ASSESSMENT OF VULNERABILITY OF URBAN AREAS TO STREET-BLOCKADES CAUSED BY QUAKE-COLLAPSED BUILDINGS

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Abstract: In this study the authors proposed a method for estimating the occurrence of "street-blockades", which became obstacles for vehicle traffic in local areas in The Great Hanshin Earthquake. Firstly the authors analyzed width of debris which were caused by collapsed buildings, in a mathematical approach using the surveyed data by aerial photographs. Secondly, the authors calculated the vulnerability of street-blockades in streets as probability of blockades. And finally a simulation of street-blockades condition was made to verify the applicability and suitability of the method.

1. INTRODUCTION

On January 17th,1995, right after the Great Hanshin Earthquake, large amount of “street-blockades” were caused by collapse of old wooden buildings or leant poles, in most cases, along narrow streets in urban areas. These street-blockades caused many obstacles to the street systems of the city districts just after the quake, such as difficulties to find evacuation routes for inhabitants, or hindrance for emergency vehicles to reach to access the target places.

The authors began to study these “street-blockades” right after the earthquake. Firstly the authors had made an analysis of occurrence situation of street-blockades by using aerial photographs and formulated its result into a GIS data. And secondly the impact of street-blockades on emergency activities of fire department, police, and self-defense force were analyzed through questionnaires. From the analyses, taking account that there are so many areas in Japan which have high density of old wooden houses, and that the ability of emergency activities depends on its mobile power which is normally got by using vehicles, the importance of taking care about the street-blockades sufficiently in planning the earthquake disaster prevention were shown.

Then, it can be said that for making urban areas which are safe against earthquake disaster, it is needed to evaluate and assess "the safety against the street-blockades" in the urban areas. For these purpose, it can be desirable to evaluate and simulate the occurrence of street-blockades according to the characteristics of buildings and street infrastructures in the areas.

In this study the authors firstly corrected bias by a mathematical method the data observed from aerial photographs in the Great Hanshin Earthquake. These bias caused by the survey restriction were removed. Secondly estimated a function which explains width of debris caused by collapsed buildings. Finally, the authors simulated the street-blockaded conditions on city districts in Kobe City, and compared with the actual situation to verify the applicability and suitability of the model.

2. USED DATA AND SURVEY AREAS

In this study the result of analysis made by the authors in 1995 are used. This analysis surveyed the situation of street-blockades occurrence by using aerial photographs which were taken one day after the earthquake (January 18th). For this analysis seven survey areas are chosen from the points of 1)damages of buildings, 2)attribute of buildings, 3)attribute of land use, 4)streets structure and so on(Figure1).For the survey areas, the places which buildings had been burnt down were excluded. Each area was chosen to be about 50ha. A street connecting two next intersections is treated as a unit of street, and is called "street link". Each survey area includes about 400 street links in average. Because of the restriction of getting attribute data of buildings, in this study six areas out of seven were chosen, which are in Kobe city.

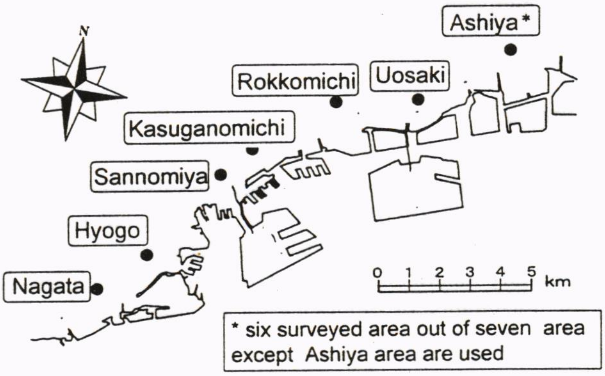

Figure 1 A Survey Area

From the analysis, a blocked rate in each street (street blocked rate) can be available. And this value is calculated by dividing maximum width of debris by street width. This street-blockades data can be classified into two types in terms of causal element. One is which caused by debris from collapsed buildings and the other is which caused by leant poles such as electric poles or traffic lights. By multiplying street-blocked rate by its street width, a maximum width of debris for each street link are obtained for product.

