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STATISTICAL ANALYSIS FOR THE RESULT OF SEISMIC RISK ASSESSMENT OF TOKYO, JAPAN

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Tokyo Metropolitan Government (TMG) conducts a community-based seismic risk assessment for all the city-blocks in the Tokyo Metropolis every five years. The seventh seismic risk assessment survey was carried out for two kinds of risks 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 due to shaking 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 (independent) variables were employed, such as the number of buildings for each structural type and construction period, the soil amplification ratio, and the liquefaction susceptibility. The regression analysis was conducted for all the 5,133 city-blocks in the Tokyo Metropolis and an accurate prediction equation was derived.

Keywords: Tokyo Metropolis, seismic risk, vulnerability function, structural type, construction age, multiple regression, soil amplification.

1 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, liquefaction, landslides and lifeline interruptions 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 in each local-community or city-block level. Recent GIS technologies enabled us to assess local seismic risk and to visualize various damage situations using building inventory data 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 in the 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 were differences in the methods to predict earthquake-induced damages. Specific seismic 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 in each city-block was evaluated in the former study. The results of the community-based seismic risk assessment were 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 efficiently, especially when parameter values change or for identifying strategic urban redevelopment plans.

2 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 an attenuation relationship 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

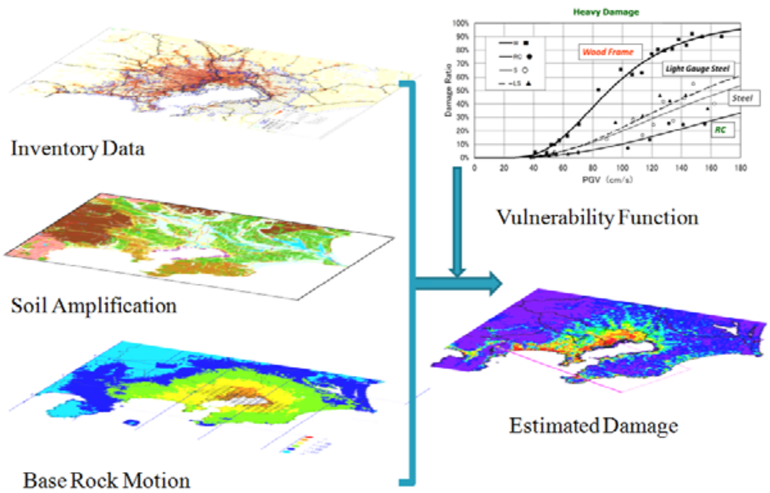

Figure 1. Flowchart of typical seismic damage assessment

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

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

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. Figure 2 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.

Combining these three elements (input seismic motion, inventory data, vulnerability function), seismic damage assessment can be carried out and the number of damaged buildings for each grid-cell or a city-block is estimated.

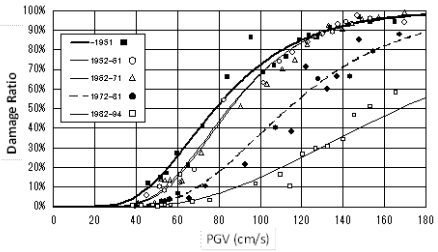

Figure 2. Vulnerability functions of wood-frame buildings in Japan used in this study

3 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 V_s=500 m/s. This assumption came from the facts that the results of damage assessment are highly affected by the assumed location and magnitude of seismic sources, and that source-models for the Tokyo and surrounding region are difficult to set up due to thick sedimentary layers and scarce historical earthquake data.

Thus in the community-based seismic risk assessment of TGM, 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 the Tokyo Metropolis was further investigated using a very dense seismic monitoring system (SUPREME) of Tokyo Gas Co. (Shimizu *et al*. 2006). Figure 3 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 a large amount variability was seen in the amplification ratios of the same soil classes for deferent methods and actual events, the values were determined as shown in Figure 4 considering the continuity of the series of the community-based seismic risk assessment study by the TMG.

4 Building Damage Ratio and Ranks of Risk

Using the estimated peak ground velocity (PGV) and the 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:

$$P_f = P(R/S < 1) = 1 - \Phi(\lambda_Z/\zeta_Z) \quad (2)$$

in which *R* is the seismic resistance of a certain class of buildings, *S* the strong motion

