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Earthquake Damage Assessment of Expressway Structures in Japan

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ABSTRACT

Fragility curves for expressway structures in Japan were proposed based on actual damage data from the 1995 Hyogoken-Nanbu Earthquake. First, spatial distributions of strong motion indices, e.g., the peak ground acceleration, the peak ground velocity, the JMA seismic intensity, were estimated using the Kriging technique, in which attenuation relations of these indices are considered as trend components. The actual damage data for expressway networks in Japan were compared with these estimated ground motion indices and then fragility curves were constructed assuming log-normal distributions. The proposed fragility curves may be used in damage estimation of expressway structures in Japan due to earthquakes.

INTRODUCTION

Japan Highway Public Corporation (JH) owns expressway networks with a total length of 6,395 km (as of April, 1998). In order to gather earthquake information at an early stage (Yamazaki, 1996) and to establish an efficient traffic control just after an earthquake, JH had deployed 123 accelerometers along its expressways (1 instrument per 40 km) before the Hyogoken-Nanbu (Kobe) Earthquake on January 17, 1995. JH further deployed 202 new seismometers along its expressways (1 instrument per 20 km together with existing ones) after the Hyogoken-Nanbu Earthquake (Fig. 1). The new instruments can measure the spectrum intensity (SI) and the instrumental JMA (Japan Meteorological Agency) intensity (Shabestari and Yamazaki, 1998) as well as the peak ground acceleration (PGA) and peak ground velocity (PGV).

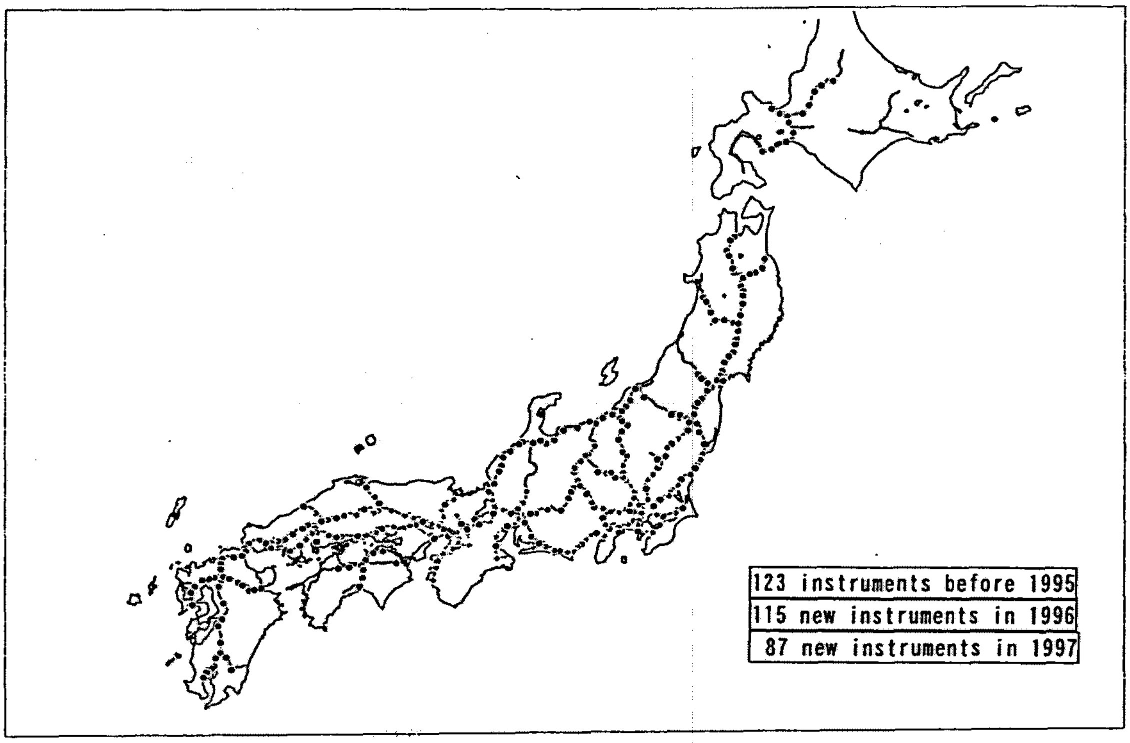


Figure 1. Location of accelerometers for expressway networks in Japan

Using earthquake information from these instruments, JH closes expressways if the PGA equal or larger than 80 cm/s^2 is recorded or reduces the maximum speed limit if the PGA equal or larger than 50 cm/s^2 is recorded. These traffic regulations continue until safety inspections for roadways are completed. But these current regulation criteria need to be examined considering the increase of number of instruments, the higher sensitivity of new instruments and the recent experiences for damaging and non-damaging earthquakes in Japan.

