

## Estimation of strong motion distribution in the 1995 Kobe earthquake based on building damage data

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### SUMMARY

The 1995 Kobe earthquake caused unprecedented damage to buildings and civil infrastructures in the city of Kobe and its surrounding areas. In order to evaluate the structural damage in this area due to the earthquake, it is important to estimate the distribution of earthquake ground motion. However, since the number of strong ground motion records is not enough in the heavily damaged areas, it is necessary to estimate the distribution using other data sources. In this paper, the fragility curves for low-rise residential buildings were constructed using the recorded motions and the building damage data from the intensive field survey by the AIJ and CPIJ group. The fragility curves obtained were then employed to estimate the strong motion distribution in the district level for Kobe and the surrounding areas during the earthquake. The results may be useful to investigate the various damages caused by the earthquake. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: 1995 Kobe earthquake; building damage; strong motion distribution; fragility curve; geographic information system

### INTRODUCTION

The Kobe (Hyogoken-Nanbu) earthquake directly struck the densely populated Kobe area and its neighbouring cities in the early morning of 17 January 1995 and caused huge direct losses to infrastructures and private properties. In order to evaluate the structural damage in this area due to the earthquake, it is important to estimate the distribution of earthquake ground motion. During the earthquake, quite a few strong ground motion records were obtained in the heavily damaged areas by several organizations [1–4]. However, they are still not enough in number for estimating the detailed spatial distribution of strong ground motion during the event. Thus, it is necessary to estimate the distribution using other data sources.

Estimation of the distribution of earthquake ground motion in the affected areas due to the Kobe earthquake has been conducted by several methods by a number of researches. One of the recent techniques involves the use of empirical and/or synthetic Green's functions [5–7]

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*Received 12 July 2000  
Revised 11 September 2000  
Accepted 11 September 2000*

to simulate strong motion time histories. The effect of bedrock topography and surface layers can be introduced using three-dimensional finite difference modelling [6] and one-dimensional velocity model [7], respectively. This method is very attractive, but requires a huge amount of expertise, input data, and computational efforts. A two-dimensional finite element analysis [8, 9] was also carried out to estimate strong ground motion at a typical cross-section to demonstrate the so-called basin-edge effect. However, it is not easy to prepare many more models to cover the entire hard-hit zone.

If strong motion indices, e.g. the peak ground acceleration (PGA), the peak ground velocity (PGV), and the instrumental Japan Meteorological Agency (JMA) intensity [10], are the matter of concern, attenuation relations are conveniently used in many cases. Several studies [11–13] have been conducted for the Kobe earthquake. However, since the number of observed records is not large enough and owing to the lack of detailed geological information on the surface deposits, this approach is not suitable to estimate the detailed distribution of strong motion indices due to the Kobe earthquake. As a statistical interpolation approach, Kriging technique was also used to predict the PGV and PGA distributions in the Hyogo Prefecture [14]. The attenuation relations that were developed based on observed data were used as the trend component in the study. It is suitable to cover a large area using such a technique, but not suitable to estimate the detailed strong motion distribution in the hard-hit zone.

As a method to estimate the intensity of shaking due to earthquakes, the damages and effects to structures/objects are often used. For the Kobe earthquake, the overturning ratio of tombstones [15] and the damage to buildings [15–17] were used to estimate the distributions of PGV and JMA intensity in Kobe and its neighbouring cities. Because the building damage was so extensive and several co-ordinated damage surveys were conducted after the earthquake, the building damage distribution might be most useful to estimate the detailed strong motion distribution in Kobe and its neighbouring cities.

We use the results of the damage survey conducted by a group of the Architectural Institute of Japan (AIJ), the City Planning Institute of Japan (CPIJ), and Hyogo Prefectural Government [18]. This survey was conducted throughout the stricken area with the same damage criteria, and the Building Research Institute (BRI), the Ministry of Construction, digitized the results of the survey to a database on GIS [19]. In this paper, fragility curves as a function of PGA, PGV and JMA intensity are developed using this building damage database and the seismic records from the mainshock. The fragility curves obtained for low-rise residential buildings are then employed to estimate the spatial distributions of the strong motion indices in the 1995 Kobe earthquake.

## GROUND MOTION RECORDS AND BUILDING DAMAGE DATA

### *Ground motion records*

In the Kobe earthquake, quite a few strong ground motion records were obtained [11] by the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA), JMA, the Ministry of Construction [3], the Ministry of Transport [4], Japan Railway group [2], Osaka Gas Company, Kansai Electric Power Company, and so on. In this study, among them, free field records were used to obtain ground motion indices for constructing fragility curves. Those records include restored clipped records [20].

