The 5th Asia Conference on Earthquake Engineering
October 16-18, 2014

SIMPLIFIED ESTIMATION METHOD FOR BUILDING DAMAGE DUE TO EARTHQUAKES IN URBAN AREAS

Saaya Iwase[1] and Fumio Yamazaki[2]

ABSTRACT

Tokyo Metropolitan Government (TMG) conducts a community-based seismic risk assessment for all the city-blocks of Tokyo Metropolis every five years. The 7th seismic risk assessment survey was carried out for two kinds of risk due to earthquakes: building damage due to strong shaking, and fire outbreak and spread. A bedrock motion with the peak ground velocity 30 cm/s was assumed uniformly for all the study areas and site amplification was considered based on topography and subsurface soil type. Building damage was evaluated using empirical vulnerability functions. In this paper, a statistical analysis was conducted for the result of the building damage assessment by the TMG. In the multiple regression analysis, the number of severely damaged buildings per unit area was considered as the dependent variable and several explanation variables were employed, such as the number of buildings for each structural type and construction period, the soil amplification factor. The regression analysis was conducted for all the 5,133 city-blocks of Tokyo Metropolis and an accurate prediction equation was derived.

Keywords: Earthquake damage estimation, Building damage, Seismic risk

INTRODUCTION

Earthquake damage assessment studies for future events have been conducted frequently by local and national governments in Japan and other countries with high seismic risk. An earthquake causes fires, landslides, liquefaction and lifeline interruption as well as damage to buildings and infrastructures. The physical and social characteristics of an area influence the degrees of various types of earthquake-induced damage. To prioritize and promote proper seismic countermeasures, it is important for local governments to grasp seismic vulnerability at each local-community or city-block level. Recent GIS technologies enabled us to assess local seismic risk and to visualize various damage situations using inventory and other natural and social data (Yamazaki *et al.*, 1995).

The Bureau of Urban Development of the Tokyo Metropolitan Government (TMG) conducts a community-based seismic risk assessment for all the city-blocks of Tokyo Metropolis every five years. The seventh seismic risk assessment survey was carried out and the result was announced in the autumn of 2013 based on building inventory, soil conditions, and some social conditions (Tokyo Metropolitan Government, 2013). The community-based seismic risk assessment by TMG is similar to damage assessments for scenario earthquakes (Tokyo Metropolitan Government, 2012). But there are differences in the methods to predict earthquake-related damages. Specific earthquake source models were assumed and the amounts of various damages were enumerated in the latter study while no specific source model was considered and only relative seismic risk of each city-block were evaluated in the former study. The results of the community-based seismic risk assessment are used for the authorities of each administrative ward or city to identify high-risk areas for which they assign higher priority for urban redevelopment.

In this paper, a simplified method to predict community-based seismic risk is proposed using a statistical approach. This method enables us to perform community-based seismic risk assessment

---

[1] Graduate Student, Department of Urban Environment Systems, Chiba University, Japan, s.iwase@chiba-u.jp
[2] Professor, Department of Urban Environment Systems, Chiba University, Japan, fumio.yamazaki@faculty.chiba-u.jp

efficiently, especially when parameter values change or identifying strategic urban redevelopment plans.

METHOD OF SEISMIC DAMAGE ASSESSMENT IN JAPAN

The seismic damage assessment usually follows the procedure shown in **Figure 1**. The earthquake input motion to a study area is assigned at the ground surface in terms of the maximum amplitude (or spectrum) of ground motion index, such as the peak ground velocity (PGV), the seismic intensity etc. If a scenario earthquake source model is given, the base rock motion is calculated in terms of attenuation relationships or numerical simulation. The surface soil characteristics are considered by soil amplification ratios of the strong motion index. The seismic input motion at the ground surface is obtained as the product of the base-rock motion and soil amplification ratio.