Hence, it may be important to clarify the relationship between the earthquake damage to expressway structures and the strong ground motion indices. In this study, the damage data of the JH's expressway structures in the Hyogoken-Nanbu Earthquake were collected and the ground motion indices along the expressways were estimated based on observed records using Kriging technique. Comparing these results, fragility curves for the expressway structures (bridges and elevated structures) in Japan were constructed. The proposed fragility curves may be used for damage estimation of expressway structures in Japan. Note that a study on bridge fragility in the United States is found in Kiremidjian and Bosöz (1997) and a study on damage estimation of national highway bridges in Japan was conducted by Sugita and Hamada (1997).

SPATIAL DISTRIBUTION OF EARTHQUAKE GROUND MOTION

The method of estimation of spatial distribution of earthquake ground motion suitable for expressway networks is proposed. Earthquake information currently obtained just after an earthquake is ground motion indices (PGA, PGV, SI and JMA intensity) recorded by the instruments connected to traffic control centers by private lines. Acceleration time histories are collected later manually. The magnitude and hypocenter of an event are informed by the Japan Meteorological Agency (JMA) within a few minutes after the occurrence of the earthquake.

Kriging technique (Cressie, 1993; Deutsch and Journel, 1992), a method of stochastic interpolation, is employed to estimate spatial distribution of ground motion indices from recorded values. In Kriging technique, observed values are realized at the observation points. Between the observation points, stochastic interpolation consisting of the trend (mean) and random components gives an estimation of the spatial distribution.

Since the earthquake motion at ground surface is affected by amplification characteristics of surface layers, the interpolation should be carried out at the (outcrop) base level as shown in Fig. 2. The amplification ratio (Onishi et. al, 1998) estimated from attenuation relationships and the digital national land information of Japan is used to convert the recorded values at the ground surface to those at the base. After the spatial interpolation by Kriging, the amplification ratio is again introduced and the spatial distribution of the ground motion indices at the ground surface is obtained.

ESTIMATION OF STRONG MOTION DISTRIBUTION IN THE 1995 HYOGOKEN-NANBU EARTHQUAKE

Strong Motion Data

In the 1995 Hyogoken-Nanbu Earthquake, a large number of strong motion records were obtained (Molas and Yamazaki, 1995b). In this study, free field records at 165 sites were used to estimate the spatial distribution of ground motion indices. Among these records, the authors obtained acceleration time histories at 99 sites. PGV and JMA intensity were calculated for these sites. For the remaining 66 sites, only PGA values were known. Amplification ratios of these indices at the recording sites were estimated from the topography and subsurface soil classification of the digital national land information. Using these amplification ratios, the recorded values at the ground surface were converted to those at the base level (Vs ≥ 300-400 m/s).

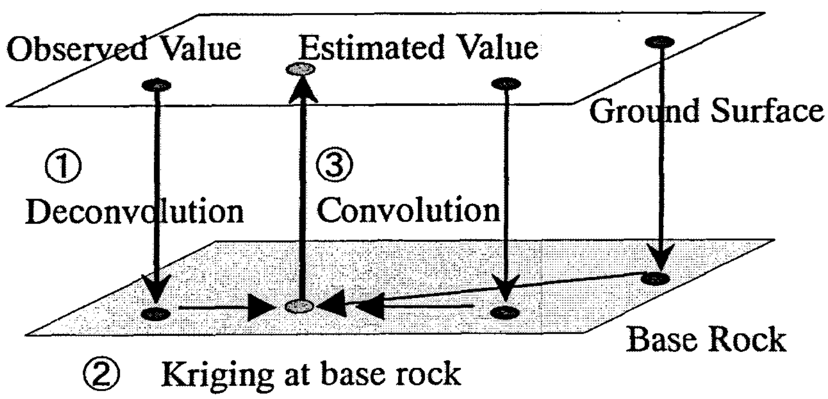


Figure 2. Schematic figure for interpolation of earthquake ground motion indices on ground surface and on base rock