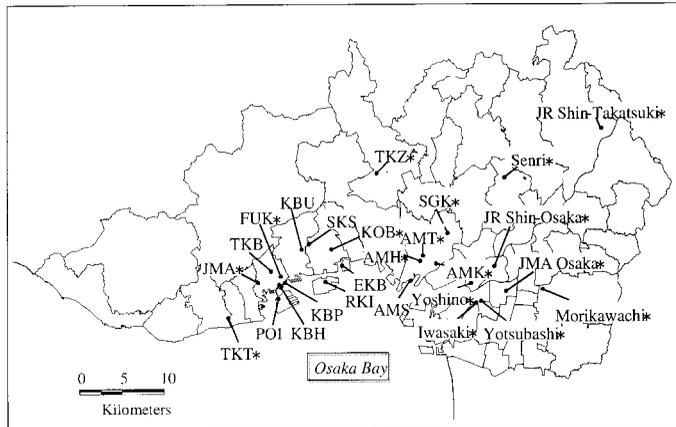


Figure 1. Location of seismometers in the 1995 Kobe earthquake. The stations with an asterisk are used in this study.

Figure 1 shows the observation points of strong ground motion in the area of Kobe, Osaka and their neighbouring cities considered in this study. From the strong motion records, 17 free field records were selected in the fragility analysis. Some records were not used in this research since the number of buildings around an observation point was not enough or severe liquefaction, which alters the nature of seismic motion, was reported around a recording site.

#### *Building damage survey*

In this paper, the ground motion distributions are estimated by using the data from the building damage survey [18], which was carried out based on the same standard [21] throughout the stricken area. The damage survey was carried out by visual inspection from the outside of buildings, for the purpose of obtaining data for urban restoration planning. The persons who engaged in the survey are mostly urban planners, architects, and researchers. The damage surveys from the structural engineering point of view [22], and for evaluating monetary losses [23] were also carried out by a group of engineers and by local governments, respectively. Since the objectives and people involved are different for all these surveys, the items and method of survey and their damage classifications are, unfortunately, all different [23]. Thus, we must select a proper data set depending on the problem of concern.

The damage survey data by the group of AIJ and CPIJ were digitized and compiled by BRI as a GIS database. Table I shows the criteria of the damage classification for wooden buildings. The building damage in the BRI data is classified into five levels: 'heavy', 'moderate', 'slight', 'no damage', and 'burned'. The burned data were excluded from this study when evaluating the damage ratio. This classification is similar to the damage state classification of ATC-38 [24].

In addition to the BRI's building damage data, the results of building damage surveys by local governments (Osaka City Fire Department [25], Osaka Prefecture [26]) are also used to reflect the ground motion indices in the slightly damaged area to fragility curves. Note that the BRI data set does not cover the areas outside of the hard-hit zone.

Table I. Classification and description of damage for wooden buildings in the survey by AIJ and CPIJ [18].

Damage classification	Criteria of damage classification	Examples of damage for wood-frame buildings
Heavy damage	Unusable building or buildings with very low possibility of re-use	Totally collapsed, layer-collapsed, severely leaning, or severe damage to foundation, columns and walls
Moderate damage	Buildings may be reused after substantial repair	Partially collapsed, or extensive cracks on walls
Slight damage	Usable buildings with slight damage or buildings with possibility of use after little repair	Falling of some roof tiles or small cracks/peeling on walls
No damage	Not damaged in appearance	
Burned	Buildings suffering from fires	

### *Building damage around the instruments*

In order to construct fragility curves for buildings, the building damage ratio around each observation point was calculated. The method of selecting the area represented by each seismometer is as follows. In case of using the BRI's building damage data, the district block (corresponding to the postal address) where a reference seismometer is placed and its surrounding blocks were selected for the corresponding area of the seismometer. In selecting the surrounding blocks, the extent of damage and the subsurface soil condition were considered: only the blocks with a similar damage level and soil condition to that of the reference block were selected.

Figure 2 shows an example of the selection of the areas represented by seismometers. In case of JMA Kobe Observatory, because there are more than 300 residential buildings in the district block and the block's topography is different from that of the surrounding blocks, only one block is selected for the corresponding area of the seismometer. In case of Fukiai Gas Supply Station (FUK), the area of the reference block is very small. Hence, there are not many residential buildings in the reference block, and the block's subsurface soil condition is similar to those of the surrounding blocks. Thus, the reference block and the surrounding several blocks were used to calculate the building damage ratio. The records from three other instruments in the figure were not used because the instrument was placed in the basement of a high-rise building (Takenaka Corp. Building) and there were no residential buildings and extensive liquefaction was reported near the instruments (Kobe Port Office, Kobe No. 8 Pier).

In case of local governments' damage data, the city or the ward (for Osaka City) where a reference seismometer is located was selected for the corresponding area represented by the seismometer. In these areas, the damage ratios are very small, and thus a large numbers of buildings are necessary to obtain non-zero (meaningful) damage ratios. If we have a damage ratio equal to zero, we cannot use such data for a regression analysis on lognormal probability paper (because the inverse operation of the normal distribution for the zero value becomes infinity).