3. CALCULATION OF PROBABILITY DISTRIBUTION OF DEBRIS CONSIDERING THE WIDTH AND LENGTH OF STREET LINKS

3.1 Bias in Observed Data of Debris Data and Needs to Correct the Data

In the data of maximum width of debris in each street link which can be available from the survey of aerial photographs, there exist two kinds of bias.

One is bias of the data, which is the effect of existence of upper-limit in terms of street width. And this bias has trend to under estimate the data. In the case which width of debris becomes wider than the street width, from survey we can just get the same value of width as the street width for the maximum width of debris because we cannot observe beyond streets. This means that in street links which street blocked rate is 100%, there are street links which actual debris width were wider than its street link width.

Second is bias that increases expectation of maximum debris width. This bias over estimates the data. And it is the bias related with the street length. The reason of this bias is that in the survey we gain the data just by maximum width of debris. But there may be several debris in a street link, and it can be thought that the number of debris increases when the street link becomes longer. So the expectation of the maximum width of debris has stronger over-bias in the longer street links.

In this study, the authors removed these two bias with a mathematical approach. At first the effect of upper limit in terms of street link width are removed, then the increasing effect of maximum debris of width which related to street link length are removed by standardizing the street link length. These two calculation steps are not done in terms of a street link itself but be calculated in terms of probability distribution of debris for some small areas. Because of the effect of upper limit in terms of street link width, only thing we can know is just that the actual maximum width of debris is over the street link width at the street link which street block rate is 100%. So in the calculation the surveyed areas are divided into sections to Japanese political city district "cho-cho-moku", and express the occurrence width of debris by a probability distribution for each city district. From the viewpoint of probability distribution, these two bias can be explained as "bias on probability distribution from the effect of upper limit in terms of street link width" and "bias on probability distribution from the increasing of maximum width of debris related with the street link length".

3.2 The Method to Correct Probability Distributions of Debris from the Point of Effect of Upper Limit in terms of Street Width

We put $h_y(y)$ as a probability density function: pdf in a city district for the observed debris width y, and put pdf $t_w(w)$ for street link width w. These two functions are obtained from the given data. By use of these two pdf, pdf $g_x(x)$ for debris x, in which effect of upper limit of street link is removed, is estimated for each city district.
When we think of a cross section of a street link, observed debris width y can be denoted as follows.

$$\begin{cases} y = x & \text{when} \quad w > x \\ & or \\ y = w & \text{when} \quad x \geq w \end{cases} \qquad \cdots\cdots\cdots\cdots (1)$$

First formula is the case when the actual debris width is smaller than the street link width and observed debris width y is equal to the actual debris width x (Figure 2-a). And second formula denotes the case when the actual debris width is bigger than street link width and observed debris width y becomes the same as the street link width w because of the effect of upper limit in terms of street link width(Figure 2-b). Now if we assume x and w are independent variables, the pdf $h_y(y)$, which is for observed debris width y, can be expressed as follows.

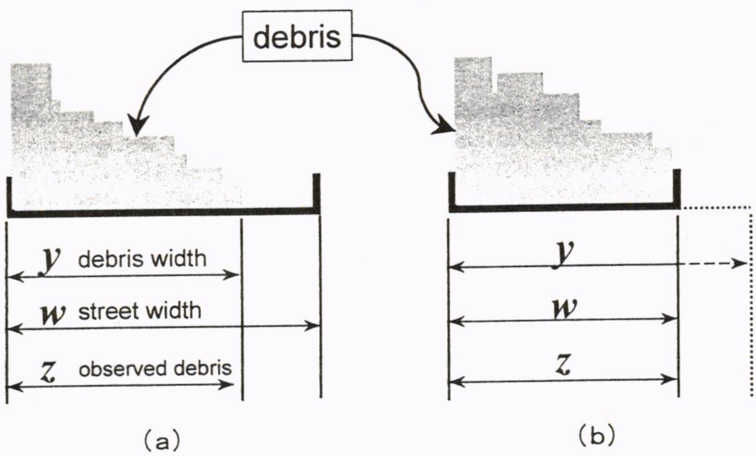

Figure 2 Across section of a street link

$$\begin{aligned} h_y(y) &= g_x(y) \cdot \int_y^{\infty} t_w(w)dw + t_w(y) \int_y^{\infty} g_x(x)dx \\ &= g_x(y) \cdot \left\{1 - \int_0^y t_w(w)dw\right\} + t_w(y) \cdot \left\{1 - \int_0^y g_x(x)dx\right\} \qquad \cdots\cdots\cdots (2) \\ &= g_x(y) + t_w(y) - \frac{d}{dz}\left\{\int_0^y g_x(x)dx \cdot \int_0^y t_w(w)dw\right\} \end{aligned}$$