Attenuation Relations at the Base

Using the converted values at the base level, the simple Kriging method (Deutsch and Journel, 1992) was employed to estimate the spatial distribution of the strong motion indices at the base. In this study, attenuation relations for strong motion indices (Molas and Yamazaki, 1995a; Shabestari and Yamazaki, 1998) were used as the trend component of Kriging. Since the attenuation relations contain the inter-event variability (deviation associated with different earthquakes), it may be preferable to construct an attenuation equation for each event if many observed values exist. For the Hyogoken-Nanbu Earthquake, the following forms including near-source saturation effect were considered for the strong motion indices:

for PGA: $$\log_{10} PGA = c_1 - \log_{10}(r + c_2) + c_3 r \quad (1)$$

for PGV: $$\log_{10} PGV = c_1 - \log_{10}(r + c_2) + c_3 r \quad (2)$$

for JMA Intensity: $$I = c_1 - 1.89 \log_{10}(r + c_2) + c_3 r \quad (3)$$

where c_1, c_2, and c_3 are coefficients to be obtained by regression analyses and r is the shortest distance (km) to the fault rapture. For the Hyogoken-Nanbu Earthquake, the fault was modeled as a vertical plane stretching in between points (134.92° E, 34.53° N) and (135.32° E, 34.76° N) with the depth of the upper edge 4.5 km (Kamae and Irikura, 1995).

Using the (converted) observed values at 149 sites whose soil classification is estimated, the attenuation relations for the Hyogoken-Nanbu Earthquake at the base are obtained as

for PGA: $$\log_{10} PGA = 3.808 - \log_{10}(r + 6.3) - 0.00128\, r \quad (4)$$

for PGV: $$\log_{10} PGV = 2.510 - \log_{10}(r + 0.1) \quad (5)$$

for JMA Intensity: $$I = 7.563 - 1.89 \log_{10}(r + 1.0) - 0.00118\, r \quad (6)$$

where c_3 for PGV is set to be zero since it was obtained as a negative value.

The obtained relation for PGV is plotted in Fig. 3 together with data points and the attenuation relation proposed by Molas and Yamazaki (1995a). The current relation looks similar as the existing one. For PGA and intensity, near-source saturation effects were clearly observed in the attenuation relationship for the Hyogoken-Nanbu Earthquake.

Method of Kriging

In the Kriging technique, a spatial auto-correlation function should be assigned. An exponential function was employed in this study. The correlation distance, which controls the influence of observed data, was assumed as 5.0 km. Note that if the correlation distance is large, the estimated distribution connects the observed points irrespective of the trend component while if the correlation distance is small, the estimated distribution approaches the trend rapidly.

In this study, Kriging technique was employed for the residuals (the converted observed values at the base minus the trend component):

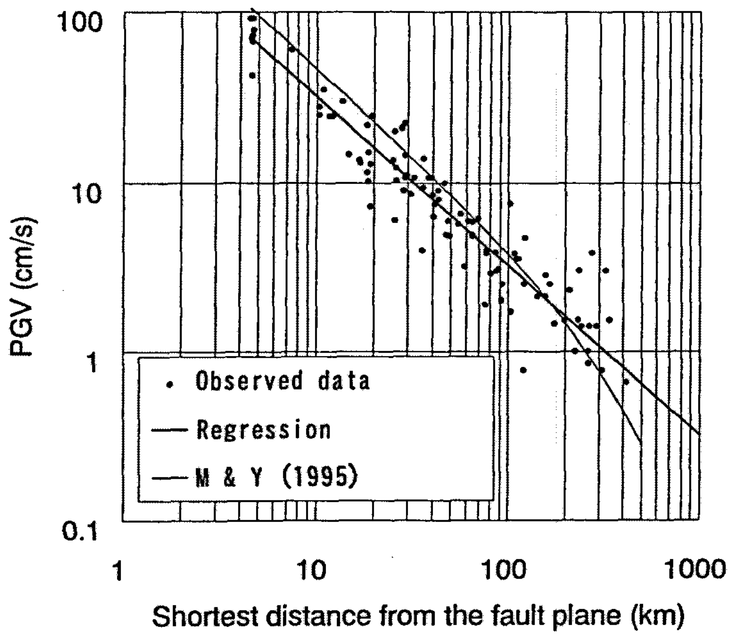


Figure 3. Attenuation relationship of peak ground velocity (converted to base-rock) in the 1995 Hyogoken-Nanbu Earthquake

$$X_{Ai} = \log_{10} PGA_{bi} - \log_{10} PGA_{mi} \quad (7)$$

$$X_{Vi} = \log_{10} PGV_{bi} - \log_{10} PGV_{mi} \quad (8)$$

$$X_{Ii} = I_{bi} - I_{mi} \quad (9)$$

where suffix *b* represents "base" and *m* represents "mean". Simple Kriging was carried out assuming the residual distributions as a zero-mean Gaussian stochastic field. Adding the trend component to the obtained random component, the strong motion indices at the base were estimated. Multiplying the amplification factors, the spatial distribution at the ground surface was then obtained.