The inventory data of exposures to assess damage, such as buildings and lifeline systems, should be prepared. This step is often the most difficult one in damage assessment of large urban areas. In seismic damage assessment studies in Japan, building inventory data are prepared by local government by assembling cadastre (land-tax register) data. For utility lifelines (e.g. water, sewer, gas), however, it is by no means easy to gather inventory data. Thus an estimation method of aggregated data in a GIS grid was proposed recently (Kobayashi *et al*., 2011). To characterize dense urban areas, a 250-m grid (raster) GIS is often used in Japan.

Vulnerability functions (or fragility curves) are used to model seismic resistance of structures of a certain category. For a strong motion index value x, the cumulative probability $F_X(x)$ of the occurrence of damage equal to or higher than rank H (such as Heavy damage) is assumed to follow a log-normal distribution such as

$$F_X(x) = \Phi\left((\ln x - \lambda)/\zeta\right) \qquad (0 < x < \infty) \qquad (1)$$

In which Φ is the cumulative probability of the standard normal distribution N(0, 1) and λ and ζ are the mean and the standard deviation of ln (x). The two parameters of the distributions, λ and ζ, can be determined by least-square fitting of actual damage data or numerical simulation results on lognormal probability paper.

Table 1 shows empirical fragility curves developed by Yamazaki and Murao (2000) from the building damage data in the 1995 Kobe earthquake. These functions are often used in earthquake damage assessments in Japan, including the community-based earthquake risk assessment of TMG.

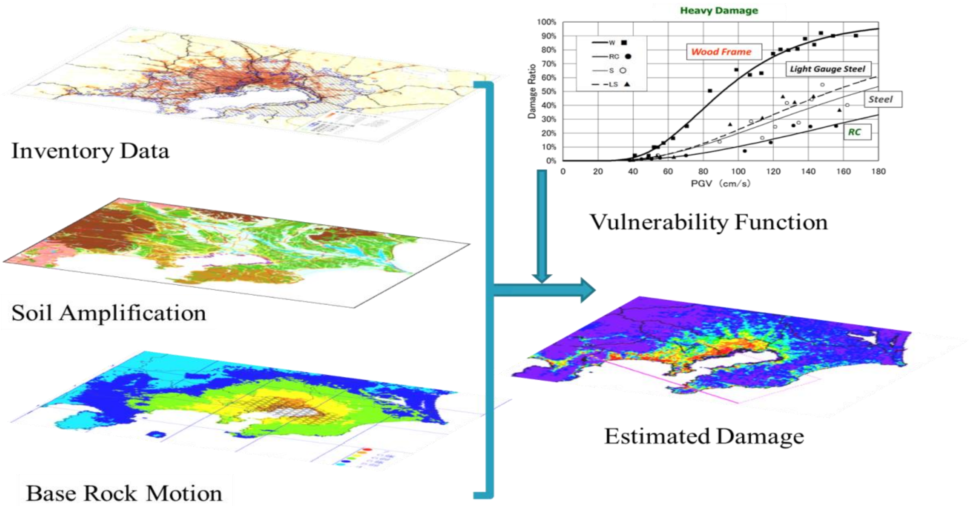


Figure 1 Flowchart of typical seismic damage assessment which estimates the number of damaged buildings for each grid-cell or a city-block using fragility curves.

Table 1 Parameters of fragility curves for all the building categories

Building construction		Construction period	λ	ζ	Building construction		Construction period	λ	ζ
1	Wooden	-1970	4.45	0.342	8	Reinforced Concrete	-1970	5.12	0.646
2		1971-1980	4.73	0.378	9		1971-1980	5.33	0.575
3		1981-1990	5.12	0.496	10		1981-	6.00	0.789
4		1991-2000	5.68	0.496	11	Steel	-1970	4.64	0.619
5		2001-	6.13	0.496	12		1971-1980	4.97	0.490
6	Light Steel	-1980	5.82	0.972	13		1981-	5.64	0.731
7		1981-	6.19	1.101	14	Others		4.45	0.342

MODEL OF EARTHQUAKE GROUND MOTION

In the community-based earthquake risk assessment of TMG, no scenario earthquake source model was used. On the contrary, in the TMG study, uniform rock motion was assumed at the base-rock with shear wave velocity Vs=500 m/s. This assumption came from the facts that the results of damage assessment are highly affected by the assumed location and maginude of seismic sources, and that source-models for the Tokyo and surrounding region are difficult to set up due to thick sedimentary layers and historical event data are scarece.

