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A sensitivity analysis for seismic hazard estimation

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ABSTRACT: The sensitivity of seismic hazard estimation was evaluated for the Kanto district, Japan. Subjective judgments required for determining an earthquake occurrence model have practically little influence on the probabilistic estimates of ground motions if common earthquake data are used to determine the seismicity parameters of the model. The effects of a ground motion attenuation equation and its randomness are very large. An agreement on the attenuation equation is needed for reducing the difference of the probabilistic estimates.

1 INTRODUCTION

A deterministic approach estimating a ground motion from an assumed fault model is used to determine an input ground motion for earthquake-resistant design. However, there exists uncertainty in the estimated result because of the uncertainty of the fault model and the randomness of a ground motion attenuation equation. Since it is practically impossible to eliminate the uncertainty in the estimation, a probabilistic approach which takes account of the uncertainties and randomness in the ground motion estimation can be considered to be more rational than the deterministic approach. However, some problems, such as the effect of subjective judgments which is necessary to determine an earthquake occurrence model, still remain to be investigated for developing the probabilistic approach for practical use. The purpose of the present study is to evaluate the sensitivity of results estimated by a probabilistic method to subjective judgments required for determining an earthquake occurrence model, to the focal depth term and the randomness of attenuation equations, to the truncation of the randomness, and to minimum magnitude.

2 METHODS

The sensitivity of seismic hazard estimation was evaluated for the Kanto district, Japan. A computer program developed by Annaka and Nozawa (1988) was used for estimating the seismic hazard. The program has the characteristics as follows: seismic source zones can be defined in three dimensional space, a finite fault model as well as a point source model can be used, two types of magnitude distribution, a characteristic earthquake model and a b-value model, can be used, and the randomness of an attenuation equation is represented by a truncated log-normal distribution.

2.1 *Earthquake occurrence models*

In order to evaluate the sensitivity to subjective judgments required for determining an earthquake occurrence model, three models were derived from three different ideas. The earthquake data with focal depths less than 100 km from 1885 through 1988 were used to determine the seismicity parameters of the models.

The first model is a tectonics model. Seismic source zones and their magnitude-frequency relationships were determined using a combination of geologic and historic data on the basis of recent researches in seismotectonics of the region. Many subjective judgments were necessary to determine the tectonics model. This model is almost the same as a model proposed by Annaka and Nozawa (1988). The seismic source zones can be divided into two groups by the difference of magnitude-frequency relationships. The occurrence of earthquakes in the seismic source zones where large characteristic earthquakes have occurred periodically is described by a characteristic model (Schwartz and Coppersmith (1984)). The frequency distribution of magnitudes is assumed to be uniform in a narrow range. Figure 1 shows the distribution of the seismic source zones of this type. The occurrence of earthquakes in the other seismic source zones where middle and small earthquakes have occurred randomly is described by a b-value model. The frequency distribution of magnitudes is given by the truncated Gutenberg-Richter relationship. The seismic source zones of this type were distributed on three planes: the upper plane of the Pacific plate, that of the Philippine Sea plate, and the horizontal plane with a depth of 5 km in the Continental plate. These zones are the same as those by Annaka and Nozawa (1988).

The second model is a simplified model. The region is mechanically divided into seismic source zones by an interval of 0.5 degrees. Figure 2 shows the division of the seismic source zones in the simplified model. Each

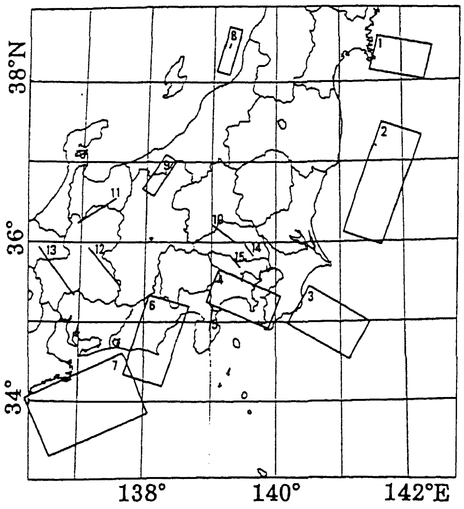

Fig.1 Distribution of the seismic source zones for the large characteristic earthquakes in a tectonics model.