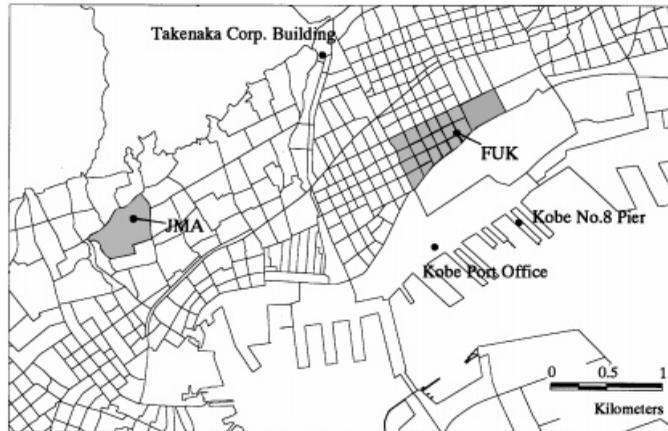


Figure 2. Example of the selection of the areas represented by seismometers. The shadow areas were used to obtain building damage ratios for JMA and FUK stations.

The building damage ratios for the areas corresponding to the 17 seismometers were calculated. In calculating the damage ratio of buildings represented by a seismometer, we should better select buildings with similar fragility characteristics. The BRI data are classified by the story class (one/two storeyed, equal to or higher than three-storeyed) and the use of buildings (residential, commercial, industrial, and others), and have no information on the structural type. The structural type, e.g. wood-frame, reinforced concrete, steel-frame, is highly related to the seismic vulnerability of buildings [27, 28]. It is also noted that the number of wood-frame buildings is largest for most areas and most of one- or two-storeyed residential buildings are made of wood-frame in Japan. Considering these facts, the low-storeyed (one- or two-storeyed) residential buildings in the BRI data were considered mostly as wood-frame buildings and hence, the damage ratio for the low-storeyed residential buildings was assumed to give the damage ratio of wood-frame buildings. Using the BRI data represented by the seismometers, the ratio of buildings with 'heavy damage' ( $R_h$ ), the ratio equal to or more than 'moderate damage' ( $R_m$ ) and the ratio equal to or more than 'slight damage' ( $R_s$ ) were calculated.

For the areas using the local government data, because the building damage criteria were different from the BRI data [23], the damage ratios calculated from the local government data should be converted to those corresponding to the BRI data. Since the earthquake ground motion was rather small in those areas, all the damaged buildings in the areas were assumed to be of wood-frame. Note that 'wood-frame' buildings have, in general, the smallest seismic resistance [27, 28]. The total number of wood-frame buildings in a city or a ward was estimated by the total number of buildings in the region [29] multiplied by the ratio of residential buildings for all the BRI data. The damage ratio of wood-frame buildings in the region was then estimated employing these assumptions. Similarly, as for the BRI data, the ratio of 'heavy damage' ( $R_h^*$ ) and the ratio equal to or more than 'moderate damage' ( $R_m^*$ ) were evaluated for the areas using the local government data.

The evaluated damage ratios based on the local government damage criteria must be then converted to those of the AIJ & CPIJ's survey (the BRI data). Since we have both the

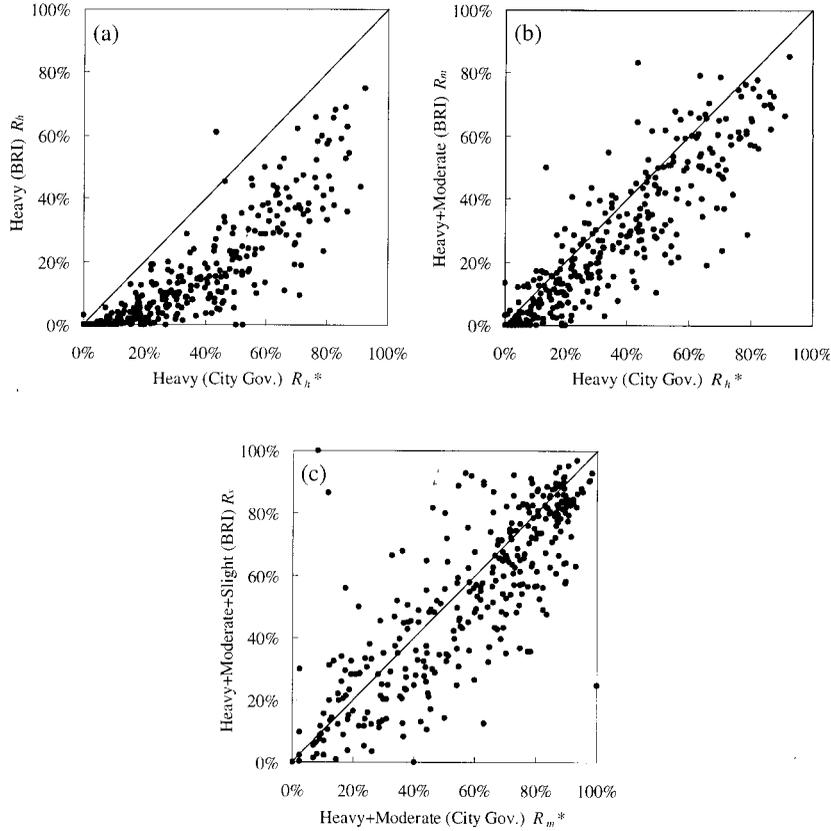


Figure 3. Comparison of damage ratios for two damage investigations (BRI and Nishinomiya City Government) in each district block of Nishinomiya City.

sets of data for Nishinomiya City, the damage ratios for the city were employed to prepare the relations for the conversion. The damage ratios of low-storeyed residential buildings in the BRI data for all the blocks in Nishinomiya City were compared to those obtained from the survey by the city government for the purpose of property tax reduction [27].