When the cumulative distribution function: CDF for y, x, w are put as $H_y(y)$, $G_x(x)$, $T_w(w)$, , Equation -(3) is obtained by the integration of Equation-(2).

$$H_y(y) = G_x(y) + T_w(y) - G_x(y) \cdot T_w(y) + C \qquad \cdots\cdots\cdots\cdots (3)$$

C: *integration constant*

If $y \to \infty$, it is clear from the property of CDF that $H_y(y) = 1, G_x(y) = 1, T_w(y) = 1$. Then it becomes $C = 0$. Now we change the variable y into x and change the form of

Equation-(3) into Equation-(4) as shown below.

$$G_x(x) = \frac{H_y(x) - T_w(x)}{1 - T_w(x)} \qquad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Equation-(4) makes it possible to calculate $G_x(x)$: CDF of corrected debris width, from $H_y(y)$: CDF of observed debris width, and $T_w(w)$: CDF of street link width. And from differentiating Equation-(4), pdf $g_x(x)$ is available.

3.3 The Method to Standardize Probability Distribution of Debris Considering the Increase of Debris with Street Length

Once the effect of upper limit of street width on probability distribution of debris is corrected, the effect of length of street links to increase the maximum width of debris are removed. As mentioned before, the expectation of observed debris width tends to become larger when the link length is longer. Then an assumption is made that maximum debris width x satisfies the following function when the street link length is l.

$$x = x_0 \cdot \theta(l) \qquad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

x_0 is independent from l, and here it is called " unified debris width". $\theta(l)$ is a monotone increasing function start from $\theta(0) = 1$. $\theta(l)$ is called "link length effect function".

Taking account the assumption, an equation to denote $g_x(x)$: pdf of corrected debris width x are considered . The equation can be obtained by integrating the probability that both x_0 and l will happen at the condition that satisfying the Equation-(5). We put $f_{x_0}(x_0)$ as pdf of standardized debris width x_0 , and $s_l(l)$ as pdf of street link length l. $g_x(x)$ can be written as follows.

$$g_x(x) = \int_0^{\infty} s_l(\theta^{-1}(x/x_0)) \cdot f_{x_0}(x_0)dx_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

under the condition of $\theta^{-1}(x/x_0) = l$

From the definition of $\theta(l)$,

$$x_0 \le x \qquad \cdots\cdots\cdots\cdots\cdots\cdots (7)$$

then the interval to integrate is changed and Equation-(6) can be rewritten as next.

$$g_x(x) = \int_0^{x} s_l(\theta^{-1}(x/x_0)) \cdot f_{x_0}(x_0)dx_0 \qquad \cdots\cdots\cdots\cdots\cdots\cdots (8)$$

under the condition of $\theta^{-1}(x/x_0) = l$

When we consider the case $\theta(l)$ is given, the problem becomes to estimate $f_{x_0}(x_0)$ which satisfies the integral equation-(8) from the functions $g_x(x), s_l(l), \theta(l)$ which are given. This problem can not be solved by accurate method. Then $f_{x_0}(x_0)$ are estimated by numerical calculation.

