

DISCRIMINANT ANALYSIS OF STREET-BLOCKADES IN KOBE CITY DUE TO THE 1995 HYOGOKEN-NANBU EARTHQUAKE

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SUMMARY

A lot of streets in Kobe City were blocked by collapsed wooden houses etc. in the 1995 Hyogoken-Nanbu Earthquake. Street-blockade obstructed emergency activities such as refuge, rescue, fire-fighting and relief at that time. As a basic study to establish a method of predicting the danger of street-blockade due to strong near field earthquakes, first the conditions of wooden house collapse and street-blockade in Nagata Ward and Higashi-Nada Ward of Kobe were investigated using aerial photographs. Through the examination of this data, it became clear that frequency distribution of the length of debris of collapsed wooden house follows the Gamma distribution. Next, discriminant analysis of street-blockades based on Mahalanobis' distance was carried out. Analytical results showed that the accuracy of discriminant analysis was satisfactory and rate of collapsed houses, street and sidewalk widths contributed significantly to the accuracy. In addition, discriminant analysis based on theory of probability were carried out and it was shown that its analysis didn't give an underestimation of overall rate of blocked links.

INTRODUCTION

The 1995 Hyogoken-Nanbu Earthquake caused severe damage in Japan, especially to Kobe City. **Fig. 1** [1] shows the location of Kobe and the number of collapsed houses in each ward of Kobe [2,3]. We can find that many houses collapsed especially in Nagata Ward and Higashi-Nada Ward. A lot of streets in Kobe were covered extensively or partially with debris of collapsed wooden houses and, as a result, it caused many street-blockades. Street-blockade obstructed emergency activities such as refuge, rescue, fire-fighting and relief at that time. Such facts clearly show us that it is very important for urban disaster prevention planning to develop a methodology for evaluation of the likelihood of street-blockade due to strong earthquakes. In general, street-blockade is caused by several factors, such as collapse of wooden houses was one of the primary causes of street-blockade. As a basic study to establish an estimation method for street-blockade due to strong earthquakes, conditions of wooden house collapse and street-blockade in Nagata and Higashi-Nada were investigated from the aerial photograph and discriminant analyses of the existence of street-blockades were carried out based on Mahalanobis' distance or using probability distributions of the length of debris of wooden houses.

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X : Eepicenter of The Hyogoken-Nanbu Earthquake (Jan.17,1995)

Fig.1 Location of Kobe City and number of collapsed houses [1]



Fig.2 Illustration of a link

Kyushu

Fig.3 Definition of right and left of a link

METHOD OF INVESTIGATING STREET ATTRIBUTES AND STREET-BLOCKADE BY WOODEN HOUSE COLLAPSE

Occurrence of street-blockade by house collapse generally depends on both the attributes of street and the level of damage to wooden houses in place-along-the-street. We paid attention to Nagata Ward and Higashi-Nada Ward of Kobe City, both of which were severely damaged areas in the earthquake. Street between the adjacent crossings was defined as a link as shown in **Fig.2** and also **Fig.3** shows the definition of the right and left in a link [4]. About 1400 links with roadway width of 3m or more were selected from both wards, respectively. In order to perform rescue, fire-fighting and emergency restoration activities, a residual roadway width of 3m or more can be necessary. In this study, streets with an initial roadway width of less than 3m were considered to be blocked regardless of the existence of wooden house collapse. In addition, each link was divided into right side and left side sub-links which have the common roadway as shown in **Fig.4**. Sub-link is expressed by attributes of street and place-along-the-street. Each attribute parameter of street, length of debris of collapsed house and remaining unblocked roadway width are denoted by the following symbols as shown in **Fig.5**, in which each symbol is as follows:







Fig.5 Remaining unblocked roadway width and length of debris of collapsed house in each sub-link

 $l_i: \text{Length of link } i (m)$ $W_{ri}: \text{Roadway width of link } i (m)$ ${}_{R}W_{Si, L}W_{Si}: \text{Sidewalk width of each sub-link of link } i (m)$ ${}_{R}N_{i, L}N_{i}: \text{Number of wooden houses of each sub-link of link } i$ ${}_{R}W_{bi, L}^{k}W_{bi}^{k}: \text{Distance from house to street}$ ${}_{R}W_{Ci, L}^{k}W_{Ci}^{k}: \text{Length of debris of house } k \text{ collapsed to road side direction}$ ${}_{R}W_{ai, L}^{k}W_{ai}^{k}: \text{Remaining unblocked roadway width}$

In the above-mentioned symbols, lower right subscript i corresponds to link i and lower left subscripts, R and L, denote either sub-link respectively. In addition, upper right subscript k corresponds to the k th wooden house of each sub-link.