Figure 3 compares the damage ratios from the two data sets: (a)  $R_h$  and  $R_h^*$ , (b)  $R_m$  and  $R_h^*$ , and (c)  $R_s$  and  $R_m^*$ . It can be seen in the figure that  $R_h$  is roughly half of  $R_h^*$  in the range up to 20%, and that the equality can almost be observed in the relationships (b) and (c) as follows:

$$R_h = R_h^*/2 \quad (1)$$

$$R_m = R_h^* \quad (2)$$

$$R_s = R_m^* \quad (3)$$

Using these relationships, the damage ratios compatible with the BRI data were estimated for the regions without the BRI data.

Table II shows the strong ground motion indices observed by the seismometers used in this study and the damage ratios of low-storeyed residential buildings near the seismometers. Note that the strong ground motion indices used in this study are the larger of the two horizontal components [30] calculated from the records.

## FRAGILITY CURVES FOR LOW-STOREYED RESIDENTIAL BUILDINGS

### *Fragility curves for residential buildings*

The fragility curves were constructed using the relationship between the damage ratio of low-storeyed residential buildings and the strong motion indices in the Kobe earthquake. For a strong motion value,  $x$ , the cumulative probability  $P_R(x)$  of the occurrence of the damage equal to or higher than rank  $R$  is assumed to be lognormal (normal for the JMA intensity) as follows:

$$P_R(PGA) = \Phi((\ln PGA - \lambda)/\zeta) \quad (4)$$

$$P_R(PGV) = \Phi((\ln PGV - \lambda)/\zeta) \quad (5)$$

$$P_R(I) = \Phi((I - \lambda)/\zeta) \quad (6)$$

where  $\Phi$  is the cumulative probability of the standard normal distribution, and  $\lambda$  and  $\zeta$  are the mean and the standard deviation of  $\ln PGA$ ,  $\ln PGV$  and  $I$ . The two parameters of the distributions, i.e.  $\lambda$  and  $\zeta$ , are determined by the least-squares method on the lognormal probability paper. The regression analysis for the damage ratio is performed on the strong motion indices. Table III summarizes the results of the regression analysis for each strong ground motion index. Figure 4 shows the fragility curves for the low-storeyed residential buildings in Japan with respect to PGA, PGV and JMA intensity based on the BRI's building damage data due to the Kobe earthquake.

### *Comparison with Hayashi's fragility curves*

Hayashi *et al.* [31] also developed fragility curves for PGV with respect to the use of buildings using the BRI's building damage data and the estimated PGV distribution obtained by a two-dimensional earthquake response analysis [9]. Figure 5 shows the comparison of the fragility curves for low-storeyed residential buildings by Hayashi *et al.* and by the authors. It is seen in the figure that, for small PGV values, Hayashi's curves show higher level of damage probability compared to ours, and for large PGV values, our relations show higher level of damage probability. This difference may have resulted from the fact that the data from slightly damaged areas such as Osaka City were considered in this study but not in Hayashi's study. The difference in the estimation of strong ground motion by the two studies may also be responsible for the difference in the fragility curves. Hayashi *et al.* estimated the ground

Table II. Strong motion indices observed in the 1995 Kobe earthquake and the damage ratios of low-storeyed residential buildings near the instruments.

Data	Observation point	PGA (cm/s <sup>2</sup> )	PGV (cm/s)	Intensity	Number of buildings	R <sub>h</sub> (%)	R <sub>m</sub> (%)	R <sub>s</sub> (%)
BRI	Amagasaki Harbor (AMH)	507	56	5.7	442	0.714	5.95	26.9
	Amagasaki Viaduct (AMK)	294	49	5.7	496	3.33	4.76	25.0
	Taketani Elementary School (AMT)	321	50	5.7	939	1.49	11.0	49.8
	Research Institute of Kansai Electric Power (SGK)	652	49	6	1,407	0.273	9.27	45.1
	JR Takatori Station (TKT)	655	119	6.5	660	57.4	85.7	95.3
	Fukiai Gas Supply Station (FUK)	806	119	6.5	122	17.7	25.7	48.7
	JMA Kobe Station (JMA)	818	91	6.4	308	5.79	18.5	71.0
	Motoyama No.1 Elementary School (KOB)	770	78	6.1	641	18.4	33.4	63.9
	JR Takarazuka Station (TKZ)	685	85	6.2	416	11.6	21.3	42.8
	JR Shin-Osaka Station	216	41	—	22,696	0	0	6.17E-02
	Yoshino Elementary School	211	31	5.4	14,505	4.14E-03	1.38E-02	0.834
	JMA Osaka Station	81	19	4.5	17,232	0	0	5.80E-03
	Yotsubashi Bridge	270	30	5.1	16,153	5.57E-03	1.86E-02	8.05E-02
	Iwasaki Gas Supply Station	172	24	5.1	16,153	5.57E-03	1.86E-02	8.05E-02
Senri Gas Supply Station	299	29	5.4	72,288	4.15E-03	1.38E-02	0.44	
JR Shin-Takatsuki Substation	297	—	—	69,063	0	0	1.74E-02	
Morikawachi Elementary School	212	27	5.3	112,557	1.33E-03	4.44E-03	1.51E-02	

Table III. Parameters of fragility curves for low-storeyed residential buildings based on the BRI data.