At first appropriate N typical points are selected as x and x_0, are denoted by vector $\{x_i\}$ and $\{x_{0j}\}$. The value of $g_x(x_i), f_{x_0}(x_{0j}), s_l(x_i, x_{0j})$ are expressed $g_{xi}, f_{x_0j}, s_{lij}$. And put F_{x_0j} as the product of multiplying f_{x_0j} by Δx_0: steps of x_0. Equation-(8) is rewritten as follows.

$$\{g_{xi}\} = [s_{lij}]\{F_{x_0j}\} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(9)}$$

So the problem is to estimate $\{F_{x_0j}\}$ such as

$$\left\|\{g_{xi}\} - [s_{lij}]\{F_{x_0j}\}\right\| \to \min \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(10)}$$

when $\{g_{xi}\}, [s_{lij}]$ are given. If Equation-(10) is differentiated with respected to F_{x_0j}, the problem changes to solve simultaneous first-degree equation.

3.4 Estimation of Link Length Effect Function $\theta(l)$

For the estimation of $\theta(l)$ the relation between debris width and link length are needed to be found. But the observed data of debris width which can be available are under biased because of upper limit of street link width. So it is needed to estimate the actual maximum width of debris without the effect of upper limit of street link width.

Now we think a situation that CDF of debris width after the correction in terms of the effect of upper limit of street link width is given for a city district.(Figure 3-[A]). The CDF of debris width for a street link with width of w_0 in this city district is drawn as Figure 3-[B]. When the street blocked rate of this street link is 100%, range of the maximum width of debris x in this street link is $w_0 \le x \le \infty$. And its pdf is available from differentiating the function [A]when $x > w_0$. When we make an assumption that actual maximum width of debris may be estimated as the median of range of value which can be possible, x_1 shown in Figure 3 is the estimated actual maximum width of debris.

By the method explained above, actual debris can be estimated for the street links with street blocked rate of 100%. Then all the street links, both 100% blocked links and not 100% blocked link, were classified into 10 meters each intervals in terms of street link length, and calculated the average of estimated debris for each interval. The result is shown in Figure 4. l'[m] is the median of link length for each intervals and x'[m] is the average of debris width for each intervals. Then Equation-(11) were got from fitting an exponential curve using the least square method.

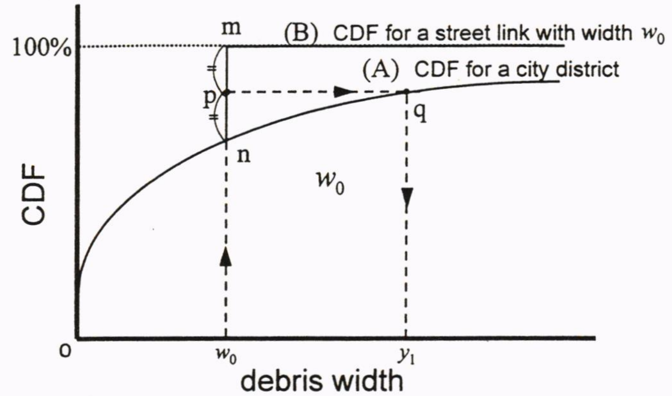

Figure 3 A Correction of the Effect of Upper Limit of a Link Width

$$x' = 1.39 \cdot exp(0.0061 \cdot l') \qquad \cdots\cdots (11)$$

Equation-(11) shows a general relation between link length and debris width. When we consider that the exponential function part of this equation explains the bias related with the length of street link, the link length effect function is written as follows. It is clear from Equation-(12) that $\theta(l)$ satisfies $\theta(0)=1$

