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RISK EVALUATION METHOD OF BUILDING COLLAPSE FROM THE EXPERIENCE OF THE KOBE EARTHQUAKE

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SUMMARY

Tokyo Metropolitan Government (TMG) recently published “The Earthquake Area Vulnerability Assessment of Tokyo” based on soil conditions, building inventory and social conditions. It shows relative seismic risks in Tokyo. “The area danger levels” were determined with respect to building collapse, fire outbreak and spread, human casualties, and access for evacuation. The method used in the report was applied to Nada Ward, Kobe City using the inventory before the 1995 Hyogoken-Nanbu (Kobe) Earthquake. The obtained “building collapse risk” was compared with the actual damage of the ward due to the earthquake. The result of the comparison indicates that the weights used in the TMG method should be adjusted since the obtained collapse risk was strongly influenced by the building density of each city block. Then a revised method to evaluate “building collapse risk” was proposed. The new building collapse risk corresponds to the severe damage ratio of buildings and it reflects the characteristics of buildings and sites. The proposed method may be useful for seismic risk assessments by local governments in Japan.

1. INTRODUCTION

In recent years, scores of earthquake damage assessment studies have been conducted by local and national governments in Japan. An earthquake causes fires, liquefaction, land slides and lifeline interruptions as well as damage to buildings and infrastructures. The characteristics of an area influence the appearance of seismic damage. It is very important for local governments, not only of prefectures but also of cities or wards, to grasp seismic vulnerability of each city block. Recently, GIS technologies enable us to assess seismic risk and to predict earthquake damage visually using inventory and other natural and social data [Yamazaki et al., 1995].

Tokyo Metropolitan Government [TMG, 1998] recently published “The Earthquake Area Vulnerability Assessment of Tokyo” based on building inventory, soil conditions, and social conditions. The earthquake area vulnerability assessment by TMG is similar to damage assessments for scenario earthquakes [TMG, 1997]. But there are differences in the methods to predict various kinds of damage. In the damage assessment of TMG, specific earthquake source models were used and amounts of various damage were enumerated while in the area vulnerability assessment of TMG, no specific source model was considered and only relative seismic risks of each city block were evaluated using rather simple methods. “The area danger levels” in the TMG report, which are basic indices to assess seismic vulnerability of each district block (corresponding to the postal address), were

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determined with respect to building collapse, fire outbreak and spread, human casualties, and access for evacuation. The method may be useful for the authority of each administrative ward to identify high-risk areas for which they give priorities for urban redevelopment.

In this study, in order to examine the assessment method of building collapse risk due to earthquakes, the method used in the TMG's report was applied to the Nada Ward, Kobe City using building inventory before the 1995 Kobe Earthquake. The obtained "building collapse risk" was compared with the actual damage of the ward due to the earthquake and a revised method to estimate "building collapse risk" which fits the actual damage was proposed.

2. APPLICATION OF THE METHOD OF TMG TO NADA WARD

2. 1 Building Collapse Risk by the Method of TMG

"The Earthquake Area Vulnerability Assessment of Tokyo" [TMG, 1998] shows high-risk zones in Tokyo. "The area risk levels" were determined with respect to building collapse, fire outbreak and spread, human casualties, and access for evacuation. In this study, the building collapse risk was adopted as a research object.

The building collapse risk by the method classified all the district blocks in Tokyo into five levels using the amount of risk calculated using weights for several elements related to seismic vulnerability of buildings. The elements are building characteristics and site characteristics. These weights were determined by experiences of six professionals. The amount of risk (simply call "risk" hereafter) for building collapse was calculated by the following equations (1) and (2):

$$Q_{kn} = D_k\,(1-W_{kn} \cdot U_{kn}) \tag{1}$$

$$U_{k\,n} = u_{1\,n} \cdot u_{2\,n} \cdot u_{3\,n} \cdot u_{4\,n} \cdot u_{5\,n} \tag{2}$$

in which k is the building category (1-19), Q is the amount of risk, D is the number of buildings per 1 km^2, W is the weight for earthquake resistant capacity of buildings of the category k, U is the weight for site characteristics, u_i's are the weights for subsurface condition (u_1), for possibility of liquefaction (u_2), for large-scale cut-and-fill (u_3), for reclaimed land (u_4), and for steep slope (u_5), n is each value by the 6 specialists. By adding Q_k's for all the structural types in a block, the amount of risk for the block is evaluated.