The values of these parameters were obtained from the newest detailed housing map [5] at the Hyogoken-Nanbu earthquake, aerial photographs [6] taken three days after the earthquake and disaster state diagram [7] drawn after early field survey as shown in **Fig.6** respectively.

Roadway attributes of each link

Roadway attribute parameters are roadway width (W_{ri}) , length of link (l_i) and angle between link *i* and perpendicular line to earthquake fault (θ_i) . These quantities were measured on detailed housing map.



(a) Detailed housing map



(b) Aerial photograph



(c) Distibution map of collapsed houses



Place-along-roadway attributes of each link

It is considered that sidewalk width $(_{R}W_{Si}, _{L}W_{Si})$, number of wooden houses $(_{R}N_{i}, _{L}N_{i})$ and distance from house to street $(_{R}W_{bi}^{k}, _{L}W_{bi}^{k})$ are place-along-roadway attributes. Sidewalk width is measured on detailed housing map and also the number of wooden houses is counted on that, referring to aerial photograph. Distance from house to street is ignored because almost all the houses in the target area were built in contact with streets.

Length of debris of collapsed wooden houses and remaining unblocked roadway

Number, collapse direction and length of debris

Debris of collapsed wooden house

Fig.7 An example of debris of collapsed wooden houses [6]

of collapsed wooden houses, which may greatly contribute to street-blockade, were obtained from aerial photographs, referring to both detailed housing map and disaster state diagram. In addition, the existence of street-blockade of each sub-link was judged from the aerial photograph. Stereoscope was used to watch the condition of collapsed houses in detail. **Fig.7** shows an example of debris of collapsed wooden houses.

STATISTICAL CHARACTERISTICS OF BOTH SUB-LINKS AND COLLAPSED WOODEN HOUSES

Frequency distributions of attributes of sub-link and some quantities related to house collapse are examined here. Sub-links with a roadway width of less than 3m or without houses were removed from statistical analysis [4]. As a result, 2172 sub-links in total were selected: 947 sub-links in Nagata Ward and 1225 sub-links in Higashi-Nada Ward.

Roadway attributes

Frequency distribution of roadway width

Fig.8 shows the frequency distribution of roadway width. From this figure, it is found that about78% of sub-links have the roadways with a width of 8m or less and the average of roadway width is about 6.26m.

Frequency distribution of angle between sub-link and perpendicular line to earthquake fault

Fig.9 shows the frequency distribution of angle between sub-link and perpendicular line to earthquake fault. From this figure, it is found that the network of links is a lattice-like.



Fig.8 Frequency distribution of roadway width



Fig.9 Frequency distribution of direction of sub-links



Fig.10 Frequency distribution of length of sub-links



Fig.11 Frequency distribution of sidewalk width



Fig.12 Frequency distribution of number of wooden houses in each sub-link

Fig.13 Frequency distribution of number of collapsed wooden houses in each sub-links

Frequency distribution of sub-link length

Fig.10 shows the frequency distribution of sub-link length. From this figure, it is found that about 65% of sub-links have the length of the range of 20 to 60m and the average of sub-link length is about 49.22m.

Place-along-roadway attributes

Frequency distribution of sidewalk width

Fig.11 shows the frequency distribution of sidewalk width. From this figure, it is found that about 74% of sub-links don't have the sidewalk and the average of sidewalk width is 0.60m.

Frequency distribution of number of wooden houses in place-along-roadway

Fig.12 shows the frequency distribution of number of wooden houses. From this figure, it is found that sub-links which have four or less houses account for close to 70% of the whole and the average of the number of houses in place-along-street is about four.



Fig.14 Frequency distribution of rate of collapsed wooden houses in each sub-link



Fig.15 Frequency distribution of remaining unblocked roadway width

Damage characteristics

Frequency distribution of number of collapsed wooden houses in place along each street **Fig.13** shows the frequency distribution of number of collapsed wooden houses in place along each street. From this figure, it is found that there are comparatively few sub-links which have the five or more numbers of collapsed houses.

