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AN INSPECTION METHOD OF SEISMIC VULNERABILITY OF EXISTING HIGHWAY BRIDGES

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Proposed is an inspection method which is capable to assess seismic vulnerability of a number of existing highway bridges without complex calculation. Total of 124 highway bridges which suffered damages during four earthquakes including the Miyagi-ken-oki Earthquake of 1978 is statistically analyzed, and factors affecting seismic damages are studied. Because fatal damages such as falling-off of superstructures are most likely developed from an excessive relative movement between the superstructure and the substructure, and from a failure of the substructures due to inadequate strength, an inspection method for the seismic vulnerability is developed based on vulnerability to develop excessive deformation and failure of substructures. Accuracy of the method is also studied.

Keywords: seismic vulnerability, seismic inspection, highway bridge, seismic damage

1. INTRODUCTION

Because seismic design procedures have been reviewed and amended several times in the light of lessons learned through past seismic damages and development of new seismic design methods, there are a number of highway bridges which are considered to have lower seismic safety from the view of current design practice. Therefore, it is of considerable importance to retrofit the existing highway bridges which have high vulnerability for seismic damages. For correctly inspecting existing highway bridges which require retrofitting, it is of great importance to develop a proper method to assess seismic vulnerability of highway bridge. Although various procedures for assessing the seismic vulnerability of existing bridges have been proposed in a wide range from simple inspection from outside to precise inspection[1),2)], a new inspection method which is capable to assess the vulnerability taking account of damage features developed in recent earthquakes is required for practical purpose.

This paper presents a simple inspection method capable to assess the vulnerability for a number of bridges at the site without complex calculation. This is developed based on a statistical analysis together with empirical experience through the past seismic damage.

2. HIGHWAY BRIDGES ANALYZED

Analyzed were 95 highway bridges which suffered damages and 19 highway bridges which suffered no damages from the Miyagiken-oki Earthquake of 1978 (M 7.4)[3)]. Ten more bridges which had experienced extensive damages during the Kanto Earthquake of 1923 (M 7.9), the Fukui Earthquake of 1948 (M 7.3)

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and the Niigata Earthquake (M 7.5) of 1964, were included. Thus, 105 damaged bridges as well as 19 undamaged bridges were considered for statistical analysis.

For detecting the factors which make bridges susceptible to seismic damage, degree of seismic damage was classified into six ranks as shown in Table 1. Value of damage rank from 0 (no damage) to 5 (falling-off of superstructure) was considered as a quantity to be analyzed in the statistical analysis. Vulnerability of seismic damage was, then, classified into three groups as shown in Table 2. The rank of seismic vulnerability was defined to identify the highway bridges with high vulnerability for suffering serious failure such as falling-off of superstructure.

Table 1 Definition of Damage Degree.

Rank of Damage Degree	Definition
0 No Damage	No failure was recognized
1 Minor Damage	Minor damage which can be recognized
2 Slight Damage	Damages which do not directly deteriorate bearing capability such as ○ Deformation of secondary member of steel structure ○ Small crack of reinforced concrete member ○ Settlement and cracks of retaining wall of approach
3 Moderate Damage	Damages which directly deteriorate bearing capability such as ○ Buckling of primary member of steel structure ○ Failure of bearing supports, pulling-out of rollers, failure of concrete supporting bearings ○ Major cracks of reinforced concrete members with width larger than 1 mm
4 Extensive Damage	Extensive damage which is likely to develop falling-off of superstructure from substructure such as ○ Extensive movement of substructure including tilting, settlement and lateral movement ○ Extensive spalling-off of concrete and rupture of reinforcements of reinforced concrete members ○ Extensive failure of concrete supporting bearings and dislodgement of bearing
5 Falling-off of Superstructure	Falling-off of superstructure from substructure

Table 2 Definition of Seismic Vulnerability.