Rank	$\lambda$	PGA (cm/s <sup>2</sup> ) $\zeta$	R <sup>2</sup>	$\lambda$	PGV (cm/s) $\zeta$	R <sup>2</sup>	$\lambda$	JMA Intensity $\zeta$	R <sup>2</sup>
R <sub>h</sub>	7.23	0.511	0.659	4.95	0.429	0.912	6.74	0.403	0.821
R <sub>m</sub>	6.82	0.429	0.722	4.65	0.382	0.885	6.44	0.351	0.835
R <sub>s</sub>	6.50	0.431	0.719	4.34	0.358	0.826	6.14	0.361	0.843

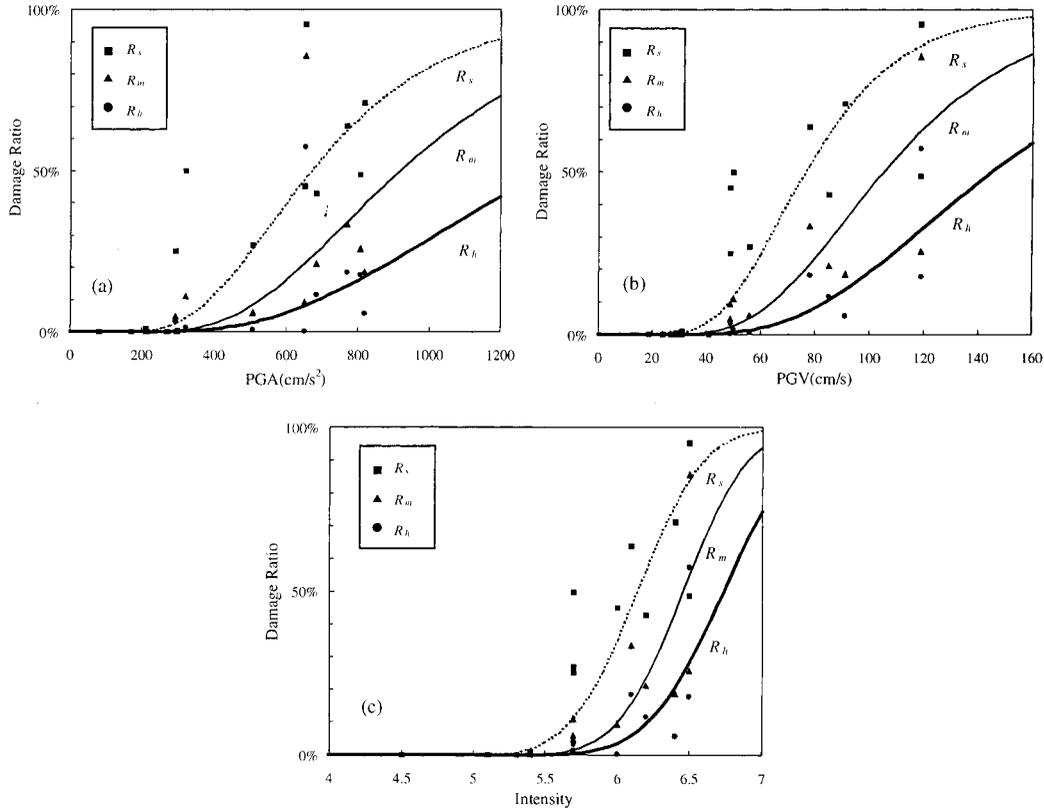


Figure 4. Fragility curves for low-storeyed residential buildings based on the BRI data with respect to (a) PGA, (b) PGV, and (c) JMA intensity.

motion distribution from the results of the response analysis for the north–south section of Sannomiya area in Kobe city, while we used the observed ground motions and the building damage data near the seismometers.

#### ESTIMATION OF GROUND MOTION DISTRIBUTIONS IN THE 1995 KOBE EARTHQUAKE

The fragility curves for the low-storeyed residential buildings were constructed for the three damage levels. Using these fragility curves and the building damage data compiled by BRI, the ground motion distributions in the Hanshin area during the Kobe earthquake were estimated. Since the fragility curves were constructed for the low-storeyed residential buildings, the corresponding building damage data were used in back-calculating strong ground motion distributions.

