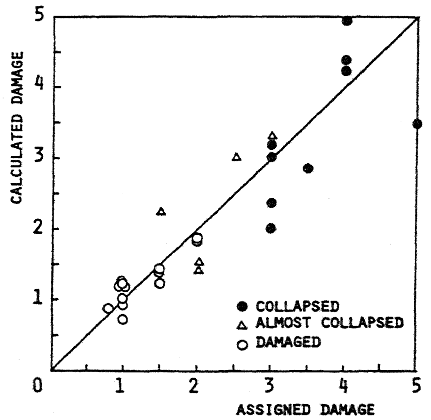

Fig.1. Correlation Between Assigned & Calculated Damage.

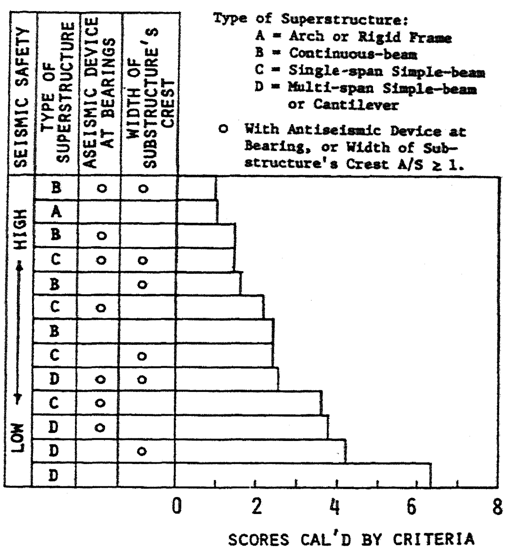

Fig.2. Relative Order of Seismic Safety for Different Types of Bridges.

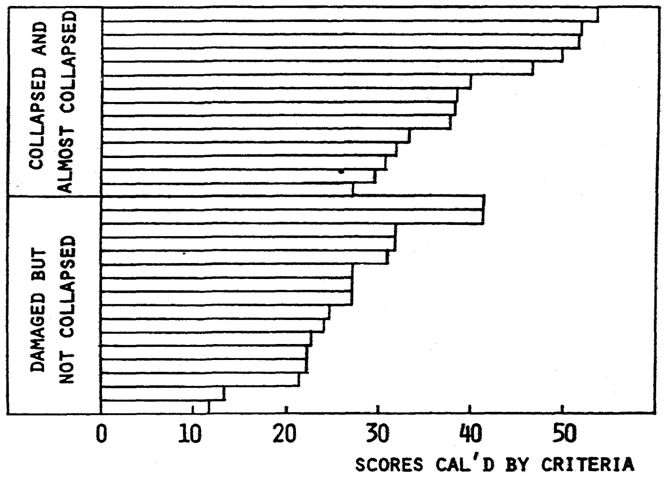

Fig.3. Scores Calculated by the Criteria for 30 Bridges Actually Damaged by Past Earthquakes.

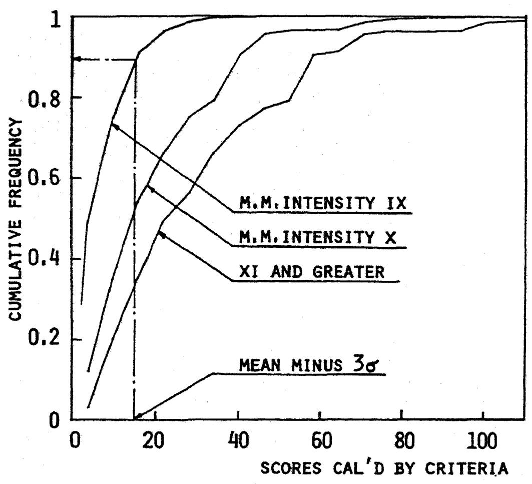

Fig.4. Distribution of Scores Calculated for 260 Bridges in Tokyo.

Table 1. Results of Statistical Analysis.