Rank	Vulnerability of Seismic Damage	Rank of Damage Degree in Table-1
Rank A—High Vulnerability	Possibility for suffering damage or damage degree is high	5 Falling-off of Superstructure or 4 Extensive Damage
Rank B—Moderate Vulnerability	Possibility for suffering damage or damage degree is moderate	3 Moderate Damage
Rank C—Low Vulnerability	Possibility for suffering damage or damage degree is low	2 Slight Damage or 1 Minor Damage or 0 No Damage

3. FACTORS AFFECTING SEISMIC VULNERABILITY OF HIGHWAY BRIDGE

For studying factors which is likely to affect the seismic vulnerability, a statistical analysis, which is often referred to as type Ⅱ quantification analysis, was made. The rank of damage degree of i-th bridge as defined by Table 1 is denoted here as Y_i. Then select M items that have likely contributed to develop seismic damage. Each item is divided into several categories. Predicted damage degree rank y_i was assumed to have a form of

$$y_i=\sum_{j=1}^{N}\sum_{k=1}^{Mj}\delta_{ijk}x_{jk} \quad \cdots\cdots (1)$$

in which x_{jk} represents a weighting factor for k-th category of j-th item, and δ_{ijk} represents a variable corresponding to category k in item j of i-th bridge. The variable δ_{ijk} is so defined that it takes a value of 1 if the characteristics of i-th bridge correspond to category k in item j, and 0 otherwise. The weighting factor x_{jk} was determined so as to minimize the sum of squares of the difference between Y_i and y_i.

For formulating an appropriate model on the damage degree rank, the items which have contributed to the damage have to be properly selected. It should be also noted here that the items considered in the analysis have to be the ones which can be definitely evaluated and easily detected from the inspection at the site. From such point of view, the items and categories were selected through the past damage experiences as shown in Table 3, in which a simple classification of 124 sample bridges as well as results of the statistical analysis which will be described later is also presented.

The items considered in Table 3 consists of five principal factors, i.e., intensity of earthquake ground motion, properties of super- and substructures, device to prevent falling-off of superstructures, and ground condition at the site.

The intensity of earthquake ground motion was introduced in the analysis in terms of peak ground acceleration, which was estimated from empirical attenuation equations[5]. Type, materials, shape and slope of superstructure were included to represent the properties of superstructure. The properties of substructure were represented in terms of type, pier height and materials. Because it is apparent from the past damage surveys that bridge damage was most likely developed due to inadequate strength and/or excessive deformation of substructures[4], the type of substructure was taken into account in two items.

The device of falling-off prevention of superstructure, which is one of the unique features of Japanese seismic design practice for highway bridges, was also considered as an important items. The device includes stoppers to prevent excessive relative movement between super- and substructures, connections either between super- and substructures or between adjacent girders, and seat length to prevent falling-off of superstructure from crest of pier and/or abutment[6].

Ground condition was considered in the analysis in terms of ground group[6], irregularity, and soil liquefaction potential. The soil liquefaction potential was evaluated in accordance with reference 6).

By analyzing the 124 sample bridges with use of Eq. (1), the weighting factors x_{jk} were determined as shown in Table 3. The correlation coefficient R was 0.801. Characteristics predicted by the weighting factors in Table 3 seem to give the overall damage susceptibility of highway bridges. For example, the effect of the device to prevent falling-off of superstructure is apparent. The weighting factor of the ground condition increases as the soil condition becomes softer, although there is unexpected disorder between the ground condition 2 and 3. The weighting factor of the intensity of peak ground acceleration also increases as the peak acceleration increases. However, in this case, the scatter of the weighting factor around the expected value from the past experience is considerable. This may be due to the insufficient estimation of the peak acceleration. It is however interesting to note that the weighting factors for the peak acceleration larger than 400 cm/sec^2 is quite large.

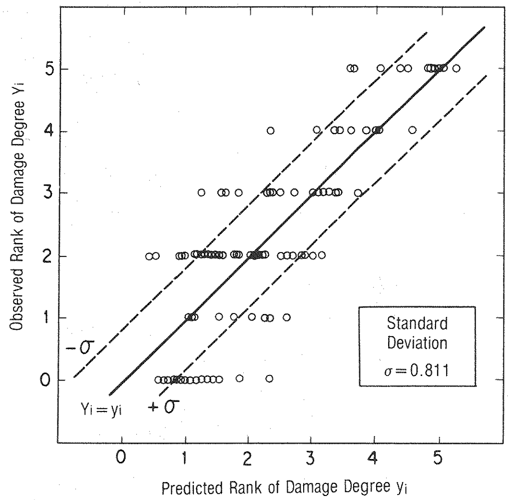

Fig. 1 Accuracy of Prediction of Damage Rank by Eq. (1).