Thus in the community-based seismic risk assessment of TMG, the input motion was considered to be uniform (PGV= 30 m/s) at the base-rock, and soil amplification was estimated from geomorphological land classification (Yamazaki *et al*., 2000). Recently the soil amplification in Tokyo Metropolis was further investigated using a very dense seismic monitoring system (SUPREME) of Tokyo Gas Co. (Shimizu *et al*., 2006). **Figure 2** shows the soil-type classification and the location of SUPREME's seismometers in Tokyo, which were used to determine the soil amplification (Maruyama *et al*., 2012). Although considerable amount variability was seen in the amplification ratios of the same soil classes for deferent methods and actual events as shown in **Figure 3**, the values were determined considering the continuity of the series of the community-based seismic risk assessment study of TMG.

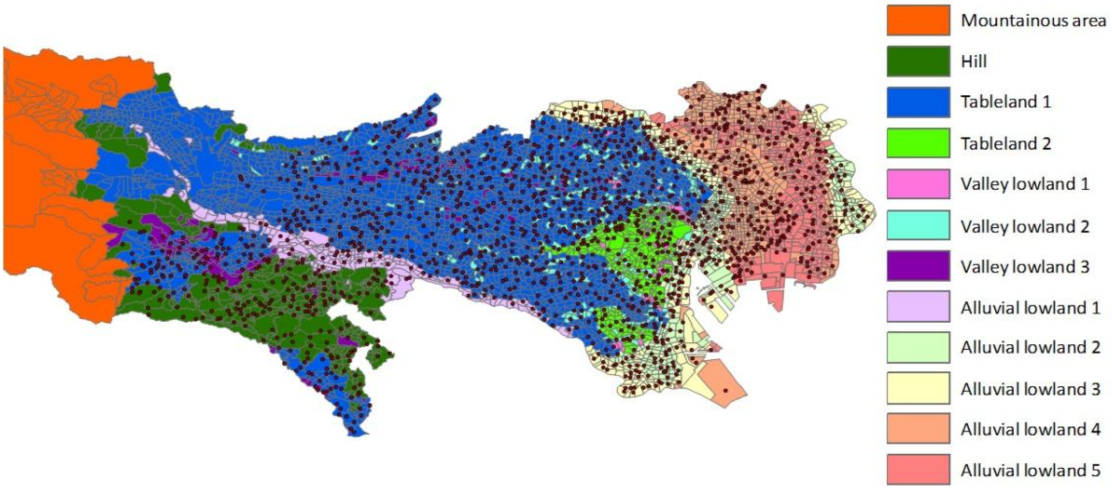


Figure 2 Soil classification map of the Tokyo metropolis and the location of SUPREME’s seismometers