First,  $R_h$ ,  $R_m$  and  $R_s$  were calculated for all the district blocks in the data set. If the number of low-storeyed residential buildings in a block was less than 10, the strong motion

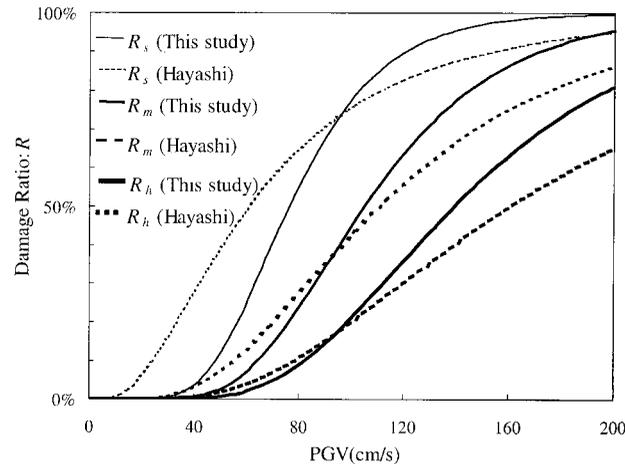


Figure 5. Comparison of the obtained fragility curves with respect to PGV with those by Hayashi *et al.* [31].

indices were not estimated for such blocks because the sample size is too small to calculate damage ratios. The buildings that suffered from fire or those which were uninvestigated were subtracted from the total number. Since the areas of the district blocks in Kobe City are, in general, smaller than those of other cities, some of them were combined when calculating the damage ratios.

Using the damage ratios calculated by the method mentioned above, three values of a strong motion index corresponding to the three damage levels were obtained by  $x_h = P_R^{-1}(R_h)$ ,  $x_m = P_R^{-1}(R_m)$ , and  $x_s = P_R^{-1}(R_s)$ . The three estimated values for PGV were compared in Figure 6 for Nishinomiya City. In the figure, it is observed that  $x_h$  and  $x_m$  are almost the same,  $x_m$  and  $x_s$  are nearly equal, and that the relationship between  $x_h$  and  $x_s$  shows a larger scatter. These tendencies were also seen for the other indices (PGA and JMA intensity) and for the results of the other cities. From these observations, the following rules were adopted to determine a single value from the three values:

- If  $R_m = 0$ ,  $x_s$  is used.
- If  $R_h = 0$  and  $R_m \neq 0$ , the average of  $x_m$  and  $x_s$  is used.
- If  $R_h \neq 0$ , the average of  $x_h$  and  $x_m$  is used.

The first rule is employed for the case where only slight damage is reported in a district block. The second rule is applied when no heavy damage and at least one moderate damage is observed in a district block, and the third rule is used when at least one heavy damage exists in a district block.

Figure 7 shows the distributions of PGA, PGV and JMA intensity in the Kobe earthquake obtained by this method. Since the strong motion indices were obtained by the back-calculation from the damage ratios of buildings, the distributions look similar to one another.

The area of JMA intensity 7 shown in Figure 7(c) almost corresponds to the belt of JMA intensity 7 shown in Figure 8, determined by JMA's field survey [32]. Some areas such as

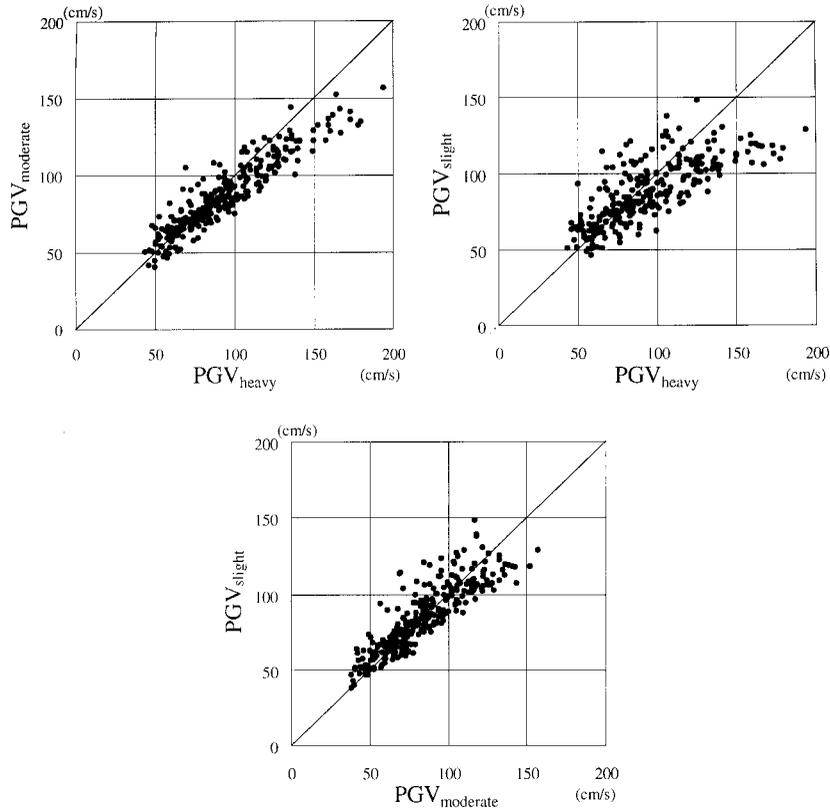


Figure 6. Comparison of three PGV values estimated from the different damage levels of low-storeyed residential buildings in Nishinomiya City.

those along the seashore were excluded from the estimation since liquefaction was reported, and hence, it was difficult to assume the validity of the fragility curves. In some district blocks, the strong motion indices were not estimated due to the shortage of the low-storeyed residential building data.