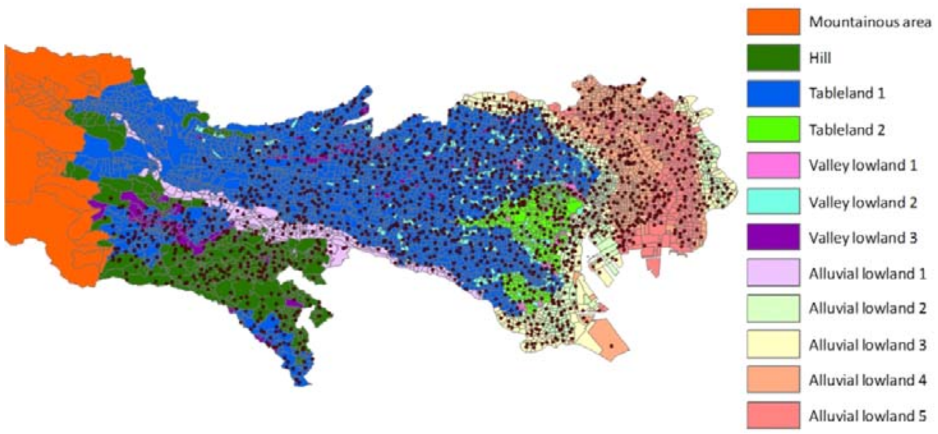

Figure 3. Soil classification map of Tokyo and the location of SUPREME's seismometers

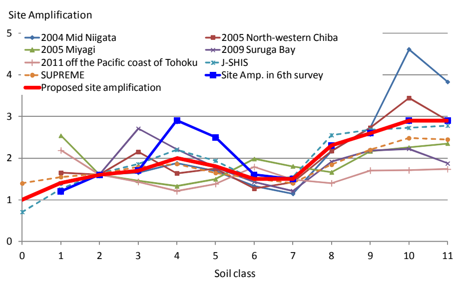

Figure 4. PGV amplification ratios for actual seismic records and by various models

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

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

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 considered 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 in city-block *i*.

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

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

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

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

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

$$r_i=N_i/a_i \qquad (6)$$

where r_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 five levels to highlight most vulnerable city-blocks where urban redevelopment plan be applied.

Figure 5 shows the result of the building damage assessment by Tokyo Metropolitan Government (2013). The building damage by shaking was calculated by Eq. (4) for each building category (Figure 2), and liquefaction-induced building damage was calculated based on the number of stories of a building and the liquefaction susceptibility of the city-block. The number of damaged buildings form the two causes (shaking and liquefaction) were finally summed up and then the results were divided by the areas of city-blocks (to produce a density map of damaged buildings). Figure 6 plots the liquefaction susceptibility map, showing the possible areal ratio to liquefy, used in the study.

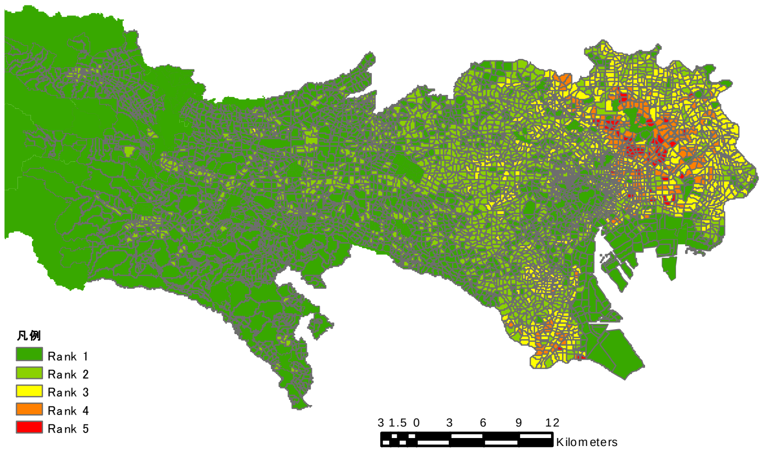

Figure 5. Result of seismic risk of buildings in each city-block by TMG (2013)

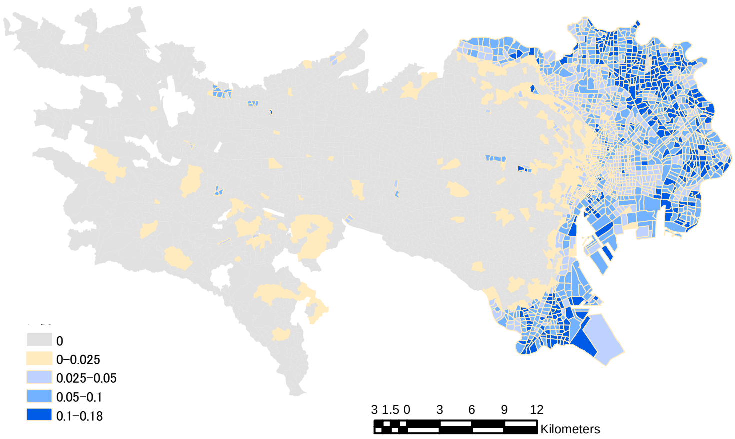

Figure 6. Areal ratio r_{Liq} of liquefaction susceptibility in each city-block by TMG (2013)