Spatial Distribution of Ground Motion in the Hyogoken-Nanbu Earthquake

The spatial distributions of PGA, PGV and JMA intensity in the Hyogoken-Nanbu Earthquake were estimated for the area shown in Fig. 4. At all the 41266 grid points corresponding to the 1 km x 1 km pixels of the digital national land information, the ground motion indices were obtained by the method described above. Figure 5 shows the estimated distribution of PGV in the Hyogoken-Nanbu Earthquake together with the observed PGV. The estimated distribution looks quite natural as well as fitting the observed values. The introduction of the attenuation relation to the trend component made this possible.

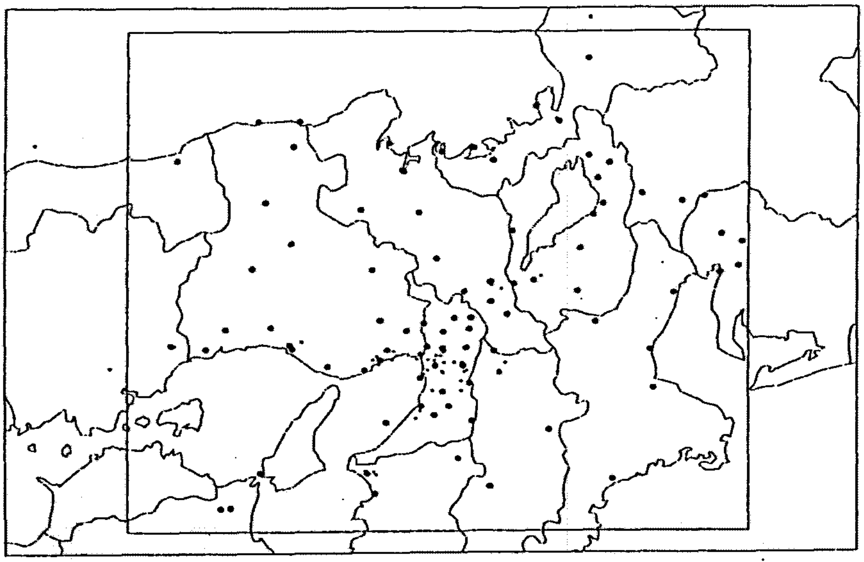


Figure 4. The area for calculation of ground motion distribution in the Hyogoken-Nanbu Earthquake

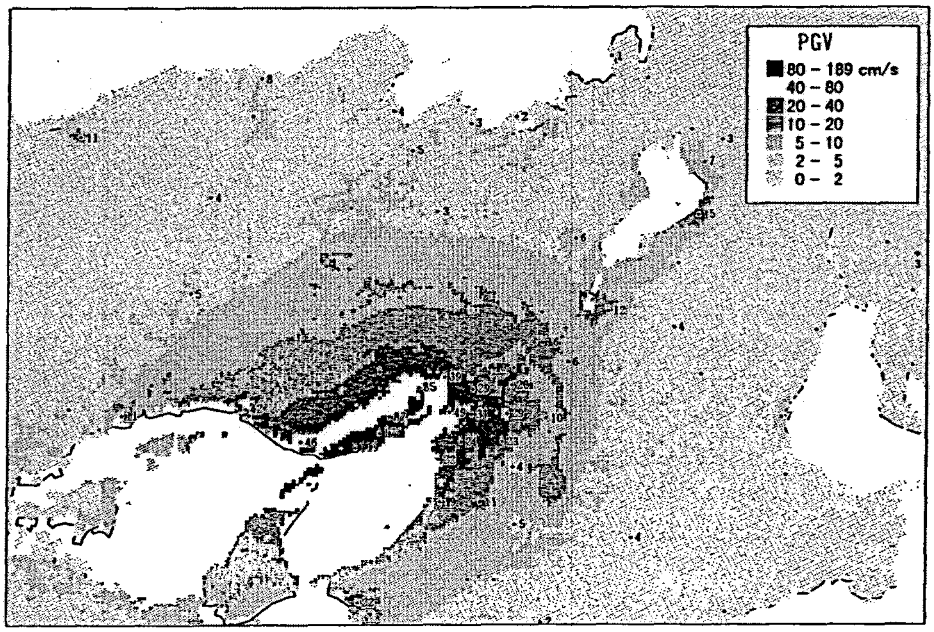


Figure 5. Estimated distribution of PGV on ground surface in the Hyogoken-Nanbu Earthquake by Kriging technique