This method is simple and easy to use. However, the physical meaning and objectivity of the weights are unclear.

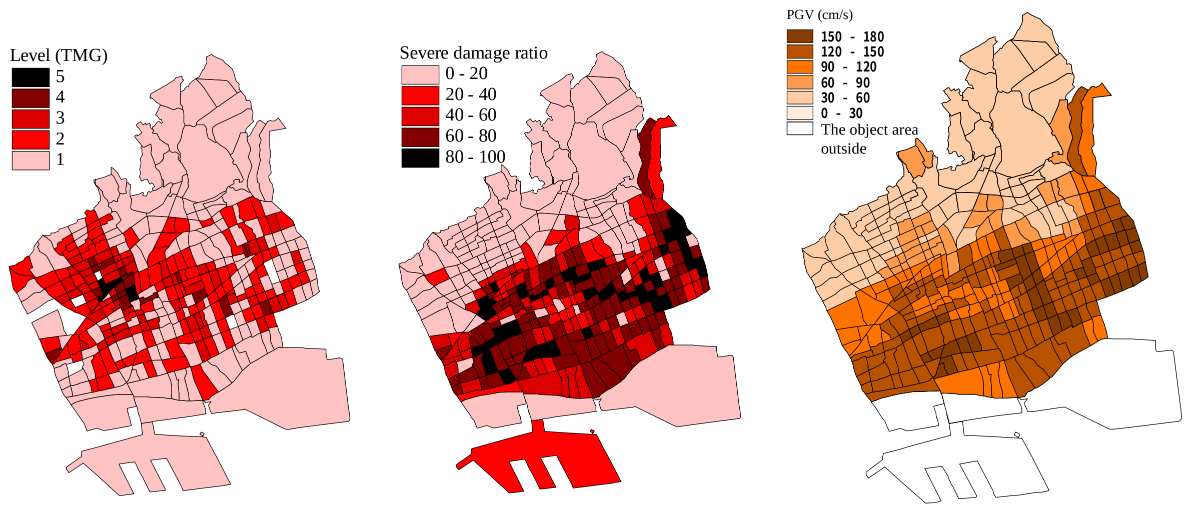
2. 2 Building Collapse Risk of the Nada Ward

The building collapse risk of the Nada Ward in Kobe City was calculated using the inventory and soil data by the method of TMG. Buildings in the Nada Ward were classified into 19 categories by the structural type and construction period. The site characteristics of each district block (Figure 1) were employed to calculate the seismic risk. As a result, the building collapse risk was determined as shown in Figure 2(a).

Figure 2(b) shows the ratio of severely damaged buildings due to the 1995 Kobe Earthquake investigated by Kobe City and Figure 2(c) shows the distribution of the peak ground velocity (PGV) estimated by Murao and Yamazaki (2000) from the building damage. The area of large PGV value in the figure almost corresponds to the belt of JMA intensity 7 determined by JMA's field survey [JMA, 1997] while this general tendency was also recognized in the distribution of high severe damage ratio in Figure 2(b). It is noticed that the distribution of building collapse risk evaluated by the method of TMG (Figure 2(a)) and the density of buildings (Figure 1(c)) look quite similar.

(a) Subsurface soil condition **(b) Liquefaction and steep slope** **(c) Number of buildings per 1 km^2**