Fig. 1 shows a comparison between the observed rank of damage degree Y_i and the predicted one y_i for the 124 sample bridges. Although the scatter of the actual rank of damage degree around the predicted one is considerable, general trends of the predicted damage degree rank are considered in reasonably good agreement with the actual one except at the low damage degree rank where the predicted damage degree rank gives rather overestimation.

The range presented in Table 3 is defined as a difference between the maximum and the minimum values of the weighting factor for j-th item. Therefore the range can be considered as an index to represent an amount of effect of j-th item for the predicted rank of damage degree y_i.

It is seen from Table 3 that because of large value of the range as well as large partial correlation coefficient, the intensity of peak ground acceleration, the design specifications referred to design, device to prevent falling-off of superstructure and ground condition may be regarded as the principal factors which affect the vulnerability of highway bridges. Although the partial correlation coefficient is not necessarily as high as that of factors described above, the effect of soil liquefaction, effect of scouring, materials of substructure and type of foundation may be considered important for the seismic vulnerability because of their pronounced range value. Old substructures and foundation consisting of plane concrete, timber, brick, masonry and other unknown construction method and materials are quite susceptible for earthquake damages.

4. EVALUATION OF SEISMIC VULNERABILITY

Based on the statistical analyses on the factors which are likely contribute to the seismic susceptibility

Table 3 Classification of 124 Sample Bridges in Terms of Item and Category Defined by Table 1.