$$\theta(l) = exp(0.0061 \cdot l) \qquad \cdots\cdots (12)$$

l: *street link length* $[m]$

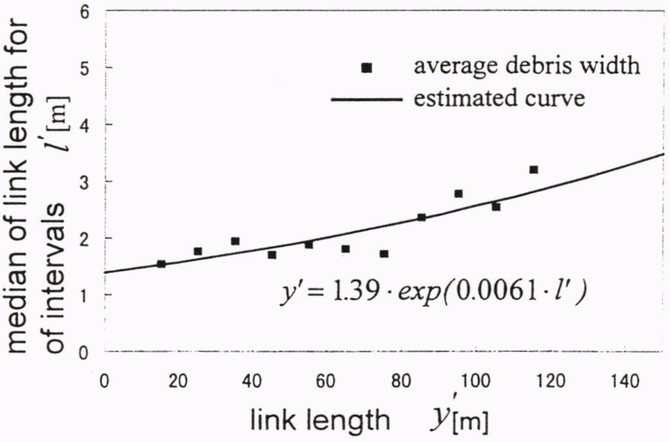

Figure 4 An estimation of $\theta(l)$

3.5 The Estimation of Probability Distribution of Standardized Debris Width

At first probability distribution of debris width which are corrected in terms of street link width were calculated by Equation-(4). Then by Equation-(10),(12), CDF of standardized debris width for each city district were calculated. Figure 5 shows an example of its CDF in a city district “Nada-ku,Fukada-cho,1-chome”. And Figure 6 shows examples that summed up the estimated result of each city districts into the areas in the cases of Nagata area and Sannomiya area. In Nagata area, where exists many comparatively narrow streets, there is much effect of upper limit of street link width. And in Sannomiya area, in which blocks are large, there is much effect related with length of street links.

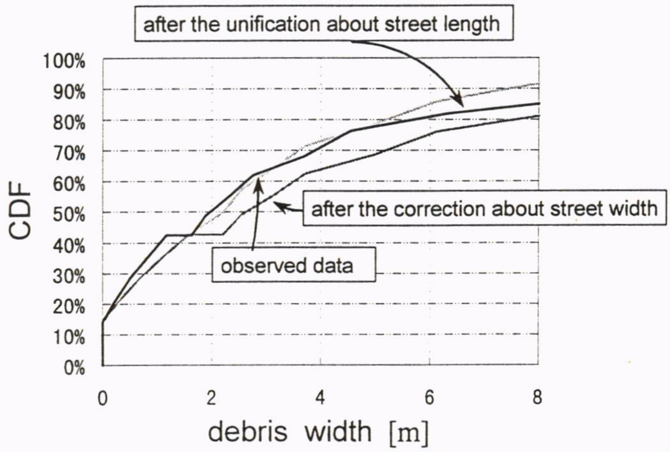

Figure 5 An example of calculated CDF

(Fukada-cho 1-chome)

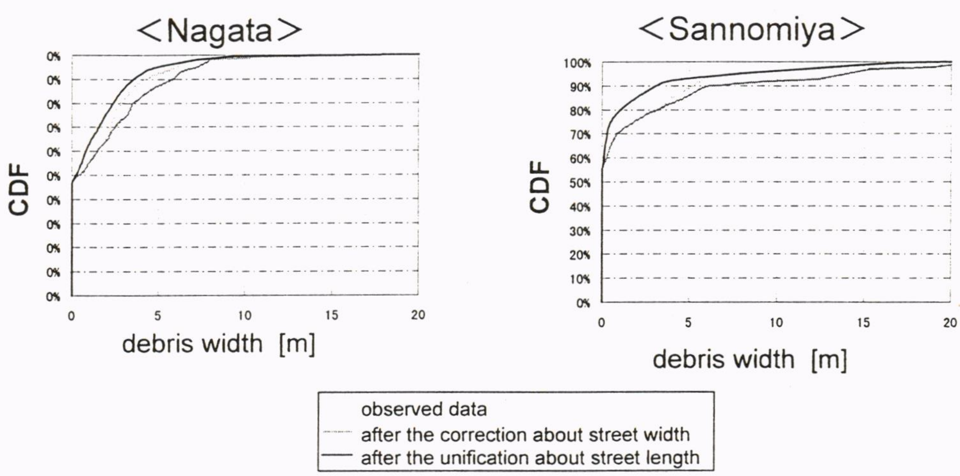

Figure 6 An Estimation of Probability Distribution for Areas

4. THE MODELING OF FUNCTION TO ESTIMATE PROBABILITY DISTRIBUTION OF DEBRIS

4.1 Approximating Probability Distribution of Standardized debris Width by Exponential Distribution

To find out factors which determine the probability distribution of debris width, relation between attributes of buildings and probability distribution of standardized debris width x_0 were analyzed. We assumed that the CDF of x_0 is denoted as follows.

$$\hat{F}_{x_0}(x_0) = 1 - b \cdot \exp(-\frac{1}{a}x_0) \qquad \cdots\cdots\cdots\cdots\cdots\cdots (13)$$

In this function a means the extent of debris. When a becomes larger, CDF shifts to the right, and debris width may become wider. b express the probability of debris occurred on a street link.