ITEM		CATEGORY		WEIGHTING	RANGE
j	NAME	k	NAME	FACTOR	
1	Ground Condition*	1	Type Ⅱ	1	1.86
		2	Type Ⅲ	1.86	
		3	Type Ⅳ	1.60	
2	Liquefaction	1	Not Observed	1	2.01
		2	Observed	2.01	
3	Type of Superstructure	1	Arch	1	3.00
		2	Simple or Cantilever	3.00	
4	Type of Bearing	1	Ordinary	1	1.15
		2	Both Bearings on a Pier Movable	1.15	
5	Max Height of Abutment or Pier	1	Less Than 5m	1	1.72
		2	Between 5 and 10m	1.72	
		3	Greater Than 10m	1.68	
6	Number of Spans	1	One	1	1.75
		2	Two or More	1.75	
7	Width of Sub-Structure's Crest	1	Less Than or Equal to 1.4m	1	1.25
		2	Greater Than 1.4m	0.80	
8	Severity of Shaking in M.M. Scale	1	Ⅸ	1	2.64
		2	X	2.41	
		3	Ⅺ and Greater	2.64	
9	Foundation	1	Pile Bent	0.15	1.36
		2	Pile Foundation	0.11	
		3	Columns of a Pier on Independent Wells	0.11	

*Classification of Ground Condition:

Type I : Ground of the Tertiary era or older (defined as bedrock), and diluvial layer with depth less than 10m above bedrock.

Type Ⅱ : Diluvial layer with depth greater than 10m above bedrock, and alluvial layer with depth less than 10m above bedrock.

Type Ⅲ: Alluvial layer with depth less than 25m having less than 5m thick liquefiable layer (see the footnote of Table 2) or soil with compressive strength less than 0.2kg/cm^2.

Type Ⅳ : Other than the above.

Table 2. Simple Criteria for Evaluating Seismic Safety of Existing Bridges with Special Emphasis on Falling-Off of Superstructures.

ITEM	CATEGORY	WEIGHTING FACTOR	REMARKS
Ground Condition	Type I	0.5	Classification of ground as specified in SERDHB*; Ground condition becomes worse as it goes from I to Ⅳ.
	Type Ⅱ	1.0	
	Type Ⅲ	1.5	
	Type IV	1.8	
Liquefaction Potential	None	1.0	Classification follows as specified in SERDHB.
	Moderate***	1.5	
	High**	2.0	
Type of Super-Structure	Arch or Rigid Frame	1.0	
	Continuous-beam	2.0	
	Simple or Cantilever	3.0	
Type of Bearing	With Anti-seismic Devices	0.6	
	Ordinary	1.0	
	Both Bearings on a Pier Movable	1.15	
Max Height of Abutment or Pier	Less Than 5m	1.0	
	Between 5 and 10m	Linear Inter-polation	
	Greater Than 10m	1.7	
Number of Spans	One	1.0	A continuous-beam is counted as one span.
	Two or More	1.75	
Width of Substructure's Crest, and Length of Suspended Jnt.	A/S ≥ 1	0.8	A=Length between end of bearing and edge of sub-structure (cm). S=Min value in SERDHB.
	A/S < 1	1.2	
	D ≥ 1	0.8	D=A/60 (Ground I to Ⅲ) D=A/70 (Ground Ⅳ) A=Length of suspended joint (cm).
	D < 1	1.2	
Severity of Shaking in M.M. Scale	Ⅸ	1.0	
	X	2.4	
	Ⅺ and Greater	3.5	
Foundation	Other Than Pile Bent	1.0	1.4 for evidently weak foundations like friction pile.
	Pile Bent	1.4	
Material of Abutment or Pier	Masonry or Plain Concrete	1.4	
	Other Than Above	1.0	

*SERDHB = Specifications for Earthquake-Resistant Design of Highway Bridges (Japan Road Association, 1971).

**Saturated sandy soil layers within 10m of ground surface with a standard penetration test N-value less than 10, a coefficient of uniformity less than 6, and a D_{20}-value of grain size accumulation curve between 0.04mm and 0.5mm, ***with a D_{20}-value between 0.004mm and 0.04mm or between 0.5mm and 1.2mm.