Item	Category	Seismic Damage Rank						Results of Statistical Analysis		
		0 No Damage	1 Minor Damage	2 Slight Damage	3 Moderate Damage	4 Extensive Damage	5 Falling-off of Superstructure	Normalized Score	Range	Partial Correlation Coefficient
①Intensity of Peak Ground Acceleration a_{max} [cm/sec^2]	$a_{max} < 200$	1 (5%)			1 (5%)			0.169	1.219	0.343
	$200 \leqq a_{max} < 300$	13 (68%)	5 (42%)	36 (65%)	8 (40%)	1 (13%)		−0.283		
	$300 \leqq a_{max} < 400$	5 (26%)	5 (42%)	18 (33%)	10 (50%)	6 (75%)	4 (40%)	0.176		
	$400 \leqq a_{max} < 500$		2 (17%)	1 (2%)	1 (5%)	1 (13%)	2 (20%)	0.936		
	$500 \leqq a_{max}$						4 (40%)	0.616		
②Design Specifications	1926 or 1939	1 (5%)		6 (11%)	6 (30%)	5 (63%)	7 (70%)	0.517	0.740	0.319
	1956 or 1964	17 (89%)	6 (50%)	41 (75%)	11 (55%)	3 (38%)	3 (30%)	−0.223		
	1971 or 1980	1 (5%)	6(50%)	8 (15%)	3 (15%)			0.284		
③Type of Superstructure	Gerber or Simply Supported Girder (2 or More Spans)	12 (63%)	7(68%)	40 (73%)	17 (85%)	8 (100%)	10 (100%)	0.081	0.390	0.161
	One-span Simply Supported Girder, or Countinuous Girder with 2-spans or More	5(26%)	3 (23%)	11 (20%)	2 (10%)			−0.232		
	Arch, Frame, One-span Continuous Girder, Cable-stayed Bridge, Suspension Bridge	2 (11%)	2 (17%)	4 (7%)	1 (5%)			−0.308		
④Shape of Superstructure	Skewed or Curved	3 (16%)	1 (8%)	4 (. 7%)				−0.396	0.424	0.122
	Straight	16 (84%)	11 (92%)	51 (93%)	20 (100%)	8 (100%)	10 (100%)	0.027		
⑤Materials of Superstructure	RC or PC	7 (37%)	5 (42%)	22 (40%)	7 (35%)	1 (13%)	6 (60%)	−0.141	0.233	0.131
	Steel	12 (63%)	7 (58%)	33 (60%)	13 (65%)	7 (88%)	4 (40%)	0.092		
⑥Slope in Bridge Axis	6% or Steeper			1 (2%)		1 (13%)	1 (10%)	0.919	0.941	0.161
	Less than 6%	19 (100%)	12 (100%)	54 (98%)	20 (100%)	7 (88%)	9 (90%)	−0.023		
⑦Device to Prevent Falling-off of Superstructure	None	1 (5%)	1(8%)	20 (36%)	8 (40%)	6 (75%)	10 (100%)	0.459	1.106	0.358
	One Device	16 (83%)	6 (50%)	28 (51%)	11 (55%)	2 (25%)		−0.181		
	Two Devices or More	2 (11%)	5 (42%)	7 (13%)	1 (5%)			−0.647		
⑧Type of Substructure	Single-line Bent Pile	1 (5%)		5 (9%)	2 (10%)		3 (30%)	0.292	0.411	0.178
	Reinforced Concrete Frame	1 (5%)	1 (8%)	9 (16%)	8 (40%)	4 (50%)	4 (40%)	0.259		
	Others	17 (89%)	11 (92%)	41 (75%)	10 (50%)	4 (50%)	3 (30%)	−0.119		
⑨Height of Pier H	$10m \leqq H$	4 (21%)	5 (42%)	12 (22%)	8 (40%)	2 (25%)	3 (30%)	0.172	0.284	0.125
	$5m \leqq H < 10m$	7 (37%)	3 (25%)	29 (53%)	7 (35%)	6 (75%)	5 (50%)	−0.038		
	$H < 5m$	8 (42%)	4 (33%)	14 (25%)	5 (25%)		2 (20%)	−0.112		
⑩Ground Condition	Extremely Soft in Group 4	1 (5%)			1 (5%)	2 (25%)		0.523	0.983	0.273
	Group 4	5 (26%)		2 (4%)	11 (35%)	4 (50%)	7 (70%)	0.224		
	Group 3	3 (16%)	8 (67%)	33 (60%)	6 (30%)	1 (13%)	3 (30%)	0.040		
	Group 2	1 (5%)	1 (8%)	8 (15%)	1 (5%)			0.112		
	Group 1	9 (47%)	3 (23%)	12 (22%)	1 (5%)	1 (13%)		−0.461		
⑪Irregularity of Supporting Ground	Irregular		1 (8%)	1 (2%)	4(20%)	1 (13%)		0.307	0.420	0.104
	Almost Uniform	19 (100%)	11 (92%)	54 (98%)	16 (80%)	7 (88%)	10 (100%)	−0.024		
⑫Effect of Soil Liquefaction	Liquefiable			4 (7%)	2 (10%)	2 (25%)	6 (60%)	0.724	0.816	0.255
	Non-liquefiable	19 (100%)	12 (100%)	51 (93%)	18 (90%)	6 (75%)	4 (40%)	−0.092		
⑬Effect of Scouring	Recognized				1 (5%)			0.312	0.315	0.033
	None	19 (100%)	12 (100%)	55 (100%)	19 (95%)	8 (100%)	10 (100%)	−0.003		
⑭Materials of Substructure	Plane Concrete in Accordance with 1926 Specs. or 1939 specs.				1 (5%)		2 (20%)	0.995	1.020	0.167
	RC, PC, Steel or Unreinforced Concrete in Accordance with Specs. in 1956 or Later	19 (100%)	12 (100%)	55 (100%)	19 (95%)	8 (100%)	8 (80%)	−0.025		
⑮Type of Substructure	Timber, Brick, Masonry, Other Old Unknown Materials		1 (8%)	1 (2%)	1 (5%)	1 (13%)	4 (40%)	0.383	0.697	0.171
	RC Piles, Pedestal Piles or Pier Supported by Two Independent Caissons	2 (11%)	1 (8%)	9 (16%)	4 (20%)	2 (25%)	2 (20%)	−0.314		
	Foundations Designed by Specs. in 1971 or Later	17 (89%)	10 (83%)	45 (82%)	15 (75%)	5 (63%)	4 (40%)	0.034		