Figure 1: Site characteristics of each district block in Nada Ward



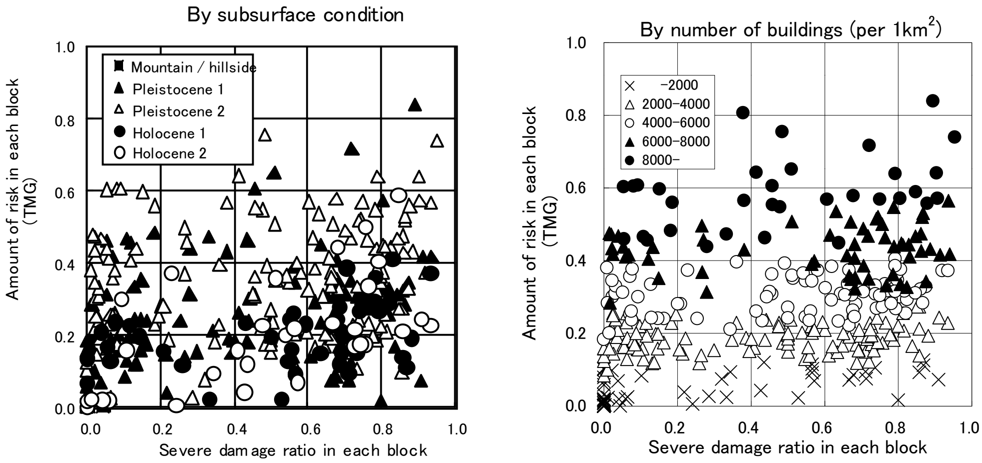
(a) Building collapse risk by the method of TMG **(b) Severe damage ratio of buildings due to the Kobe Earthquake** **(c) Distribution of estimate PGV in the Kobe Earthquake**

Figure 2: Building collapse risk and actual damage in Nada Ward

2. 3 Building Collapse Risk by the Method of TMG and Actual Damage in the Nada Ward

The building collapse risk and the actual damage ratio for each district block were compared in Figure 3. In the figure, the amount of risk was standardized to have a value between 0 to 1. The left figure shows the influence of the subsurface soil condition while the right figure shows the influence of the density of buildings (number of buildings per 1 km^2). It seems that these two factors, the building collapse risk and the actual severe damage ratio, do not look highly related although the former is strongly influenced by the building density of each district block.

In the method of building collapse risk evaluation by TMG, the amount of risk is the product of the number of buildings per unit area and the term consisting of the weights as shown in equation (1). Thus the risk in densely built-up areas became high by this method. “The building collapse risk” by TMG may be related to the human casualty and the evacuation risk since these risks are related to the number or density of buildings. However, “the collapse of a building” itself is usually not influenced by the density of buildings in an area. Hence a revised amount of risk, which divides the evaluated amount of risk (by TMG method) by the total number of buildings in the block, is proposed.



(a) Comparison by subsurface soil condition (b) Comparison by density of buildings

Figure 3: Comparison between the collapse risk (TMG) and the actual damage due to the Kobe Earthquake in Nada Ward

3. NEW EVALUATION METHOD OF BUILDING COLLAPSE RISK COMPATIBLE WITH ACTUAL DAMAGE RATIO

3. 1 Modifications to the Method of TMG

We will introduce modified “building collapse risk” as an index that reproduces the actual severe damage ratio of buildings in Nada Ward due to the Kobe Earthquake. First, in equation (1), " D_k: the number of buildings per 1 km^2" is replaced by "N_k: the ratio of buildings with category k in number". By this, the building collapse risk which reproduces the severe damage ratio can be obtained. Next, the weights used in equation (1) were examined. In the method of TMG, the weights for the seismic resistance of buildings and the site condition are simply multiplied when evaluating the collapse risk. However, the collapse risk may be affected by the both parameters at the same time. Hence matrix-type weights should be introduced to consider the joint effect of the building resistance and the site condition (intensity of strong motion) on the collapse risk.

The seismic resistance of buildings was determined based on the fragility curves proposed by the present authors [Murao and Yamazaki, 2000], which consider the structural type and construction period. The site condition was classified into five subsurface soil types (mountain, terrace, alluvial fan, delta and reclaimed land) from borehole logging data of Nada area and geomorphological land classification maps. In this study, matrix-type weights were determined and then the building collapse risk which is equivalent to the result of a fragility analysis was obtained.

3. 2 Method of New Building Collapse Risk Evaluation

A new building collapse risk evaluation method is proposed in this study. In the proposed method, "P_i: the building collapse risk" is defined in the following equation as an index instead of "the amount of risk" in the method of TMG.

$$P_i = \sum_{k=1}^{m} N_k \cdot W_{kl} \tag{3}$$

in which k is the building category (1-14), l indicates the subsurface soil condition (1-4), N_k is the ratio of buildings with category k in number, W_{kl} is the matrix-type weight for building category k and soil condition l. Classifying the collapse risk into 5 levels, a risk level of each block is obtained. By this equation (3), the effect of the building density is removed from the collapse risk evaluation, and more realistic risk that represents the building characteristics and site condition of an area can be calculated.