FRAGILITY CURVES FOR EXPRESSWAY BRIDGES

In the Hyogoken-Nanbu Earthquake, tremendous damage occurred to expressway structures and facilities, e.g., bridges and elevated structures, embankments, toll gates. In this study, JH's 216 bridge structures on 4 routes were investigated. In doing this, bridges without

Table 1 Damage of JH's expressway bridge structures in the 1995 Hyogoken-Nanbu Earthquake

Route	Section	Damage Rank of Bridges					Total
		As	A	B	C	D	
Chugoku Expressway	Suita JCT- Yamazaki IC	4	0	7	5	55	71
Kinki Expressway	Suita JCT- Yao IC	0	0	0	0	30	30
Meishin Expressway	Nishinomiya IC- Kyoto S. IC	3	4	5	1	74	87
Daini Shinmei Road	Suma IC - Akashi West IC	0	0	1	2	25	28
Total		7	4	13	8	184	216

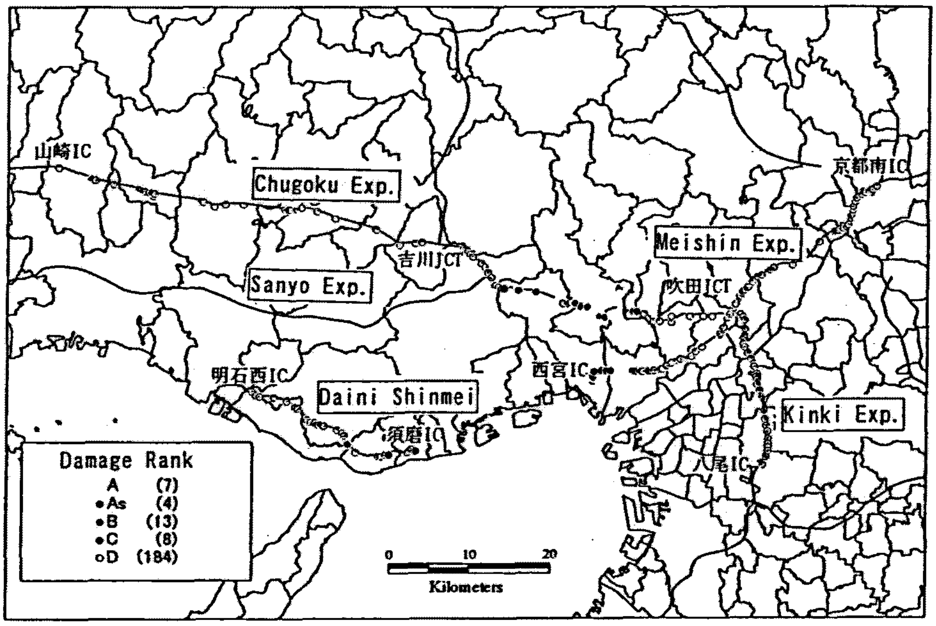


Figure 6. Location and damage rank of JH's expressway bridge structures in the 1995 Hyogoken-Nanbu Earthquake

damage in the same routes were also considered since they provide useful information. Table 1 summarizes damage ranks of the JH's bridge structures and the locations of the bridges are plotted in Fig. 6. It is seen in the figure that the highest damage rank (As) bridges are concentrated along the Meishin and Chugoku Expressways.