of highway bridges, a practical evaluation method of the seismic vulnerability was developed. Basic principles for developing the evaluation method are that the method can be used to assess the seismic vulnerability of a number of existing highway bridges based on a simple inspection without complex calculation. Furthermore, the method should be able to detect the highway bridges which have high possibility for suffering severe damages (Rank A in Table 2) when subjected to the ground shaking with seismic intensity of JMA V (Japan Meteorological Agency's Intensity Scale). The JMA Intensity V is often referred to as the intensity with a peak ground acceleration larger than 0.25 G.

Furthermore for developing the evaluation method, the following considerations were subsequently added to in the statistical analyses described in the preceding chapter;

a) Bacause the objectives of the method are to evaluate the seismic vulnerability of highway bridges subjected to ground shaking of JMA Intensity V, peak ground acceleration can be dropped from the evaluation items assuming the peak ground acceleration larger than 0.25 G.

b) Evaluation on strength of reinforced concrete pier at the mid-height where main reinforcements are terminated was newly introduced. This needs some explanations, i. e., in the design specifications issued older than 1980, main reinforcements were terminated at the mid-height, i. e., 12 times of diameter of reinforcement higher than the point where reinforcements can be terminated on the basis of design calculation. This implies that the redundancy of bond length was only 12 times of diameter of main reinforcements. The redundancy for the bond was increased in the 1980 Specifications to the length equivalent with the effective width of the pier in addition to 12 times of diameter of main reinforcements. This was made because significant failures were often developed in the recent earthquakes due to such effects[7].

c) Because fatal damages such as falling-off of superstructure were most likely developed from excessive relative movement between the superstructure and the substructure, and from failure of substructures due to inadequate strength, the evaluation of the seismic vulnerability should be made separately for the deformation and the strength of bridge.

d) Even if there are serious conditions, final evaluation often fails to take account of such serious condition if the remaining factors are in good condition. It is also true for adverse condition. Consequently it was judged that those bridges with at least one significant condition either in good or bad are to be predicted absolutely low or high in the seismic vulnerability. Such significant conditions considered are;

- ○ Those designed in accordance with the 1980 Specifications shall be classified in Rank C unless appreciable disorder of the bridge is detected.
- ○ Those constructed by timber, brick, masonry or older unknown materials shall be classified into Rank A.
- ○ Those with single-line bent pile foundation which is constructed on loose alluvial sandy layer vulnerable to develop liquefaction or very loose clayey deposits shall be classified into Rank A.
- ○ Single-span simply supported girder with a span length less than 15 m shall be classified into Rank C.

Table 4 shows an inspection format of the proposed method. All factors considered in the statistical analysis excluding the ground intensity were included in the evaluation. Seven new items regarding to the strength of reinforced concrete pier due to the termination of main reinforcements and the disorder of fixed bearing, pier column and foundations were included because they are essential for evaluating the strength and deterioration of substructure. It should be noted here that for those bridges in which main reinforcements of the pier are either not terminated at mid-height or terminated with enough bond length in accordance with the 1980 Specifications, the evaluation point P_c is to be assigned as 1.0.

Evaluation points of the inspection format in Table 4 were determined based on overall engineering judgments based on the statistical analysis as well as the past experience of seismic damages[5),8)]. Therefore the evaluation points are not necessarily coincident with the results of the statistical analysis. Higher evaluation points were assigned for bridges designed by older design specifications (item 1 of Table 4), gerber bridges, or simply supported girder with 2-span or more (item 2), bridges constructed on very soft soils (item 9), and bridges with considerable disorder at fixed bearing and pier column (item 17 and 18). As a natural consequence, it implies that the older bridges, which are constructed on very soft soils, with considerable disorders are to be predicted to have high seismic vulnerability. In view of the fact that the predicted seismic vulnerability from the statistical analysis has a considerable scatter, an inclusion of such an engineering decision is reasonable for the inspection.