Frequency distribution of rate of collapsed wooden houses in place along each street

Fig.14 shows the frequency distribution of rate of collapsed wooden houses in place along each street. From this figure, it is found that number of sub-link with collapsed wooden house rate of 50-60% is the greatest in the sub-links except those with collapsed wooden house rates of 0 and 100%.

Frequency distribution of remaining unblocked roadway width

Fig.15 shows the frequency distribution of residual roadway width. As mentioned above, links with remaining unblocked roadway width of less than 3m are considered to have been blocked and street with roadway width of less than 3m is of course regarded as blocked one. Equation (1) denotes the condition of blockade of sub-link.

$$W_{ai}^{k} = W_{ri} + W_{si} + W_{bi}^{k} - W_{ci}^{k} < 3.0(m)$$
⁽¹⁾

in which all symbols should be referred to the forgoing explanatory notes about **Fig.5**. Lower right subscripts, R and L, are omitted for simplicity. From

this figure, percentage of blocked sub-links is found to be about 10%. Incidentally the rates of street-blockade in Nagata Ward and Higashi-nada Ward were 5% and 13% respectively. Though these rates are not so high, we shouldn't overlook that there are many sub-links which have residual roadway width of 3-3.5m.

Frequency distributions of number of wooden houses collapsed to road side direction

Fig.16 shows the frequency distribution of number of wooden houses collapsed to road side direction. From this figure, it is found that percentage of



Fig.16 Number of collapsed wooden houses in each direction



Fig.17 Frequency distribution of length of debris of collapsed wooden houses

wooden houses collapsed to road side direction is 35%. The wooden houses in this district may have structural characteristics of being easy to collapse to road side direction.

Frequency distribution of length of debris of collapsed wooden houses

Fig.17 shows the frequency distribution of length of debris of collapsed wooden houses. The number of sub-links in each range of the length of the debris shown in **Fig.17** was converted into the number per unit length as shown by the line graph in **Fig.18**. It was fortunately found that this distribution obeys a Gamma distribution as shown in **Fig.18**. The probability density function of the Gamma distribution is defined as Equation (2).



Fig.18 Probability density curve for length of debris of collapsed wooden houses



Fig.19 Probability distribution curve for length of debris of collapsed wooden houses

$$f(x) = \frac{\lambda^k x^{k-1} e^{-\lambda x}}{\Gamma(k)} \quad (x \ge 0)$$
⁽²⁾

in which x is random variable and $\lambda(>0)$ and k(>0) are constants. $\Gamma(k)$ represents the Gamma function as Equation (3).

$$\Gamma(k) = \int_0^\infty e^{-x} x^{k-1} dx \tag{3}$$

The relations among constants(λ , k), average and variance in the Gamma distribution are as follows.

Average=
$$\frac{k}{\lambda}$$
, Variance= $\frac{k}{\lambda^2}$ (4)

In the case of **Fig.18**, the average and variance are 3.52 and 3.85 respectively, therefore λ and k are calculated as being 0.92 and 3.22 from Equation (4) respectively. **Fig.19** shows the cumulative distribution curve corresponding to **Fig.18**. Equation (2) can be very useful to prediction of the street-blockade brought about by house collapse.



Fig.20 Relation between rate of collapsed wooden houses and maximum length of debris in each sub-link

Relation between rate of collapsed wooden houses and maximum length of debris in each sub-link

Fig.20 shows the relation between the rate of collapsed wooden houses and maximum length of debris in each sub-link. From this figure, it is found that the maximum length of debris in each sub-link tends to increase with the increase in the rate of collapsed wooden houses in each sub-link.

Relation between rates of collapsed wooden houses and wooden houses collapsed to road side direction

Fig.21 shows the relation between the rates of collapsed wooden houses and wooden houses collapsed to road side direction. From this figure, it is shown that there is not an obvious relation between them.

Rate of links with wooden houses which collapsed from both sides

Fig.22 shows the rate of links with wooden houses which fell from both sides. From this figure, it is found that the rate of links with wooden houses which fell from both sides 13 %. This fact suggests that houses subjected to strong earthquake tend to fall on the front door side and although each length of debris is short, street-blockades may occur by butting of debris from both sides.