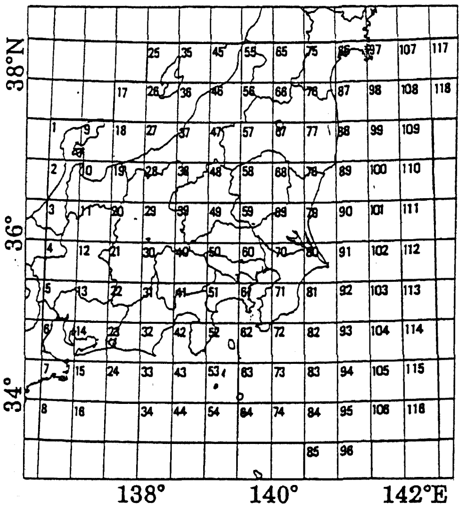

Fig.2 Division of the seismic source zones in a simplified model.

seismic source zone is represented by a horizontal plane with a constant depth. The depth of the plane was determined by averaging the focal depths of earthquakes with magnitudes greater than or equal to 4.0. The coefficients of a and b in the Gutenberg-Richter relationship were determined from the magnitude-frequency distribution of earthquakes with magnitudes greater than or equal to 6.0 from 1885 through 1988. Maximum magnitude for each seismic source zone is selected to be equal to the maximum magnitude of disastrous earthquakes occurred in the zone after A.D. 1600. Few subjective judgments were needed for determining the seismicity parameters of each seismic source zone.

The third model is an earthquake catalog model. Earthquakes are assumed to repeatedly occur exactly the same as the sequence of an earthquake catalog. The catalog, which is compiled from Utsu (1979,1981,1982a,1982b, 1985) and the seismological bulletins of the Japan Meteorological Agency, includes the earthquakes with magnitudes greater than or equal to 5.5 from 1885 through 1988. The earthquakes with magnitudes less than 6.0 from 1885 through 1925 are not completely compiled. Figure 3 shows the epicentral distribution of the earthquakes included in the catalog. The focal depths of earthquakes from 1885 through 1925 are not determined, but they are divided into three categories by Utsu. The focal depth is assumed to be 10 km in the case of VS (very shallow), and 40 km in the case of S (shallow). For this model, no other subjective judgments except the assumption of focal depths were required.

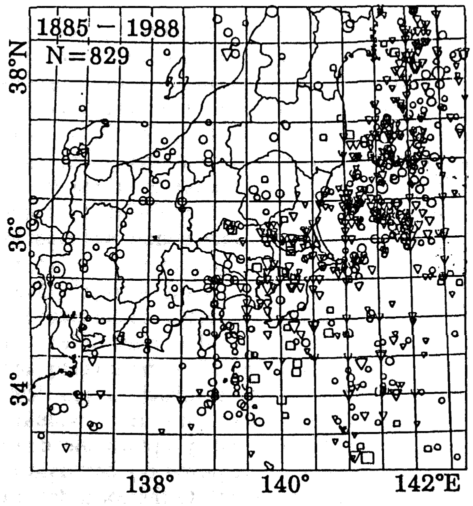

Fig. 3 Epicentral distribution of earthquakes used in an earthquake catalog model. Symbols represent the ranges of focal depths: circles 0-30km, triangles 31-60km, and squares 61-99km.

2.2 *Attenuation models*

Many earthquakes have occurred in the uppermost mantle beneath the Kanto district as shown in Fig.3. Nevertheless the effect of focal depth is not explicitly included in a large number of attenuation equations proposed in the past. In order to evaluate the sensitivity to the focal depth term in attenuation equations for peak horizontal ground acceleration, two attenuation equations were used.

The first equation is proposed by Annaka et al. (1990). It explicitly includes a focal depth term as follows:

$$\log PGA=0.614M+0.00501Hc-2.031\log D+1.377 \quad (1)$$

$$D=(\Delta^2+0.45H^2)^{1/2}+0.220\exp(0.699M),$$

where PGA is the mean peak ground acceleration (cm/s^2) of two horizontal components, M is magnitude, Hc is the depth of the center of a fault plane in km, and Δ and H are horizontal and vertical distances in km, respectively, from a site to the point on the fault plane where the value of $(\Delta^2 + 0.45H^2)^{1/2}$ becomes minimum. Common logarithms are used. Fault extent is taken into account.

The attenuation equation (1) was determined from the data of earthquakes with focal depths less than 100 km from 1971 through 1989. The distribution of data is shown in Fig.4. The term 0.00501Hc was introduced because the multiple correlation coefficient fairly increased by this term. The phenomenon that PGA for deeper earthquakes in the epicentral distance greater than about 100 km is larger than that for shallower earthquakes if the other conditions are the same can be explained by this term. The coefficient 0.45 was determined as the value of c which minimizes the summation of squared residuals when distance term was represented by $(\Delta^2 + cH^2)^{1/2}$. The expression of D was constrained by the condition that a peak ground acceleration becomes independent on magnitude at the fault surface. The constant 1.377 was determined so that the attenuation equation can be applied to a site whose subsurface S wave velocity is about 400 m/s. PGA depends on site conditions, especially the subsurface S wave velocity of the site. The relation between station corrections and subsurface S wave velocities is shown in Fig.5. Station correction is defined by the mean of log(observation/calculation). The trend that station correction decreases with increasing subsurface S wave velocity is clearly seen.