An evaluation on the seismic vulnerability is made by Table 5 based on the point X representing the

Table 4 Inspection Format for Seismic Vulnerability of Highway Bridges.

Point of Inspection		Foctors of Inspection	Evaluation
Inspection for Vulnerability to Develop Excessive Deformation	Inspection Format (A) Inspection for Deformation of Superstructure	① Design Specifications	4.0: 1926 Specs. or 1939 Specs. 2.0: 1956 Specs. or 1964 Specs. 1.0: 1971 Specs. or 1980 Specs.
		② Superstructure Type	3.0: Gerber Girder or Simply-supported Girders with Two Spans or More 1.5: Simply-supported Girder or Continuous Girders Consisting of Two Spans or More 1.0: Arch, Frame, Continuous Girder (One Span), Cable-stayed Bridge, Suspension Bridge
		③ Shape of Superstructure	1.2: Skewed or Curved Bridge 1.0: Straight Bridge
		④ Materials of Superstructure	1.2: RC or PC 1.0: Steel
		⑤ Gradient	1.2: 6% or Steeper 1.0: Less Than 6%
		⑥ Falling-off Prevention Device	2.0: None 1.0: One Device
		P_A=①×②×③×④×⑤×⑥	P_A=
	Inspection Format (B) Inspection for Deformation of Substructure	⑦ Type of Substructure	2.0: Single-line Bent Pile Foundation 1.0: Others
		⑧ Height of Pier H	2.0: $H \geqq 10m$ 1.5: $5 \leqq H < 10m$ 1.0: $H < 5m$
		⑨ Ground Condition	5.0: Extremely Soft in Group 4 2.5: Group 4 2.0: Group 3 1.2: Group 2 1.0: Group 1
		⑩ Effects of Liquefaction	2.0: Liquefiable 1.0: Non-liquefiable
		⑪ Supporting Ground Condition	1.2: Irregular 1.0: Almost Uniform
		⑫ Scouring	1.5: Recognized 1.0: None
		P_B=⑦×⑧×⑨×⑩×⑪×⑫	P_B=
Inspection for Vulnerability to Develop Failure Due to Inadequate Strength of Substructure	Inspection Format (C) Inspection for Strength of RC Pier at Termination of Reinforcement	⑬ Shear Span Ratio (h/D)	2.0: $1 < h/D < 4$ 1.0: $h/D \geqq 4$ 0.5: $h/D \leqq 1$
		⑭ Tension Cracks in Flexure at Terminated Point of Main Reinforcement	2.0: Cracks Wil Occur 1.0: Cracks Will Possibly Occur 0.3: Cracks will Not Occur
		⑮ Safety Factor for Yield Strength at Terminated Section of Main Reinforcement — (15-1) S_{fn}	3.0: $S_{fn} \leqq 1.1$ 2.0: $1.1 < S_{fn} < 1.5$ 0.5: $S_{fn} \geqq 1.5$
		⑮ — (15-2) S_{mn}	3.0: $S_{mn} \leqq 1.1$ 2.0: $1.1 < S_{mn} \leqq 1.3$ 1.0: $1.3 < S_{mn} < 1.5$ 0.5: $S \geqq 1.5$
		⑯ Shear Stress σ (tf/m^2)	3.0: $\sigma \geqq 45$ 2.0: $30 \leqq \sigma < 45$ 1.0: $15 \leqq \sigma < 30$ 0.5: $\sigma < 15$
		P_C=⑬×⑭×(15-1)×(15-2)×⑯	P_C=
	Inspection Format (D) Inspection for Strength of Substructure	⑰ Failure of Fixed Supports and Proximity	5.0: Extensive Failure 2.0: Small Failure 1.0: None
		⑱ Extraordinary Damage of Pier	5.0: Extensive Damage 2.0: Small Damage 1.0: None
		⑲ Materials of Substructure	2.0: Plane Concrete Older Than 1926 Excluding Gravity-type Abutment 1.0: Others
		⑳ Construction method of Foundation	2.0: Timer Pile, Masonry, Brick, Other Old Construction Methods 1.5: RC Piles, Pedestal Piles. Pier Supported by Two Independent Caissons 1.0: Foundation Designed by 1971 Specs. and Other Later Specs.
		㉑ Foundation Type	1.5: RC Flame Supported by Two Independent Caisson Foundations 1.0: Others
		⑫ Extraordinary Failure of Foundation	2.0: Recognized 1.0: None
		P_D=⑰×⑱×⑲×⑳×㉑×㉒	P_D=
Evaluation of Deformation and Strength			$X = P_A \times P_B$= and $Y = P_C \times P_D$=