RESULTS OF DISCRIMINANT ANALYSIS OF STREET-BLOCKADE IN KOBE CITY BASED ON MAHARANOBIS' DISTANCE

Discriminant analysis of street-blockade in Nagata Ward and Higashi-nada Ward was carried out based on Mahalanobis' distance first. In this analysis, six predictor variables were considered: roadway width, sidewalk width, number of houses, angle between a link and perpendicular line to earthquake fault, length of sub-link and rate of collapsed houses. All sub-links are classified into blockade group (*Group 1*) and un-blockade group (*Group 2*). **Table 1** shows the centroid of each group. Each centroid is expressed by a set of mean values of predictor variables of the corresponding group. These groups and their centroids are imaged as **Fig. 23**.



Fig.21 Relation between rates of collapsed wooden houses and wooden houses collapsed to road side





8 1	Table 1	Centroid of	each	group
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			Mean value of e	ach predictor	variable	
	Roadway	Sidewalk	Number of	Angle of	Length of	Collapsed hous
	width (m)	width(m)	roadside houses	sub-link (°)	sub-link (m)	rate (%)
	<u>x</u> 1	<u>x</u> 2	x3	<u>x</u> 4	<u>x</u> ₅	x ₆
Group 1 (Blocked sub-links)	4.62	0.15	4.03	78.97	54.12	73.47
Group 2	6.44	0.65	3.20	83.36	48.69	33.60



Fig.24 Concept of discriminant analysis of street-blockade based on Maharanobis'





Table 2 Accuracy of discriminant analysis of sublink-blockade based on Maharanobis' distance (Case A-S-S)

		Predictio		
Case A-S-S		Number of	Number of	Total
		blocked sub-links	unblocked sub-links	
results	Number of blocked sub-links	133	80	213
Survey	Number of unblocked sub-links	326	1633	1959
	Total	459	1713	2172
	Accuracy(%)	29.0	95.3	81.3

Discriminant analysis of street-blockade based on Mahalanobis' generalized distance

Fig.24 shows the concept of discriminant analysis based on Mahalanobis' generalized distance [8,9]. The square of Mahalanobis' generalized distance D_i (*m*) between *link i* and the centroid of *Group m* is represented as Equation (5).

$$D_{i}^{2}(m) = \sum_{j=1}^{n} \sum_{k=1}^{n} (x_{ij} - \overline{x}_{j}(m)) S^{jk}(x_{ik} - \overline{x}_{k}(m))$$
(5)

in which $S^{\#}$: individual element (j,k) of inverse matrix of pooled variance-covariance matrix

 x^{jk} : *j* th variable on *link i*, $\bar{x}_j(m)$: mean of the *j* th variable in *Group m*

For example, $D_i^2(1) < D_i^2(2)$ means that sub-link *i* belongs to Group 1 : the set of blocked links.

Results of discriminant analysis of street-blockade in Nagata Ward and Higashi-Nada Ward

Results on sub-links

Table 2 shows the accuracy of discriminant analysis of blockade of the sub-links in both wards. It is found that the overall accuracy is 81.3%. In order to examine the contribution of each predictor valuable to accuracy, discriminant analyses were carried out removing only corresponding data from all data one by one. **Table 3** shows the comparison of the contribution of six variables to accuracy. Generally, if an important variable is removed, accuracy of analysis lowers. It is found that the contribution to accuracy is high in order of the rate of collapsed wooden houses, roadway width and sidewalk width and also the other variables do not contribute to the accuracy.

Table 3	Contribution	of	predictor	variables
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Disregarded predictor variables	Nothing	Roadway width (m) $\overline{x_1}$	$\frac{\text{Sidewalk}}{\text{width(m)}}$	Number of roadside houses $\overline{x_3}$	Angle of sub-link (°) $\frac{1}{x_4}$	Length of sub-link (m) $\overline{x_5}$	Collapsed house rate (%) $\overline{x_6}$
Accuracy (%)	81.3%	75.8%	80.5%	82.1%	81.9%	81.9%	68.0%

Table 4 Accuracy of discriminant analysis of
sublink-blockadebased
on
Maharanobis' distance (Case B-S-S)

	Case B-S-S		Predictio		
			Number of	Number of	Total
			blocked sub-links	unblocked sub-links	
	results	Number of blocked sub-links	176	37	213
	Survey	Number of unblocked sub-links	158	1801	1959
		Total	334	1838	2172
		Accuracy(%)	52.7	98.0	91.0

Table 5 Six patterns of discriminant analyses

Parameter for seismic damage				
Rate of collapsed houses	Rate of houses collapsed to road side direction			
Case A-S-S	Case B-S-S			
Case A-F-S	Case B-F-S			
Case A-F-F	Case B-F-F			