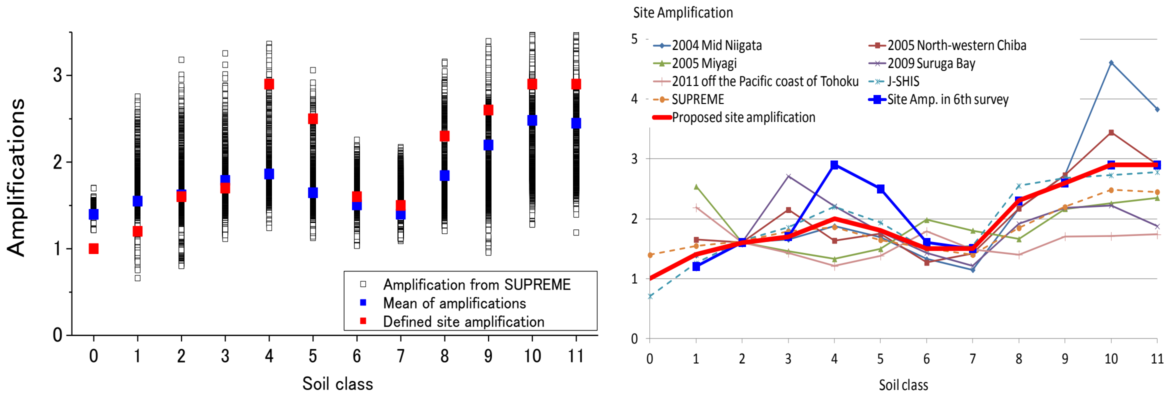


Figure 3 PGV amplification ratios for soil classes estimated from the geomorphologic map installed in SUPREME (left) and those for actual seismic records and various models (Maruyama *et al*., 2012)

BUILDING DAMAGE RATIO

Using the estimated peak ground velocity (PGV) and building inventory data for each city-block, and the vulnerability functions in terms of structural type and construction period, the number of heavily damaged buildings in each city-bock was calculated. From the basic reliability theory, the probability of damage occurrence P_f is obtained by the following equation:

$$P_f = P\,(R/S < 1) = 1 - \Phi\,(\lambda_Z/\zeta_Z) \tag{2}$$

in which R is the seismic resistance of a certain class of buildings, S the strong motion index (e.g. PGV), and the both are assumed to be lognormal. Assuming the independence between R and S, the two parameters are determined as

$$\lambda_Z = \lambda_R - \lambda_S \quad \text{and} \quad \zeta_Z = (\zeta_R^{\,2} + \zeta_S^{\,2})^{0.5} \tag{3}$$

Equation (2) represents the case in which both R and S are random variables following the lognormal distribution. In most seismic damage assessment studies in Japan, S is often assumed as deterministic because deterministic seismic source models are often employed. In the community-based seismic risk study of TMG, it is not necessary to adopt this assumption since no source model was used. But considering the continuity of the methodology used in the series of survey, the seismic input at the ground surface was assumed to be deterministic, represented by PGV_i, depending on the soil class of city-block i.

Thus for a building of category k standing on soil class l, the damage probability is calculated as

$$P_f^k(PGV_l) = \Phi((\ln PGV_l - \lambda_k)/\zeta_k) \tag{4}$$

The total number of damaged buildings for all the category(k=1, 2, , m) in a city-block i is obtained by

$$N_i = \sum_{k=1}^{m} n_{ki} \cdot P_f^k(PGV_l) \tag{5}$$

Since the area of each city-block is different, the number of damaged buildings in each block is divided by its area a_i as

$$y_i = N_i / a_i \tag{6}$$

where y_i is the density of damaged buildings in city-block i. This r_i is used as the index representing the seismic risk of buildings due to shaking. This risk quantity is further categorized into 5 levels to highlight most vulnerable city-blocks where urban redevelopment plan should be applied.

REGRESSION ANALYSIS ON THE RESULT OF BUILDING DAMAGE STUDY OF TMG

The earthquake risk study by TMG includes a lot of parameters of buildings and soil conditions as well as building inventory data. Thus a multiple regression analysis was attempted in order to identify significant parameters influencing the final relative seismic risk. If a simplified approximation relation is obtained, parametric studies can be conducted without much computational efforts. Thus it will be conveniently used in urban planning. First a linear multiple regression was carried out for all the 5,133 city-blocks as

$$y = a_0 + \sum_{j=1}^{n} a_j x_j \tag{7}$$

where y is the dependent variable (the total number of damaged buildings per unit area), x_j are explanatory variables, n is the number of explanatory variables, a_0 and a_j are constants to be obtained by regression.