In terms of present points $\{x_{0j}\}$ which were used to estimate the unified debris width, $\{F_{x_0}(x_{0j})\}$ is calculated by Equation-(10) and also $\{\hat{F}_{x_0}(x_{0j})\}$ is calculated by Equation-(13). Parameters a and b were estimated by numerical calculation with minimizing the value of χ^2 which express degree of differences between two values. Figure 7 shows the case of a city district "Nada-ku,Hukada-cho,1-chome". From the figure it can be said that approximation by Equation-(13) is sufficient enough.

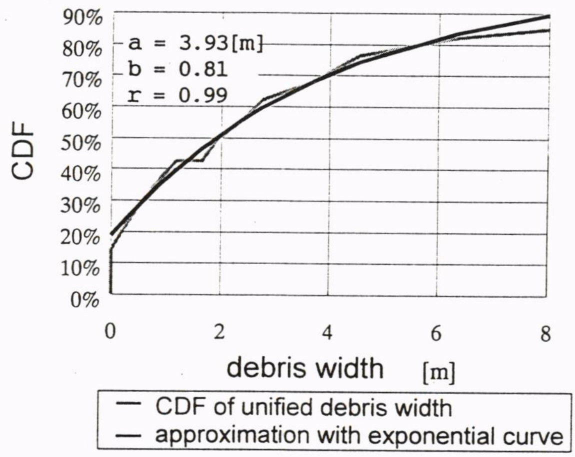

Figure 7 An example of Approximation of CDF

4.2 The Fact Analysis of Parameters a , b of a Probability Distribution of Standardized Debris

The relation between parameter a,b for each city district and attributes of buildings or its damage in city district were analyzed. 118 city districts out of 382 were chosen as samples by removing city districts in which number of links is smaller. Each city district is about 1-4ha. Estimation functions shown as follows were obtained by trying with several variables and formulations. A unit of a is meters here(Figure 8).

$$a = 2.32 \cdot X_1^{0.379} + 0.189 X_2^{2.23} + 4.41 \cdot X_3^{12.0}$$
$$b = \frac{1}{1 - 0.179 \cdot \ln X_4 - 0.346 \cdot \ln X_5} \quad \cdots\cdots\cdots\cdots\cdots\cdots (14)$$

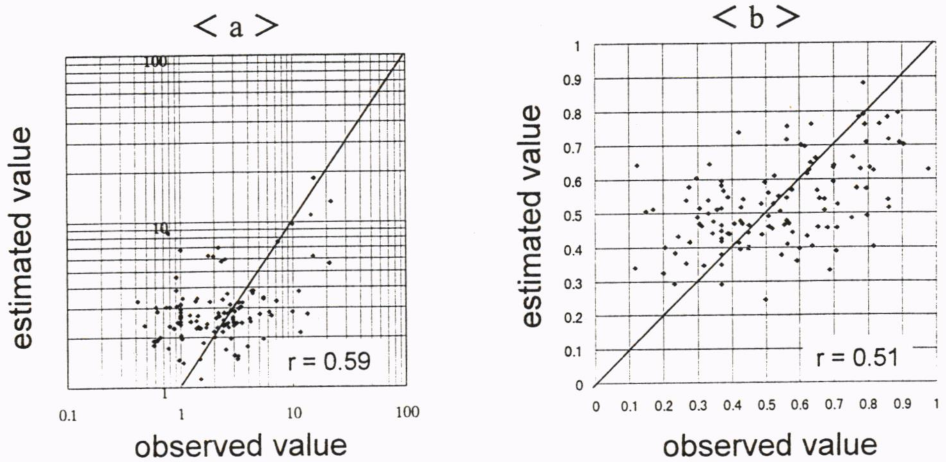

Figure 8 A Result of Estimating *a,b*

X_1 : *collapsed building ratio*

$$= \frac{\#\,of\ entirly\ collapsed\ buildings}{\#\,of\ whole\ building - \#\,of\ burnt\ out\ buildings - \#\,of\ uncertain\ buildings}$$

X_2 : *average floors (gross floor area / building caverage)*

X_3 : *building density(building caverage / sitearea)*

X_4 : *wooden buildings ratio*

X_5 : *old buildings ratio (ratio of buildings built before 1950)*

And Table 1 shows the changes of a and b of each areas with the attribute of buildings and its damage. As all the variables are macroscopic data, the estimating functions cannot explain sufficiently enough. But mostly suitable result were obtained as general trends.