Figure 7 plots the relation between the damage ranks of the bridges along the Chugoku Expressway and the estimated PGV values at the bridge locations obtained by Fig. 5. Significant damage is seen to occur at the locations of large PGV values. A similar comparison was conducted for other routes and the relation between the damage rank and estimated PGV is plotted in Fig. 8 for all the 216 bridges. It is also observed for other strong motion indices (PGA and I) that the damage rank becomes higher as the motion becomes larger. Based on these data, fragility curves for bridge structures are constructed assuming log-normal distributions (normal distribution for the intensity) for the cumulative probability P_R of occurrence of the damage equal or higher than rank R as follows:

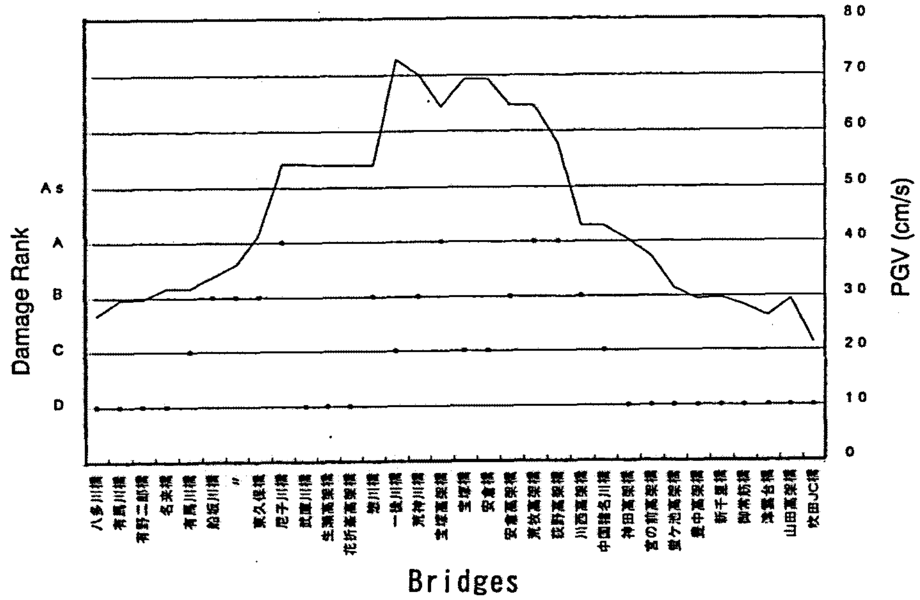


Figure 7. Relationship between damage rank and estimated PGV for 32 bridges on Chugoku Expressway

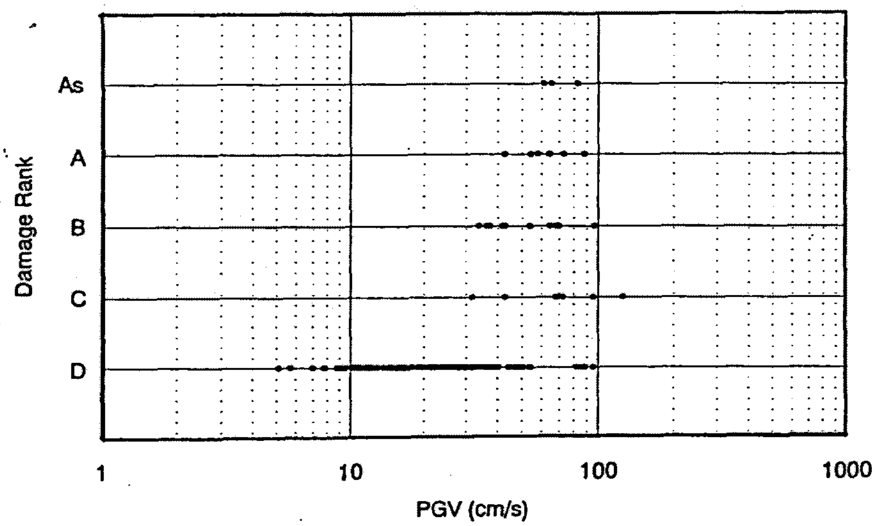


Figure 8. Relation between damage rank and estimated PGV for JH's 216 bridges in the Hyogoken-Nanbu Earthquake

$$P_R(PGA) \quad = \Phi((\ln PGA - \lambda)/\zeta) \qquad (10)$$

$$P_R(PGV) \quad = \Phi((\ln PGV - \lambda)/\zeta) \qquad (11)$$

$$P_R(I) \quad = \Phi((I - \lambda)/\zeta) \qquad (12)$$

where Φ is the standard normal distribution and λ and ζ are the mean and standard deviation of *ln PGA*, *ln PGV* and *I*. The two parameters of the distributions are determined by the least square method on the log-normal probability paper and the results are listed in Table 2.