3. 3 Reliability Analysis to Obtain Damage Probability

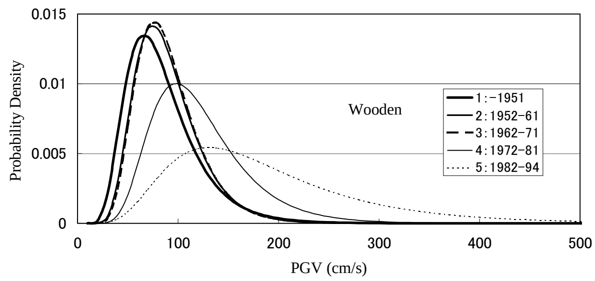
The method to determine the weights for building collapse risk applicable to other areas in Japan is proposed using the basic reliability analysis theory [Ang and Tang, 1984; Okada and Nakano, 1988]. The vulnerability functions (fragility curves) for severely damaged buildings developed by the authors [Murao and Yamazaki, 2000] were used as the resistance of buildings. Figure 4 shows the probability density functions for the seismic resistance of various kind of buildings with respect to PGV. In these functions, the seismic resistance for each structural type and construction period was modeled by a log-normal distribution based on the actual damage data in Nada Ward due to the 1995 Kobe Earthquake. It is observed in the figure that the seismic resistance of buildings has large variability even for the same structural type and construction period. The values of the two parameters of the log-normal distributions are listed in Table 1.

Figure 5 shows the probability density functions of the estimated PGV in the Kobe Earthquake for different topographical conditions in Nada Ward. These functions were also obtained by a statistical analysis of the estimated PGV values in Nada Ward and the values of their parameters are shown in Table 1. The peak PGV value of the density function becomes large in the order of softer ground: mountain, terrace, alluvial fan, and delta. The PGV value is widely distributed for mountain and alluvial fan while the range is comparatively narrower for terrace and delta. But, of course, this observation is the case for Nada Ward in the Kobe Earthquake; not necessarily the general trend of strong ground motion in Japan.

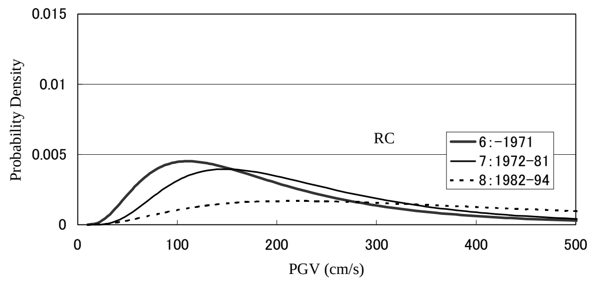
Using the basic reliability analysis theory, the probability for severe damage P_f is obtained by the following equation:

$$P_f = P\,(R/S<1) = 1\text{-}\Phi\,(\lambda_z/\zeta_z) \tag{4}$$

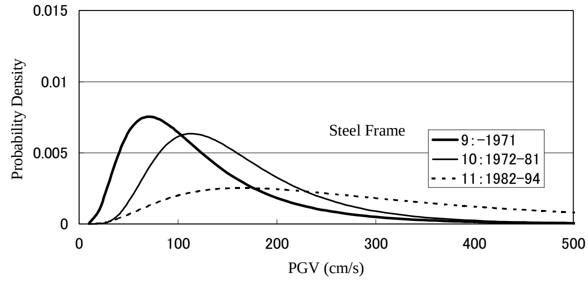
in which R is the probability density function for the seismic resistance of buildings, S is the probability density function for the strong motion index (e.g. PGV), Φ is the cumulative probability of the standard normal distribution, $\lambda_z=\lambda_r - \lambda_s$, and $\zeta_z =(\zeta_r^{2}+\zeta_s^{2})^{1/2}$, assuming independence between R and S. Using this equation, the weights for the building collapse risk can be calculated and the values are shown in Table 1. Figure 6(a) plots the comparison of the weights for the building collapse risk evaluated by equation (4) and the severe damage ratio observed in the Kobe Earthquake. It is seen that the obtained weights are compatible with the actual severe damage ratio. The building collapse risk of Nada Ward calculated by this method is plotted in Figure 6(b). Comparing this figure with the distribution of severe damage ratio in Figure 2(b), they look quite similar. Thus, it is conducted that the severe damage ratio was almost reproduced by the proposed method.