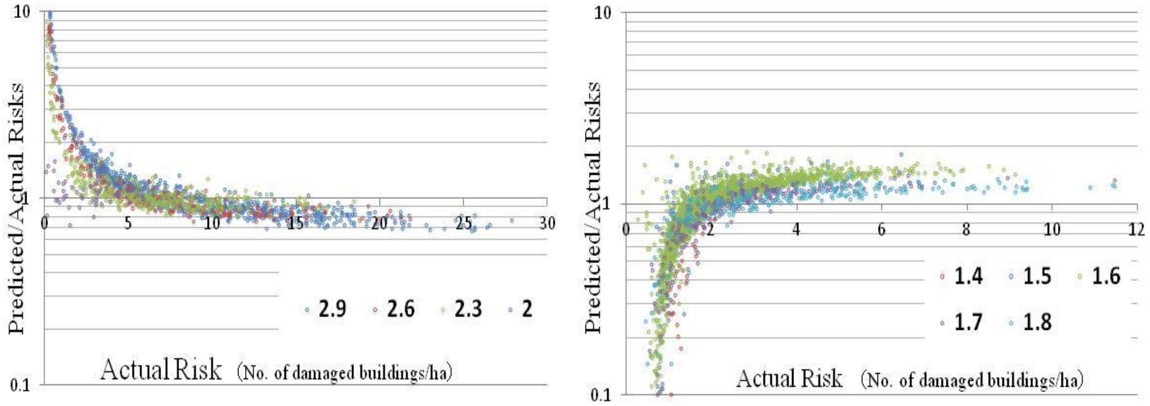
First, the number of independent variables were set as 14: the number of buildings for 13 building classes (wooden: 5, Reinforced Concrete: 3, Steel: 3, Light-gauge Steel: 2) divided by the area of each city-block, the soil amplification ratio in each city-block. The results of the regression showed the possible existence of multicollinearity among the explanation variables. It is strange the number of damaged buildings increases by a decrease in building density. Therefore it is necessary to choose the explanation variables to compose an optimal model. In this study, AIC (Akaike's Information Criterion) was used to choose proper explanation variables by the following equation (Akaike, 1973):

$$AIC = n\left(\ln\left(2\pi\frac{Se}{n}\right)+1\right)+2(p+2) \tag{8}$$

in which n is the number of data points, p is the number of explanation variables and Se is the residual sum of squares. Since the numbers of buildings in some classes are not so many and the seismic resistances of reinforced concrete (RC) and light-gauge steel (LS) buildings of new seismic codes are high, those with negative coefficients were excluded from explanation variables in the second-stage regression. Then the final regression equation was built using the variables and coefficients provided by AIC.

Figure 4 compares the density of damaged buildings (y_i) between the rigorous calculation and the simplified approach for all the city-blocks. As a result, a remarkable tendency appeared with respect to the soil amplification ratio (A_R). Based on the A_R values, 5,133 blocks were divided into 2 groups (1.4-1.8 and 2.0-2.9), then regression was performed separately for the two data groups, by removing unnecessary explanation variables using AIC.

Table2 shows the explanation variables and their coefficients obtained from this process. **Figure 5** shows the result of regression for the two groups. The soft soil area (A) has high soil amplification ratios (1,557 blocks) and the medium soil area (B) has low amplification ratios (3,576 blocks). In this figure, large deviations are still seen in low risk blocks but points converge to 1.0 for large risk blocks. Thus it was revealed that the number of damaged buildings per unit area depends on the soil amplification ratio as well as the building density for assumed vulnerability functions.