In the above discrimant analyses, the rate of collapsed houses is used as a valuable which represents seismic damage. Though the rate of collapsed houses may be a relatively practical parameter, the rate of wooden houses collapsed to road side directioncan be more appropriate than that because of more direct relation to street-blockade. **Table 4** shows the accuracy of discriminant analysis which uses the rate of wooden houses collapsed to road side direction in stead of the rate of collapsed houses. As compared with **Tables 2**, it is found that the accuracy of discriminant analysis with the rate of wooden houses collapsed to road side direction in stead of the rate of wooden houses collapsed to road side direction is quite higher than that with the rate of collapsed wooden houses.

Results on links

The results of discriminant analysis of street blockade of sub-links were mentioned in the foregoing paragraph. Street-blockade of full links, however, should be estimated for the purpose of prediction of street-blockade. Four ways to predict the blockade of full-links are considered. **Table 5** shows all patterns of discriminant analysis of blockades of sub-links or full-links. In this table, Cases A and B denote the discriminant analysis with the rates of collapsed houses and houses collapsed to road side direction

Table 6 Accuracy of discriminant analysis of
link-blockade using prediction
results of sub-link based on
Maharanobis' distance (Case A-F-S)

		Predictio		
1 (Case A-F-S	Number of	Number of	Total
		blocked sub-links	unblocked sub-links	
results	Number of blocked sub-links	129	58	187
Survey	Number of unblocked sub-links	238	963	1201
	Total	367	1021	1388
	Accuracy(%)	35.1	94.3	78.7

Table 8 Accuracy of discriminant analysis of
full-link-blockade from prediction
results of sub-link based on
Maharanobis' distance (Case B-F-S)

	Predictio		
Case B-F-S	Number of	Number of	Total
	blocked sub-links	unblocked sub-links	
Number of blocked sub-links	157	30	187
Number of unblocked sub-links	131	1070	1201
Total	288	1100	1388
Accuracy(%)	54.5	97.3	88.4
	Case B-F-S Number of blocked sub-links Number of unblocked sub-links Total Accuracy(%)	Predictic Number of blocked sub-links Number of blocked sub-links Number of unblocked sub-links 157 Number of unblocked sub-links 131 Total 288 Accuracy(%) 54.5	Prediction results Number of blocked sub-links Number of ublocked sub-links Number of ublocked sub-links Number of unblocked sub-links 157 30 Number of unblocked sub-links 131 1070 Total 288 1100 Accuracy(%) 54.5 97.3

Table 7 Accuracy of discriminant analysis of
link-blockade based on Maharanobis'
distance (Case A-F-F)

		Predictio		
(Case A-F-F	Number of	Number of	Total
•		blocked sub-links	unblocked sub-links	
results	Number of blocked sub-links	109	78	187
Survey	Number of unblocked sub-links	175	1026	1201
	Total	284	1104	1388
	Accuracy(%)	38.4	92.9	81.8

Table 9	Accuracy of discrimina	ant ana	lysis of
	full-link-blockade	based	on
	Maharanobis' distance	e (Case	B-F-F)

		Prediction results			
	Case B-F-F	Number of	Number of	Total	
		blocked sub-links	unblocked sub-links		
results	Number of blocked sub-links	130	57	187	
Survey	Number of unblocked sub-links	116	1085	1201	
	Total	246	1142	1388	
	Accuracy(%)	52.8	95.0	87.5	

Table 10 Accuracy and number of actually blocked links misjudged as being unblocked in each case

(a)) Accuracy
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(b) Number of misjudged links

	Parameter for seismic damage				Parameter for seismic damage		
	Rate of collapsed houses (Case A-*-*)	Rate of houses collapsed to road side direction (Case B-*-*)			Rate of collapsed houses (Case A-*-*)	Rate of houses collapsed to road side direction (Case B-*-*)	
Case *-S-S	81.30%	91.00%		Case *-S-S	80	37	
Case *-F-S	78.70%	88.40%		Case *-F-S	58	30	
Case *-F-F	81.80%	87.50%		Case *-F-F	78	57	

respectively and also symbols, F and S, represent full-link and sub-link respectively. For example, Case B-F-S means the discriminant analysis of blockade of full-links based on the result of discriminant analysis of blockade of sub-links. In this case, each full-link is judged to be blocked when at least one of its sub-links is blockaded. **Tables 6**, **7**, **8** and **9** show the accuracy of each discriminant analysis. These results are summarized in **Table 10** together with those of **Tables 2** and **4**. From these tables, it is found that Case B-S-S is the best in respect of accuracy and also Case B-F-S is the best in respect of number of misjudged links among actually blocked links. From the viewpoint of disaster prevention, it is quite important that the number of misjudged links in actually blocked links is small.