Figure 9 compares the estimated strong motion indices and the observed ones. The estimated indices almost correspond to the observed ones. However, some differences are observed in PGA at JR Takatori station (TKT) and in PGV at Fukiai Gas Supply Station (FUK). The difference between the estimation and the observation was large at these two locations, probably due to the regional difference in building characteristics. In the back-calculation method used in this study, the low-storeyed residential buildings were assumed to have similar fragility characteristics in the entire area studied. However, this assumption is more or less not true. If an area has a higher old building ratio than other areas have, the building damage ratio in the area becomes large, and hence, larger strong motion indices are estimated. Re-estimation of distributions of strong motion indices [33, 34] can be carried out for the areas that have building damage data associated with detailed building inventory, e.g. structural type and

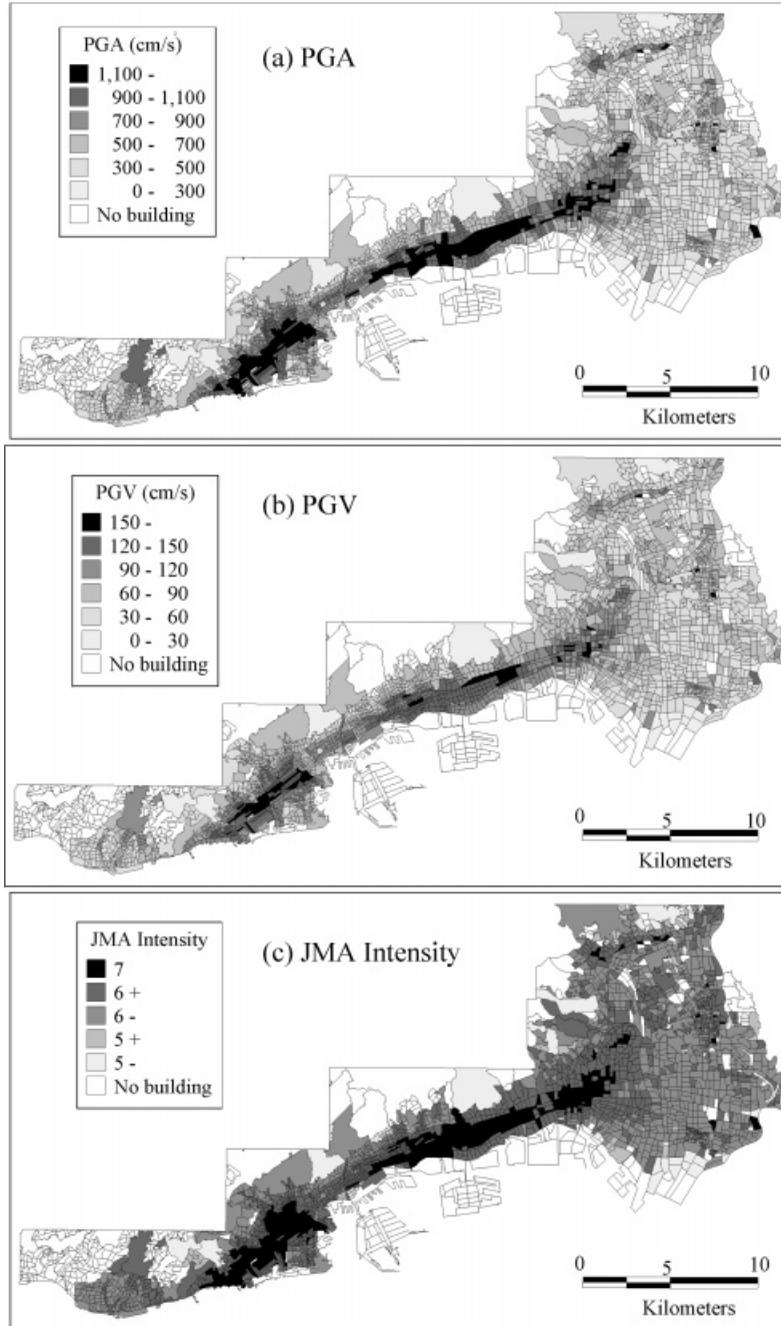


Figure 7. Distribution of PGA, PGV and JMA Intensity in the 1995 Kobe earthquake estimated from the damage ratios of low-storeyed residential buildings.