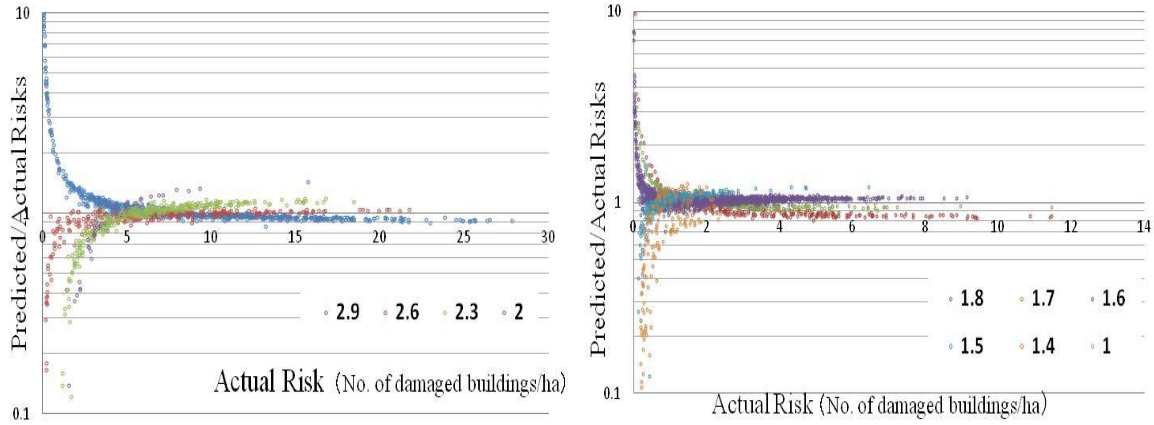


(a) High soil amplification ratio blocks (2.0-2.9) (b) Low soil amplification ratio blocks (1.4-1.8)

Figure 4 The result of regression for all the 5,133 blocks at once

Table 2 The explanation variables and their coefficients obtained by dividing blocks into two groups

	variables		(A)	(B)		variables		(A)	(B)
1	wooden	-70	0.42	0.20	8	Reinforce Concrete	-70	0.19	0.04
2		71-80	0.40	0.09	9		71-80	0.03	0.04
3		81-90	0.13	0.04	10		81-	0.01	0.02
4		91-00	0.004	0.01	11	Steel	-70	0.48	0.25
5		01-	0.001	0.003	12		71-80	0.22	0.08
6	Light Steel	-80	-	0.03	13		81-	0.12	0.02
7	Soil amplifications ratio		3.48	1.46		Intercept		-9.23	-9.23

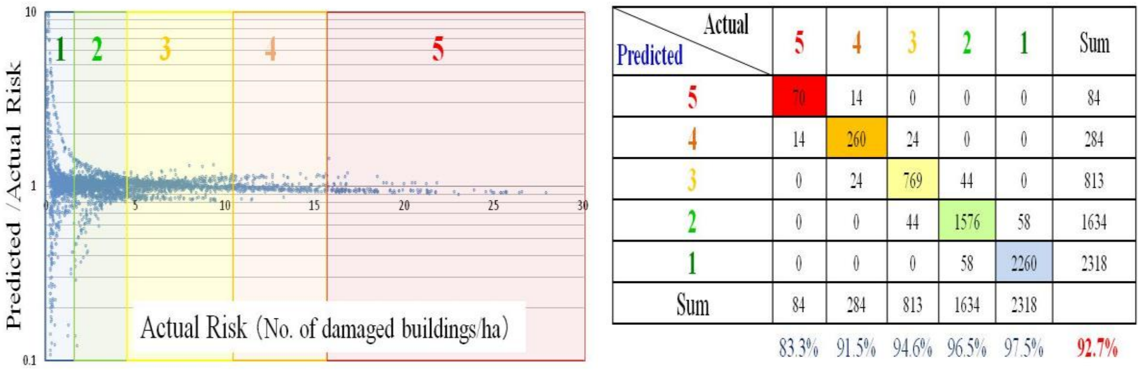


(a) High soil amplification ratio blocks (2.0-2.9) (b) Low soil amplification ratio blocks (1.4-1.8)