RESULTS OF DISCRIMINANT ANALYSIS OF STREET-BLOCKADE IN KOBE CITY BASED ON THEORY OF PROBABILITY

As shown in the above-mentioned **Fig.18**, the frequency distribution of debris of collapsed wooden houses approximately follows the Gamma distribution. It can be possible to evaluate the probability that street-blockade will happen using this distribution.

Probability of blockade of link i

The above-mentioned Equation (1), which represents condition of street-blockade, is rewritten as Equation (6).

$$W_{ci}^k > L_i^{*k} \tag{6}$$

where L_i^{*k} is the shortest length of debris of collapsed house for street-blockade and calculated as $W_{ii} + W_{si} + W_{bi}^{k}$ -3.0. When wooden house k collapses to road side direction, probability that blockade of sub-link *i* does not occur, $W_{ci}^{k} \le L_i^{*k}$, is expressed by P_{dL^*} as shown in **Fig.25**. P_{dL^*} is obtained by integrating the probability function in the region of 0 to L_i^{*k} . Hence probability that blockade of sub-link *i*



Fig.25 Probability of street-blockade in sub-link with wooden houses which fell on road side

occurs, $W_{ci}^k > L_i^{*k}$, is written as Equation (7).

$$\overline{P}_{dL^*} = 1 - P_{dL^*} \tag{7}$$

The probability, P_{i0}^k , that sub-link *i* will be blocked due to collapse of wooden house *k* is expressed by Equation (8).

$$P_{i0}^{k} = P_{ri} \times P_{f} \times \overline{P}_{dL^{*}}$$
(8)

in which P_{ri} and P_f denote the rate of collapsed wooden houses of sub-link *i* and the rate of wooden houses collapsed to road side direction respectively. From **Fig.16**, it is found that number of wooden houses collapsed to road side direction: N_c=984 and also, number of collapsed wooden houses: N_d=2794. Therefore, P_f is obtained as follows:

$$P_f = \frac{N_c}{N_d} = \frac{984}{2747} \times 100 = 35.82\%$$
(9)

In the following, P_f is always set to be 35.82%.

The probability, \overline{P}_{i0}^{k} , that sub-link *i* will be unblocked when wooden house *k* collapse is expressed by Equation (10).

$$\overline{P}_{i0}^{k} = 1 - P_{i0}^{k} \tag{10}$$

Therefore the probability, $_{L}\overline{P_{i}}$, that left side

sub-link *i* with $_L N_i$ houses will not be

blockaded is written as Equation (11).

$${}_{L}\overline{P_{i}} = ({}_{L}\overline{P_{i0}}^{k}){}^{L^{N_{i}}}$$

$$(11)$$



Fig.26 Frequency distribution of probability of street-blockade



Fig.27 Comparison of accuracy of discriminant analysis using probability function

And also the probability, $_{R}\overline{P_{i}}$, that right side sub-link *i* with $_{R}N_{i}$ houses will not be blockaded is written as Equation (12).

$${}_{R}\overline{P}_{i} = ({}_{R}\overline{P}_{i0}^{k}) {}^{LN_{i}}$$

$$(12)$$

Therefore the probability, \overline{P}_i , that link *i* with $(_L N_i + _R N_i)$ houses will not be blockaded is expressed as Equation (13).

$$\overline{P}_{i} = {}_{L}\overline{P}_{i} \times {}_{R}\overline{P}_{i} = ({}_{L}\overline{P}_{i0}^{k}) {}^{LN_{i}} \times ({}_{R}\overline{P}_{i0}^{k}) {}^{RN_{i}}$$
(13)

As a result, the probability, P_i , that link *i* with $({}_LN_i + {}_RN_i)$ houses will be blockaded is obtained as Equation (14).

$$P_i = 1 - \overline{P_i} \tag{14}$$

Results of discriminant analysis of street-blockade in Nagata Ward and Higashi-Nada Ward based on theory of probability