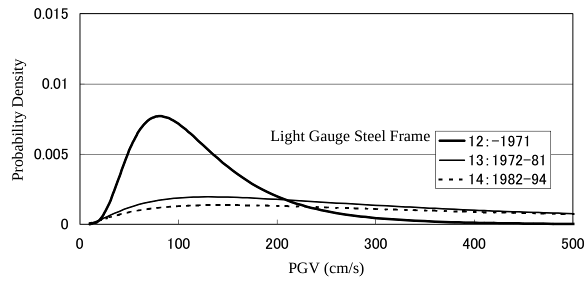
(a) Wooden



(b) Reinforce Concrete (RC)



(c) Steel Frame



(d) Light Gauge Steel Frame

Figure 4: Probability density functions for the seismic resistance of buildings with respect to PGV

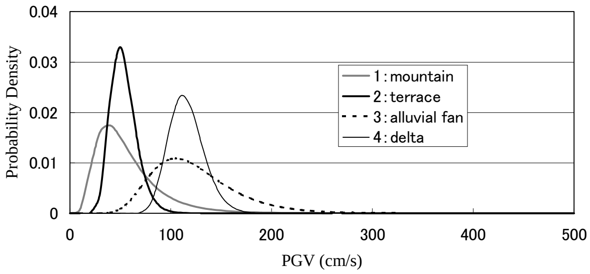
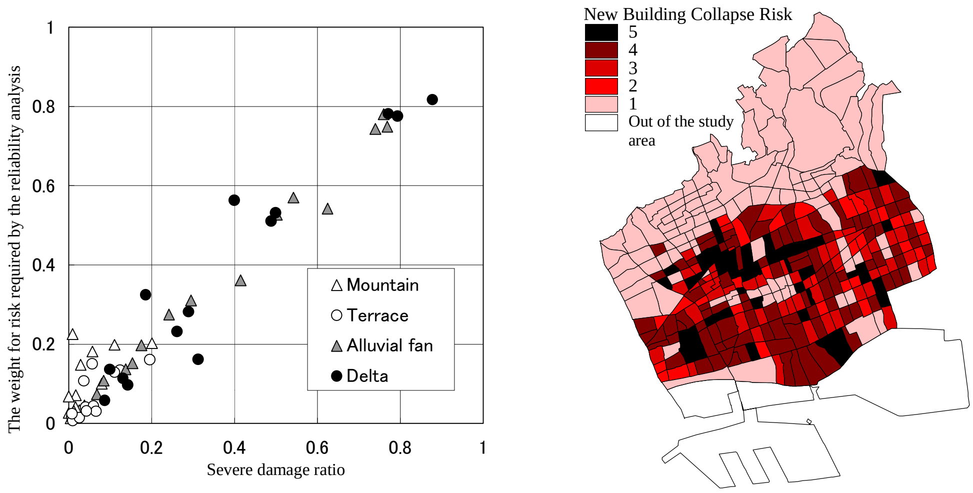


Figure 5: Probability density function of the estimated PGV in the 1995 Kobe Earthquake for different topographical conditions in Nada Ward

Table 1: Parameters of the probability density functions and obtained weights that reproduce the severe damage ratios due to the Kobe Earthquake

			λ_r	ζ_r	Mountain	Terrace	Alluvial Fan	Delta
			-	-	1	2	3	4
λ_s		-	-	-	3.90	3.95	4.76	4.74
ζ_s		-	-	-	0.53	0.24	0.33	0.15
Wooden	-1951	1	4.36	0.41	24.6	19.5	77.9	80.8
	1952-61	2	4.44	0.35	19.8	12.6	74.8	78.3
	1962-71	3	4.45	0.34	19.1	11.6	74.6	78.2
	1972-81	4	4.73	0.38	10.1	4.1	52.7	51.0
	1982-94	5	5.12	0.50	4.6	1.7	27.5	23.1
RC	-1971	6	5.12	0.65	7.1	4.4	31.0	28.2
	1972-81	7	5.33	0.58	3.4	1.3	19.7	16.1
	1982-94	8	6.01	0.79	1.3	0.6	7.3	5.8
Steel Frame	-1971	9	4.64	0.62	18.2	15.0	57.0	56.2
	1972-81	10	4.97	0.49	6.8	3.0	36.1	32.4
	1982-94	11	5.64	0.73	2.7	1.4	13.7	11.3
Light Gauge Steel Frame	-1971	12	4.70	0.55	14.8	10.7	54.2	53.1
	1972-81	13	5.82	0.97	4.1	3.1	15.2	13.6
	1982-94	14	6.19	1.10	3.1	2.4	10.8	9.7