Figure 5 The result of the segmented regression

EVALUATION BY RANKS OF RISK

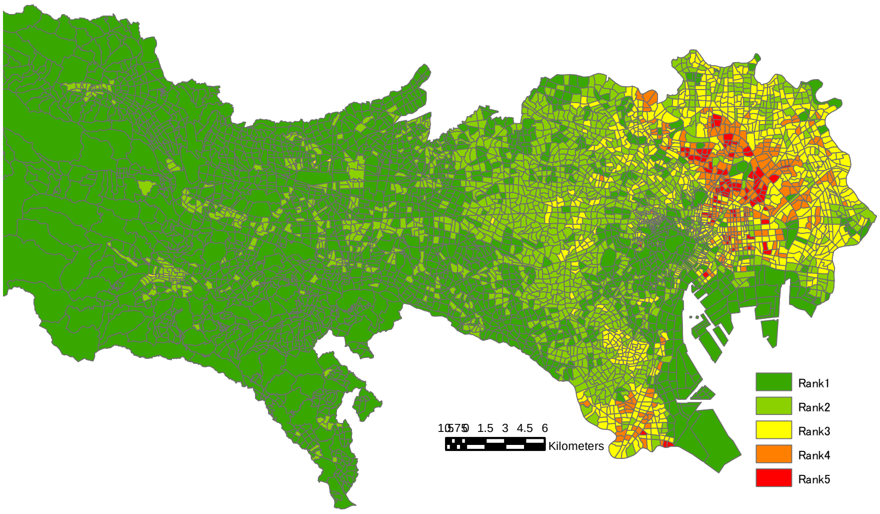
Figure 6(a) compares the density of damaged buildings between the rigorous calculation by TMG and simplified method in this study. Although some deviations are still seen, the result of the regression analysis is considered to be acceptable for parametric studies. The predicted results are classified by five ranks based on the risk value. **Figure 6(b)** shows the confusion matrix which compares the number of city-blocks belonging to each rank. It is seen from the plots that high risk-rank blocks (Ranks 4 and 5) are mostly located in high soil amplification ratios areas. Since the number of possible damaged buildings per area is the risk index in this study, it is considered that many vulnerable buildings, such as old-coded wooden houses, are standing densely in such high risk city-blocks. Thus, it is expected that to reduce this seismic risk index, the replacement of small vulnerable houses to high seismic-resistant buildings of small numbers is most effective. **Figure 7(a)** shows the result of regression in this study. Compared with the rigorous calculation shown in **Figure 7(b)**, the simplified method gave similar risk ranks for most of the city-blocks in Tokyo.



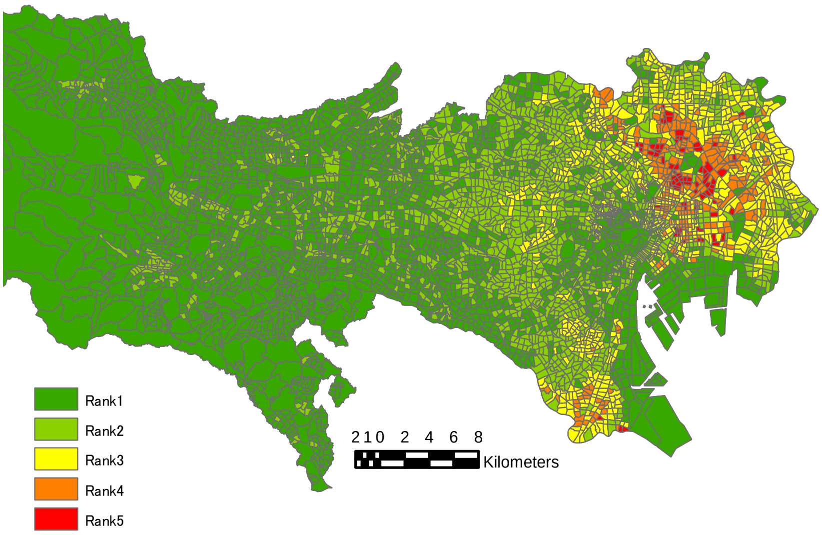
Actual / Predicted	5	4	3	2	1	Sum
5	70	14	0	0	0	84
4	14	260	24	0	0	284
3	0	24	769	44	0	813
2	0	0	44	1576	58	1634
1	0	0	0	58	2260	2318
Sum	84	284	813	1634	2318	
	83.3%	91.5%	94.6%	96.5%	97.5%	92.7%