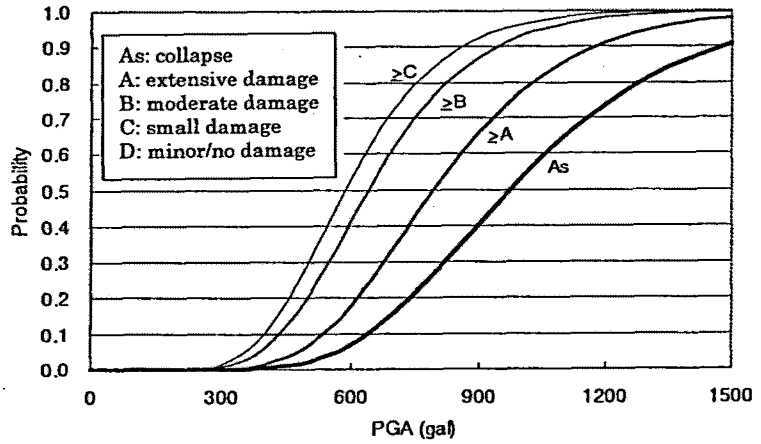
Figure 9 shows the empirical fragility curves of highway bridge structures for PGA and

PGV. In spite of rather sparse data in Fig. 8, the obtained fragility curves look reasonable. However, it is obvious that the fragility curves are dependent on the seismic code used (Sugita and Hamada, 1997) and the structural type of bridges (Kiremidjian and Bosöz, 1997). Retrofitted bridges may have larger strength than before. A further research, especially by an analytical approach, is necessary to introduce these effects to the proposed fragility curves.

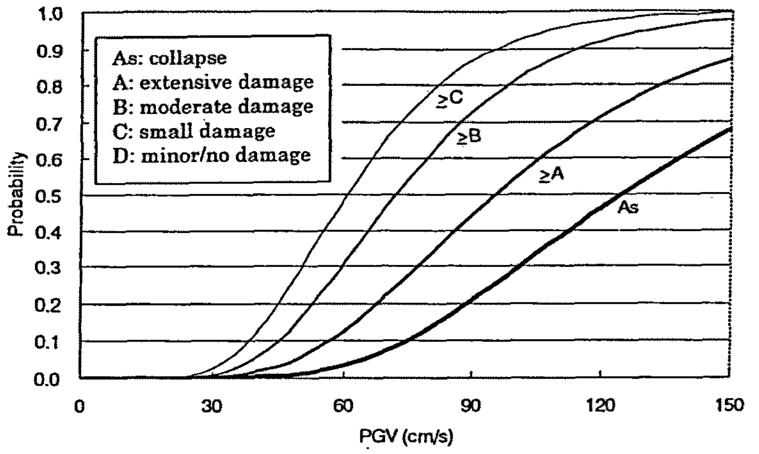
Table 2 Coefficients of fragility curves for expressway bridge structures in Japan

Damage Rank	*PGA* (cm/s^2)		*PGV* (cm/s)		*JMA Intensity*	
	λ	ζ	λ	ζ	λ	ζ
≥C	6.36	0.298	4.10	0.352	6.01	0.272
≥B	6.47	0.301	4.28	0.364	6.15	0.292
≥A	6.68	0.305	4.55	0.404	6.36	0.333
As	6.89	0.326	4.82	0.400	6.59	0.352

(* ***This table was revised May, 1999 since errors were found in the values.***)



(a) PGA



(b) PGV

Figure 9. Fragility curves of bridge structures for PGA and PGV derived from the damage data due to the Hyogoken-Nanbu Earthquake

CONCLUSIONS

As a first step for the proposal of appropriate expressway traffic control immediately after earthquakes, the relationship between the strong motion indices and the damage of highway structures from recent earthquakes in Japan was investigated. First, the spatial distributions of strong motion indices, e.g., the peak ground acceleration, the peak ground velocity, the JMA intensity, were estimated for the 1995 Hyogoken-Nanbu Earthquake using the digital national land information and Kriging technique. In this approach the recorded data are satisfied at the recording sites and the attenuation relations of the strong motion indices are considered as a trend component. The actual damage data for expressway networks in the Hyogoken-Nanbu Earthquake were compared with these estimated ground motion indices and then fragility curves were constructed assuming log-normal distributions. Although the proposed fragility curves are still tentative, they may be used in damage estimation of highway structures in Japan due to earthquakes. Combining with a seismometer network, the proposed methodology can be easily introduced to a real-time damage assessment of expressway networks.

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