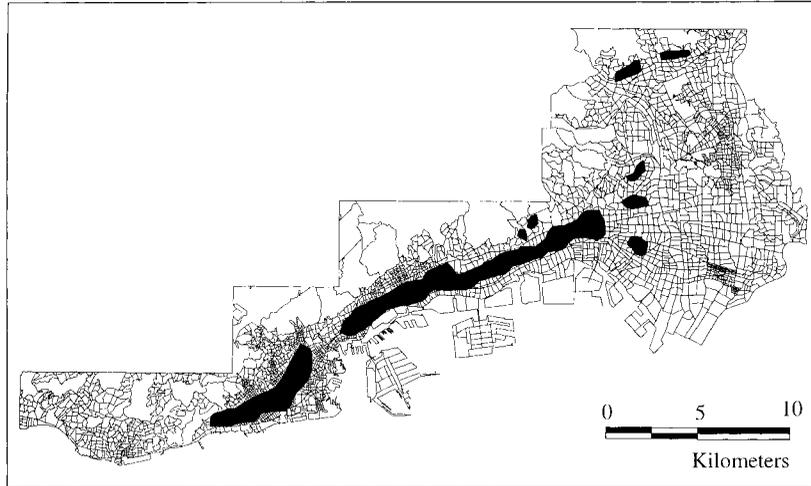


Figure 8. Belt of JMA Intensity 7 determined by JMA's field survey [32].

construction year. Fragility curves for damage assessments should be developed, if possible, using such revised strong motion distributions. For TKT and FUK stations, however, the detailed building inventory is not available, and hence, we cannot verify the reasoning mentioned above.

Another possible reason for the discrepancy for TKT is non-linear soil response under strong incident motion. Pore water pressure buildup is suspected at this site [35]. Thus the peak horizontal acceleration might be suppressed.

## CONCLUSIONS

In order to evaluate the damage of structures due to an earthquake, it is necessary to estimate ground motion distributions in the stricken area. In the 1995 Kobe earthquake, however, the number of strong motion records was not large enough to estimate the detailed spatial distribution of ground motion. Hence, the building damage data obtained by the same standard throughout the affected area were employed to estimate the strong motion distributions in the event. Comparing the recorded strong motion indices (PGA, PGV and JMA intensity) and the building damage ratios in the surrounding areas of the instruments, the fragility curves for one- and two-storeyed residential buildings were constructed. Using the obtained fragility curves and the building damage ratios in all the district blocks, the spatial distributions of the strong motion indices were back-calculated for the area struck by the Kobe earthquake. The estimated strong motion distributions were in good agreement with the reported intensity distribution. The estimated distributions may be conveniently used in the investigation of the performance of structures due to the earthquake.

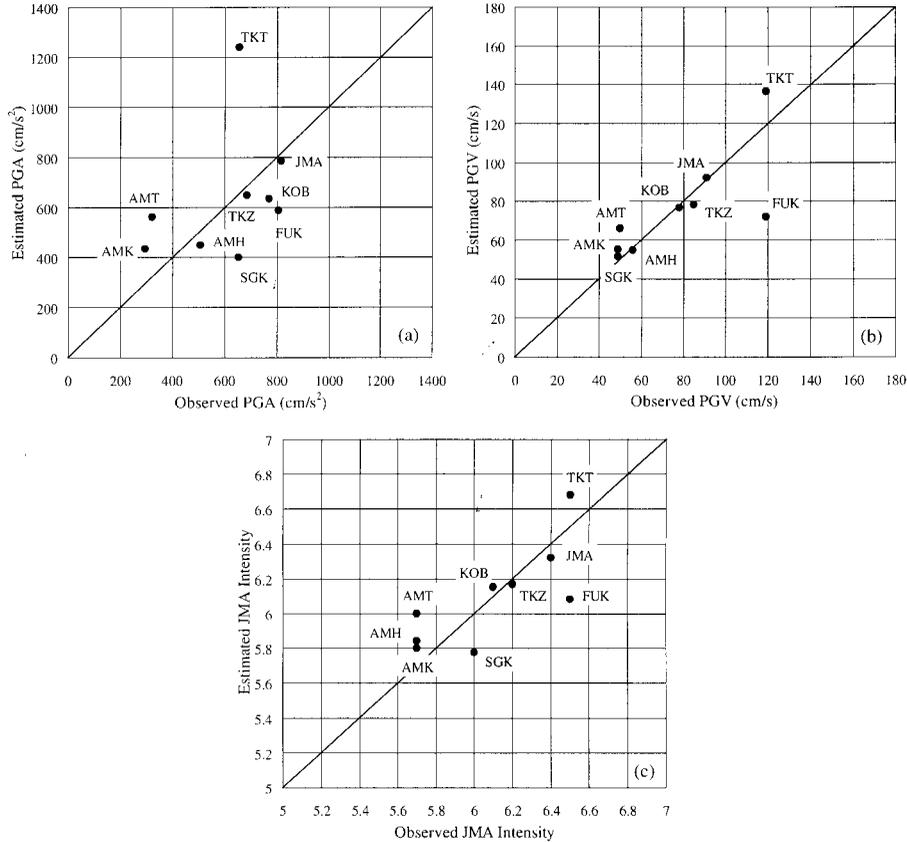


Figure 9. Comparison of observed strong motion indices and estimated values from the fragility curves for the low-storeyed residential buildings.

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