(a) The result of regression (b) Confusion matrix

Figure 6 Predicted and actual seismic risk and confusion matrix for the ranks of seismic risk



(a) The simplified method



(b) TMG (2013)

Figure 7 Results of seismic damage risk of buildings in each city-block

CONCLUSIONS

In this paper, a statistical analysis was conducted for the result of the building damage assessment by the Bureau of Urban Development of the Tokyo Metropolitan Government (TMG), which includes 14 parameters on soil condition and building inventory data for given fragility curves. The earthquake risk study by TMG includes a lot of parameters of buildings and soil conditions as well as building inventory data. Thus a multiple regression analysis was attempted in order to identify significant parameters influencing the final relative seismic risk. In a multiple regression analysis, the number of heavily damaged buildings per area was considered as the dependent variable and several explanation variables were employed, such as the number of buildings for each structural type and construction period, the soil amplification factor. The regression analysis was conducted for all the 5,133 city blocks of Tokyo Metropolis and an accurate prediction formula was derived. The result may be conveniently used to identify dominant factors influencing the building seismic risk due to strong shaking and to assess the effects of countermeasures for reducing seismic risk in dense urban areas.

ACKNOWLEDGMENTS

The building inventory and soil classification data used in this study were provided from the Bureau of Urban Development of Tokyo Metropolitan Government.

REFERENCES

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle, *Proceedings of the 2nd International Symposium on Information Theory*, Petrov, B. N., and Caski, F. (eds.), Akadimiai Kiado, Budapest: 267-281

Kobayashi, T., Yamazaki, F., and Nagata, S. (2011). Estimation of the distribution of water-pipeline length based on other infrastructure data, P*roc. 32nd Asian Conference on Remote Sensing*, Taipei, Paper No. 417, CD-ROM, 6p.

Maruyama, Y., Fushioka, S., and Yamazaki, F. (2012). Evaluation of site amplifications in the Tokyo metropolis based on ground motion records and spatial geomorphologic datasets, *Proceedings of the 5th Asian-Pacific Symposium on Structural Reliability and its Applications*, 605-610.

Shimizu, Y., F. Yamazaki, S. Yasuda, I. Towhata, T. Suzuki, R. Isoyama, E. Ishida, I. Suetomi, K. Koganemaru, and W. Nakayama, (2006). Development of Real-Time Safety Control System for Gas Supply Network, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 132(2), 237-249.

Tokyo Metropolitan Government (2012). *Earthquake Damage Assessment of Tokyo for Near-Field Earthquakes*, http://www.bousai.metro.tokyo.jp/taisaku/1000902/1000401.html

Tokyo Metropolitan Government (2013). *The 7th Community Earthquake Risk Assessment Study*, http://www.toshiseibi.metro.tokyo.jp/bosai/chousa_6/download/kikendo.pdf

Yamaguchi, N. and Yamazaki, F. (2000). Fragility Curves for Buildings in Japan based on Damage Surveys after the 1995 Kobe Earthquake, *12th World Conference on Earthquake Engineering*, CD-ROM, 8p, 2000.

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, 1416-1423.

Yamazaki, F. and Murao, O. (2000). Vulnerability Functions for Japanese Buildings based on Damage Data due to the 1995 Kobe Earthquake, *Implications of Recent Earthquakes on Seismic Risk*, Series of Innovation in Structures and Construction, Imperial College Press, Vol. 2, 91-102.

Yamazaki, F., Wakamatsu, K., Onishi, J., and Shabestari, K.T. (2000). Relationship between Geomorphological Land Classification and Site Amplification Ratio Based on JMA Strong Motion Records, *Soil Dynamics and Earthquake Engineering*, 19, 1, 41-53.