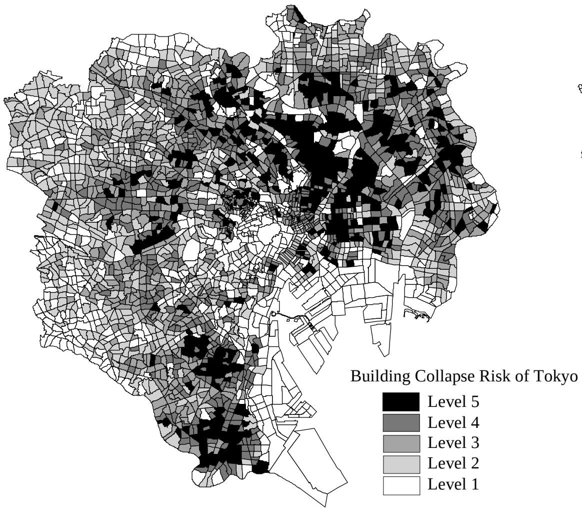
(a) **(b)**

Figure 6: (a) Comparison between the actual severe damage ratio and the evaluated severe damage probability; (b) The proposed building collapse risk of Nada Ward

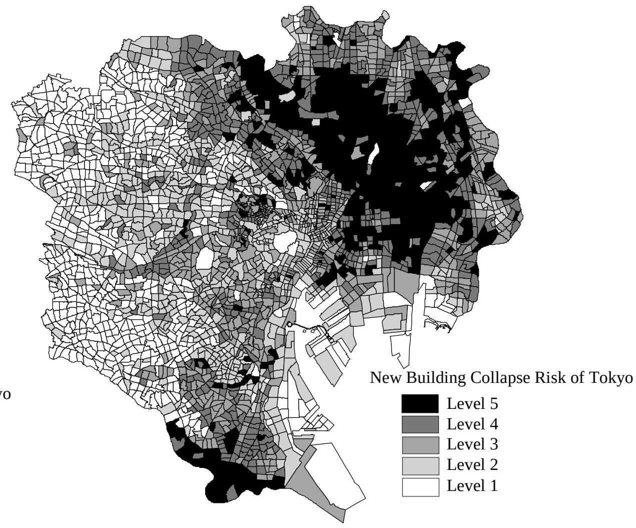
3. 4 New Building Collapse Risk of Tokyo

Using the method proposed above, the building collapse risk in Tokyo was evaluated. In calculating the new building collapse risk, the median of PGV in mountain areas was assumed to be 30cm/s, which was used in the damage assessment study of TMG (1997) for near-field earthquakes. The median values of PGV in other topographical conditions were obtained by multiplying the amplification factors proposed by Yamazaki et al. (1999) using the observed records by JMA-87-type accelerometers. The logarithmic standard deviation of PGV was assumed as the record-to-record (intra-event) variation in the attenuation relation of PGV proposed by Molas and Yamazaki (1995).

Under these assumptions, the new building collapse risk of Tokyo was calculated and it was compared with that by TMG as shown in Figure 7. It is seen in the figure that the risk level in the eastern part of Tokyo (lowland with soft soil) is large by the proposed method while the high-risk blocks are distributed outside of Yamanote Line circle (highly built-up wooden building areas) by the TMG method. Soil condition and building type are dominant factors to determine the collapse risk in the proposed method. In the method of TMG, the density of buildings per unit area almost determines the building collapse risk. However, since the Urban Planning Bureau of TMG uses this building collapse risk in the selection of areas for urban redevelopment, the risk by the TMG method may have different meaning from the risk evaluated by the proposed method.