For collapsed building ratio and building coverage, data from buildings damage data by Building Research Institute: Ministry of Construction(Japan) were used. And other all data were gained from the data in city district unit surveyed by Kobe city.
In general, it is natural to think that collapse of buildings are strongly related to the characteristics of an earthquake. But an attribute data which indicates the characteristics of an earthquake does not exist in a level of small unit such as city districts, and in this study collapsed building ratio are contained as an indirect indication.

Table 1 The Attributes of Surveyed Areas

	Uosaki		Rokkomiti		Kasuganomiti	
	average	standard deviation	average	standard deviation	average	standard deviation
a [m]	3.58	5.42	3.30	1.50	1.65	2.18
b	0.64	0.23	0.73	0.29	0.46	0.15
X_1	0.45	0.11	0.43	0.20	0.14	0.10
X_2	1.65	0.69	1.83	0.47	1.87	0.31
X_3	0.57	0.08	0.74	0.05	0.73	0.12
X_4	0.65	0.21	0.65	0.17	0.75	0.17
X_5	0.20	0.14	0.24	0.17	0.04	0.03

	Sannomiya		Hyogo		Nagata	
	average	standard deviation	average	standard deviation	average	standard deviation
a [m]	7.38	7.08	2.53	1.84	2.80	1.85
b	0.43	0.21	0.48	0.17	0.57	0.20
X_1	0.22	0.08	0.50	0.11	0.61	0.20
X_2	4.31	1.30	2.02	0.29	1.73	0.41
X_3	0.80	0.13	0.73	0.08	0.76	0.11
X_4	0.25	0.18	0.65	0.15	0.75	0.20
X_5	0.03	0.04	0.10	0.05	0.30	0.16

X_1 : *collapsed building ratio*

$$= \frac{\#\,of\ entirly\ collapsed\ buildings}{\#\,of\ \ wholebuilding - \#\,of\ burnt\ out\ buildings - \#\,of\ uncertain\ \ buildings}$$

X_2 : *average floors (gross floor area / building caverage)*

X_3 : *building density(building caverage / sitearea)*

X_4 : *wooden buildings ratio*

X_5 : *old buildings ratio (ratio of buildings built before 1950)*

5 THE ESTIMATION OF STREET-BLOCKADE CONDITION

5.1 The Definition of Street-Blockade Probability and the Method of a Simulation of Street-Blockades Occurrence

The authors defined that “a street-blockade” is "the situation which the available width of a street-link for someone after an earthquake is smaller than a certain standard width", and probability that the situation may happen is called "street-blockade probability". Then vulnerability of street-blockades on each street link is reflected by the street-blockade probability.

The authors calculated the street-blockade probability of street links in several areas by using the debris width estimating function modeled in CHAPTER 4. Then by comparing the probability with real condition in the case of The Great Hanshin Earthquake, reproductively of the method to simulate street blockaded condition and suitability and applicability of this study is discussed.

Firstly from the attribute data of buildings and collapsed building ratio, parameters of probability distribution of standardized debris width a, b are estimated by using Equation-(14). But actual value of a, b will be given as distributions of which have averages of a and b. In this study, it is assumed that the distribution of value of a is given as log-normal distribution (a standard deviation $\sigma_a = 0.849$), and the distribution of value of b is given as normal distribution (a standard deviation $\sigma_b = 0.175$). At this time standard deviation of both values are estimated from the residual distributions. Secondly, by giving random values which follow the distributions of the parameters, parameters a, b are determined stocastically for each street link. Then from Equation-(13) probability distributions of standardized debris width are obtained for each street link. And from Equation-(5),(12), probability distributions of debris which contain the effect of street link length for each street link are simply calculated.