First the probability of blockade of each link was calculated according to Equations (7)-(14). **Fig.26** shows the relation between probability of street-blockade and number of the links corresponding to each range of the probability. Red and blue parts of each bar denote the blocked and unblocked links respectively and also line graph shows percentage of actually blocked links in each bar. From this figure, it is found that the percentage of actually blocked links rapidly increases at blockade rate of about 40%. The green line in **Fig.27** shows the relation between the accuracy of analysis for all links and threshold value of probability to discriminate the

blocked and unblocked links. In addition, blue and red lines represent the accuracy of analysis for the actually blocked and unblocked links respectively. It is shown from this figure that these three lines intersect almost at one point corresponding to the threshold probability of 40%. This means that the probability of 40% is well-balanced threshold value for discriminant analysis. Therefore the threshold probability in the following analysis is set to be 40%.

Table11showstheaccuracyofdiscriminantanalysisofstreet-blockadebased on the theory of probability.From thecomparisonbetween Tables 8 and 11, it is

Table 11 Accuracy of discriminant analysis of
street-blockade based on theory of
probability

Case C		Prediction		
		Number of	Number of	Total
		blocked links	unblocked links	
Survey results	Number of blocked links	173	14	187
	Number of unblocked links	86	1115	1201
Total		259	1129	1388
Accuracy(%)		66.8	98.8	92.8

found that the accuracy of discriminant analysis of street-blockade based on the theory of probability is higher than those based on Maharanobis' distance. Furthermore it is notable that the rate of actually blocked links misjudged is quite small.

EXAMPLE OF DISCRIMINANT ANALYSIS OF STREET-BLOCKADE IN KOBE CITY USING RATE OF COLLAPSED HOUSES IN TARGET AREA

In general, the rate of collapsed houses in target area is given as an unique value of that area. **Fig.28** shows the relation between the rate of links estimated to be blocked based on Maharanobis' distance and the percentage of collapsed houses in target area. The percentage of collapsed houses was increased every 10% from 0 to 100%. **Fig.29** shows the relation between the rate of links estimated to be blocked and the rate of houses collapsed to road side direction in target area. **Figs.30** and **31** show the rates of links estimated to be blocked by using rates of collapsed houses and house collapsed to road side direction in target area are13.8% and 38.6% respectively, which are represented by red small squares. From these figures, it is found that the rate of blocked links are underestimated in **Figs. 28** and **29**. On the contrary **Figs. 30** and **31** show that the rate of blocked links are overestimated.



Fig.28 Effect of overall rate of collapsed wooden houses in whole region on rate of blocked links (Maharanobis' distance)



Fig.29 Effect of overall rate of wooden houses collapsed to road side direction in whole region on rate of blocked links (Maharanobis' distance)



Fig.30 Effect of overall rate of collapsed wooden houses in whole region on rate of blocked links (Gamma distribution)



Fig.31 Effect of overall rate of wooden houses collapsed to road side direction in whole region on rate of blocked links (Gamma ditribution)

CONCLUSIONS

The purpose of this work was to examine methods of estimating the occurrence of street-blockade due to strong earthquakes. First, conditions of wooden house collapse and street-blockade due to the 1995 Hyogoken-Nanbu Earthquake in Nagata Ward and Higashi-Nada Ward were investigated using aerial photographs taken three days after the earthquake. From this investigation, it was found that the rates of blocked links and collapsed wooden houses were 13.5% and 38.6% respectively. In addition, the percentage of wooden houses collapsed to road side direction was about 35% out of collapsed houses and the frequency distribution of length of debris of collapsed wooden houses followed the Gamma distribution. Next, both discriminant analyses of street-blockade based on Mahalanobis' distance and theory of probability were carried out. From the results of analysis based on Mahalanobis' distance, its accuracy was found to be 80% or more and also percentage of collapsed houses, street width and sidewalk width among six predictor variables contribute much to the accuracy though influence of other variables to accuracy was relatively low. From the results of analysis using the probability distribution of length of debris of collapsed wooden houses, it is notable that the accuracy was 90% or more and also rate of actually blocked links misjudged as being unblocked was relatively small. Furthermore, when overall rate of collapsed houses in target area is used, the overall rate of blocked links is underestimated by discriminant analysis based on Mahalanobis' distance and overestimated by discriminant analysis based on theory of probability. In conclusion, methods of discriminant analysis presented here can be improved for more accurately and easily estimating the occurrence of street-blockade due to strong earthquakes.

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