(a) Building collapse risk by TMG (1998)



(b) Building collapse risk by the proposed method

Figure 7: Comparison of building collapse risk in Tokyo by two methods

4. CONCLUSIONS

In this study, the building collapse risk of the Nada Ward, Kobe City was calculated based on the method of Tokyo Metropolitan Government (TMG) using building inventory and soil condition data. The evaluated building collapse risk was compared with the actual building damage due to the 1995 Kobe Earthquake. Since the number of buildings in unit area is a dominant factor to determine the building collapse risk by the TMG method, the evaluated risk was high for densely built-up areas and it was not very good agreement with the actual damage distribution. We considered that “the collapse of a building” itself is not influenced by the density of buildings in an area. Hence a revised method, which divides the evaluated amount of risk by the total number of buildings in an area (removing the effect of building density in an area), was proposed.

As the index of building collapse risk, the severe damage ratio of buildings in a city block is considered. Based on the actual damage in Nada Ward due to the Kobe Earthquake, the probability density functions for the seismic resistance of buildings and the peak ground velocity (PGV) were obtained. These functions consider the structural type and construction period for the building resistance and the topographical condition for the ground motion intensity. Employing the basic reliability analysis theory, the severe damage probability of buildings was evaluated analytically and it was confirmed that the obtained the severe damage ratio reproduce the actual one.

The proposed method was further applied to the building collapse risk evaluation of Tokyo and its result was compared with that by the TMG method. It is observed that the building collapse risk in the eastern lowland of Tokyo is large by the proposed method while the high-risk zone is distributed in highly built-up wooden building areas by the TMG method. These observations can be explained by the fact that the soil condition and building type are dominant factors to determine the collapse risk in the proposed method and the density of buildings per unit area almost determines the building collapse risk in the TMG method.

The physical meaning of *building collapse risk* was interpreted properly by the proposed approach and it is generally applicable to entire Japan. Assessment of building collapse risk in urban areas is one of the important factors to be considered in urban planning. Hence the proposed method may be conveniently used by local governments in Japan for the seismic risk assessment of district level.

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REFERENCES

Ang, A. H-S., and Tang, W. H. (1984), *Probability Concepts in Engineering Planning and Design*, Vol. II, John Wiley & Sons.

Japan Meteorological Agency (1997), “Report on the Hyogo-ken-Nanbu Earthquake”, *Technical Report of JMA*, No. 119 (in Japanese).

Molas, G. L., Yamazaki, F. (1995), “Attenuation of Earthquake Ground Motion in Japan Including Deep Focus Events,” *Bulletin of the Seismological Society of America*, 85, 5, pp. 1343-1358.

Murao, O., and Yamazaki, F. (1999), “Re-estimation of Strong Ground Motion in Nada Ward based on Inventory and Building Damage Data”, *Journal of Structural and Construction Engineering*, AIJ, 523 (in Japanese).

Murao, O., and Yamazaki, F. (2000), “Development of Fragility Curves for Buildings Based on Damage Survey Data of a Local Government after the 1995 Hyogoken-Nanbu Earthquake”, *Journal of Structural and Construction Engineering*, AIJ, 527 (in Japanese).

Okada, T., and Nakano, Y. (1988), “Reliability Analysis on Seismic Capacity of Existing Reinforced Concrete Buildings in Japan”, *Proceedings of the 9th World Conference on Earthquake Engineering*, Vol. VII, pp. 333-338.

Tokyo Metropolitan Government (1997), *The Report on the Damage Assessments for Scenario Earthquakes in Tokyo due to Near-field Earthquakes* (in Japanese).

Tokyo Metropolitan Government (1998), *The Fourth Report of Survey of the Earthquake Area Vulnerability Assessment* (in Japanese).

Yamazaki, F., Katayama, T., Nanbu, S., Kato, T., and Tsubokawa, H. (1995), “Earthquake Scenario of Urban Residential Areas Using Microscopic GIS Data”, *Proceedings of the Fifth International Conference on Seismic Zonation*, 2, pp. 1416-1423.

Yamazaki, F., Wakamatsu, K., Onishi, J., and Yamauchi, H. (1999), “Relationship between Geomorphological Land Classification and Soil Amplification Ratio Based on JMA Strong Motion Records”, *Bulletin of Earthquake Resistant Structure Research Center*, No. 32, Institute of Industrial Science, The University of Tokyo, pp. 17-33.