5.2 An Example of Simulating Street-Blockade Condition

The authors tried a simulation on the areas where aerial photographs were taken. At this simulation standard width for definition of street-blockades is settled at 3.0[m] from the viewpoint of vehicle traffic.

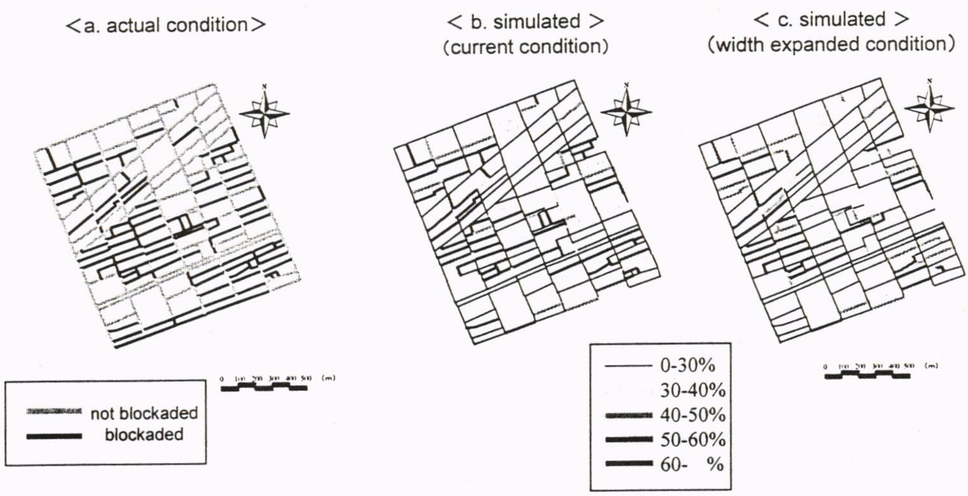

Figure 9 Street-Blockade Probability Map

(Rokkomichi Area)

Figure 9-a shows blockaded street links based on the survey of aerial photographs in Rokkomichi area. And Figure 9-b shows the result of street blockade probability shown by several ranges of percentage. From these two figure the trend that there were comparatively many street-blockades in area which have high percentage of street blockades can be seen.

Figure 10 shows a comparison of street-blockade probabilities among different width of street links. It is clear that street blockade probability decrease with the increase of link width. And a graph indicates the rate of street links which blockaded in the Great Hanshinn Earthquake. This shows that the rate of street links which probability is over 40-50% is nearly the same as the actual rate of street blockaded links.

Figure 9-c is the result of simulation in the case that level of infrastructure improved. In this simulation, all street links with a width less than 4.0[m] were assumed to be improved to 4.0[m]. This simulation tells us that to widen narrow streets is an effective measure to reduce the street-blockades in a area.

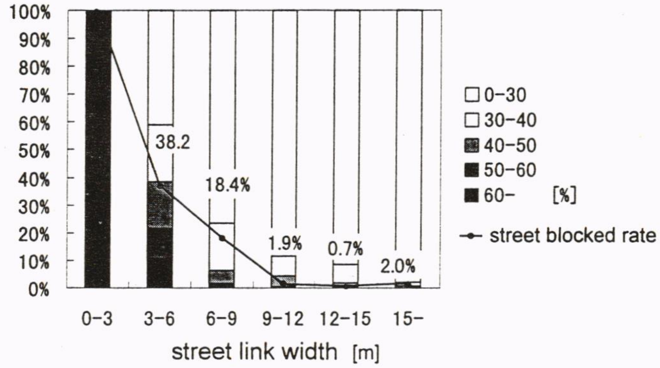

Figure 10 Street-Blockade Probability in terms of the Width of Links

6. CONCLUSION

The main results of this study are as the followings,

1) A method for estimating vulnerability of street-blockades caused by collapsed buildings in a earthquake was proposed.
2) A numerical approach was developed to make the debris width data observed from aerial photographs applicable in a normal analysis.
3) By considering probability distribution of debris width, a model to explain width of debris according to the attribute of buildings such as collapsed buildings ratio, wooden building ratio, was developed.
4) From the results above, probability of street-blockades can be calculated, and the street-blockades occurred in the Great Hanshin Earthquake can be somewhat reproduced.

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