vulnerability for excessive deformation and the point Y representing the vulnerability for failure of substructure. It should be noted that for those bridges with at least one significant condition, which was described in the preceding pages, is to be predicted in either Rank A or B depending on the significant condition, with regardless of the point X and Y.

Table 5 Evaluation for Seismic Vulnerability of Highway Bridges.

Rank of Seismic Vulnerbility	Evaluation Points		
	X	Y	
		$P_C = 1.0$	$P_C \neq 1.0$
A—Vulnerable	$X \geqq 60$	$Y \geqq 10$	$Y \geqq 100$
B—Moderate	$20 \leqq X < 60$	$5 \leqq Y < 10$	$50 \leqq Y < 100$
C—Safe	$X < 20$	$Y < 5$	$Y < 50$

Note) Out of two ranks obtained from X-point and Y-point, higher rank (A is the highest) should be taken as the final ranking of the bridge inspected. For obtaining evaluation points X and Y, refer to Table-2.

5. APPLICABILITY OF EVALUATION METHOD

Applicability of the evaluation method was studied through the analysis of the 124 sample bridges. It should be noted here that two assumptions were introduced in this analysis, i. e., because reliable and sufficient informations on disorder of fixed bearing, pier column and foundation at the time of the outbreak of earthquake were unknown, the strength of substructure could not be evaluated. Therefore, damage vulnerability was assessed only from the point X. Second assumption is that although the evaluation

Table 6 Accuracy of Evaluation Method.

(a) Comparison of Predicted and Actual Rank of Damage Vulnerability

Rank		Predicted Seismic Vulnerability Rank A	B	C	Total
Seismic Vulnerability Rank Actually Developed	A	15	3	0	18
	B	6	6	8	20
	C	5	11	70	86
Total		26	20	78	124

(b) Probability of Correct Inspection

Seismic Vulnerability Rank	Probability of Correct Inspection
A	$\frac{15}{18}=83\%$
B	$\frac{6}{20}=30\%$
C	$\frac{70}{86}=81\%$
Total	$\frac{15+6+70}{124}=73\%$

method was developed to predict the seismic vulnerability of bridges subjected to the ground shaking of JMA Intensity V (peak ground acceleration larger than approximately 0.25 G), it was applied to the bridges subjected to smaller acceleration than 0.25 G. This may result in some errors in the estimated results.

Table 6 shows a comparison of predicted and actually developed rank of seismic vulnerability. It is seen that the rank of seismic vulnerability of 91 bridges among 124 bridges were correctly predicted. Defining a probability of correct inspection P_c as a ratio of a number of bridges correctly predicted divided by a number of total bridges, it becomes 73 %, which seems reasonably satisfactory for practical purpose. The probability of correct inspection can also be defined for each seismic vulnerability rank of A, B and C, and it takes a value of 83 %, 30 % and 81 % for the Rank A, B and C, respectively. It is important to note that the probability of correct inspection P_c is quite small for Rank B although it is sufficiently high for Rank A and C. This implies that the probability of correct inspection is satisfactory for those bridges which are either highly susceptible or quite safe against earthquake. However, for those bridges which have the moderate susceptibility, the probability of correct inspection is very poor.

6. CONCLUDING REMARKS

The preceding pages presented the factors which had likely contributed to develop the seismic damage of highway bridges and an evaluation method proposed to assess the seismic vulnerability of a number of existing highway bridges without complex calculations.

Although accuracy of the proposed method is insufficient for assessing the seismic vulnerability of bridges with moderate susceptibility, it provides a realistic basis for assessing the seismic vulnerability of bridges which are either highly susceptible or quite safe against seismic disturbances.

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