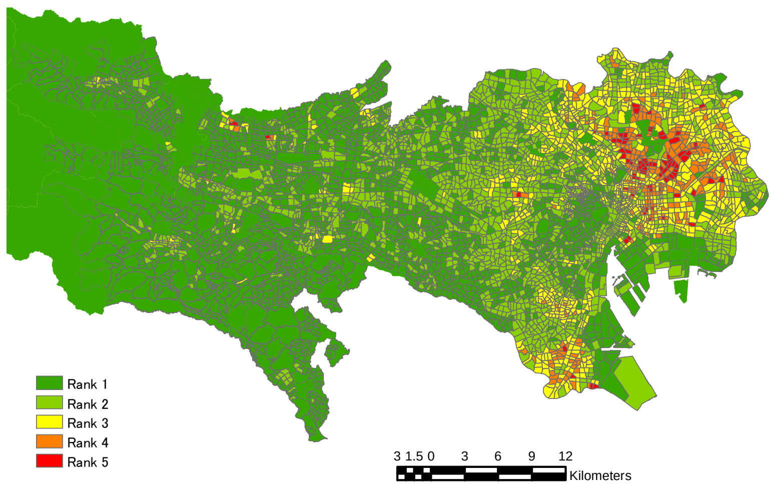

Figure 7. Result of seismic risk of buildings in each city-block by linear regression in this study

5 Regression Analysis for 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 (Figure 5). 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.

A linear multiple regression was carried out for all the 5,133 city-blocks as

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

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 16: the number of buildings for 14 building classes (wooden: 5, reinforced concrete: 3, steel: 3, light-gauge steel: 2, others: 1) divided by the area of each city-block, the soil amplification ratio, and the areal ratio of high liquefaction susceptibility in each city-block. The results of the regression showed the possible existence of multicollinearity among the explanation variables. For example, the coefficient for the areal ratio of liquefaction susceptibility became a negative value although it is supposed to be positive. This can explained by the fact that the blocks of high liquefaction susceptibility are similar with high soil-amplification zones. Thus these two variables presented multicollinearlity in the multiple regression.

Since the numbers of buildings of some classes are not so many and the seismic resistance of reinforced concrete (RC) and steel buildings of new seismic codes is high, those with negative coefficients were excluded from explanation variables in the second-stage regression. Figure 7 shows the result of the regression in the second-stage. Compared with the rigorous calculation shown in Figure 5, the simplified method gave similar risk ranks for most of the city-blocks in Tokyo.

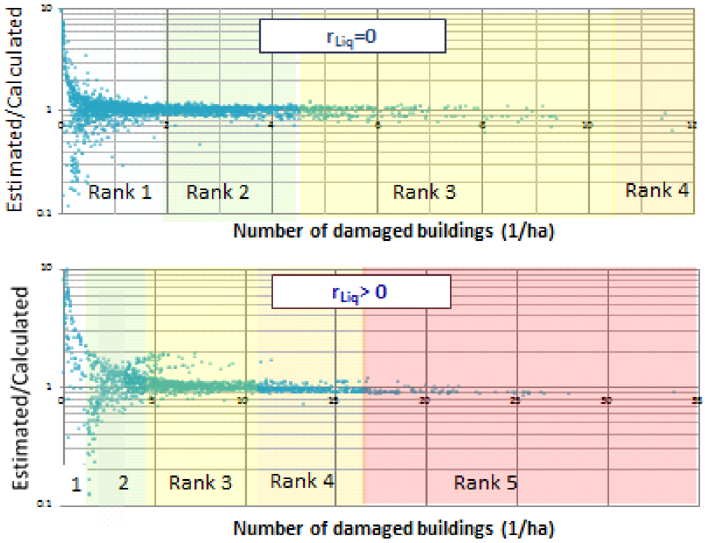

Figure 8. Results of seismic risk of buildings in each city-block by linear regression in this study, the upper for no liquefaction areas and the lower for liquefaction susceptibility areas.

Figure 8 compares the density of damaged buildings (r_i) between the rigorous calculation and the simplified approach for all the city-blocks. Although some deviations are still seen, the result of the regression analysis is considered to be acceptable for parametric studies. It is seen from the plots that high risk-rank blocks (Ranks 4 and 5) are mostly located in high liquefaction susceptibility areas, where soil amplification ratios are also high. Since the number of possible damaged buildings per area is used as 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.

6 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). 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 ratio, and the liquefaction susceptibility. The regression analysis was conducted for all the 5,133 city blocks in the Tokyo Metropolis and an accurate prediction formula was derived. The result may be conveniently used to identify dominant factors influencing seismic risk of buildings due to strong shaking and to assess the effects of countermeasures for reducing seismic risk in dense urban areas.

References

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

Maruyama, Y., Fushioka, S., and Yamazaki, F., 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, 2012.

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

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

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

Yamaguchi, N. and Yamazaki, F., 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., Earthquake Scenario of Urban Residential Areas Using Microscopic GIS Data, *Proceedings of the Fifth International Conference on Seismic Zonation*, 2, 1416-1423, 1995.

Yamazaki, F. and Murao, O., 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, 2000.

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