The second equation is proposed by Kawashima et al. (1984). It does not explicitly include a focal depth term as follows:

$$\log PGA = 0.216M - 1.218\log(\Delta + 30) + 2.994, \qquad (2)$$

where PGA is peak ground acceleration (cm/s^2), M is magnitude, and Δ is epicentral distance in km. When fault extent was considered, Δ was used as the horizontal distance to the center of the fault plane.

The randomness of the attenuation equations is assumed to be represented by a truncated log-normal distribution with standard deviation β. The log-normal distribution is truncated at $\pm k \cdot \beta$ from the center. The probability density of the truncated log-normal distribution is normalized so that the total probability within the truncated range can be unity. The coefficient k is hereafter called the truncation factor.

The standard deviation of the residuals by the attenuation equation (1) is 0.23 in common-log scale. In order to test the validity of the assumption of the log-normal distribution, the residuals were plotted on the normal probability chart as shown in Fig.6. If the residuals are completely represented by the log-normal distribution, the plotted data should locate just on the straight line. The departure from the line is not remarkable within the range $\pm 3\beta$ from the center. It indicates that the randomness of the attenuation equation, at least within the range of three standard deviations, can be represented by the log-normal distribution.

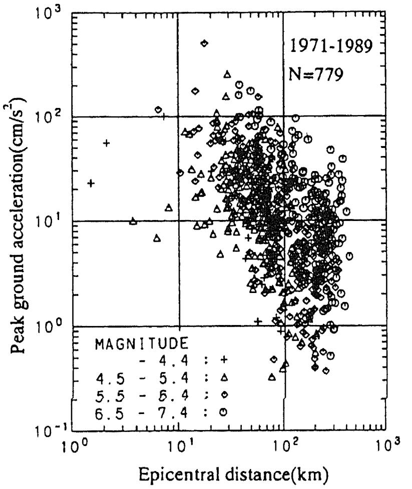

Fig.4 Distribution of data used to derive attenuation equation (1).

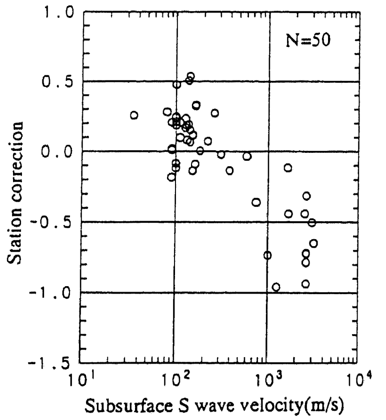

Fig.5 Relation between station correction and subsurface S wave velocity.

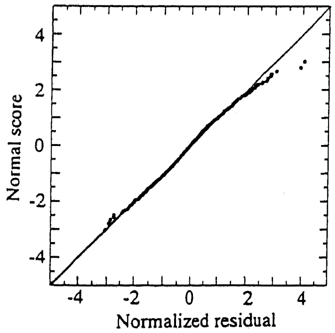

Fig.6 Plot on the normal probability chart.

The standard deviations of the residuals by attenuation equation (1) were separately determined for nineteen sites with the number of PGA data greater than or equal to 20. The histogram of the standard deviations is shown in Fig.7. Most of them distribute in the range from 0.15 to 0.30.

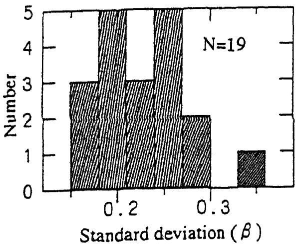

Fig.7 Histogram of the standard deviations of 19 sites.

3 RESULTS

In order to evaluate the sensitivity of seismic hazard estimation, variation of seismic hazard curves for a selected site and contour maps of expected PGA for several return periods were examined.

3.1 *Effect of the randomness of attenuation equation*

The tectonics model and attenuation equation (1) were used. The randomness of the attenuation equation was represented by the truncated log-normal distribution. The standard deviation β is fixed to be 0.20. The range of truncation is represented by the truncation factor k. Variation of hazard curves by changing k from 0 to 10 at Tokyo (139°46'E, 35° 40'N) is shown in Fig.8. The difference of hazard curves between k=3 and k=10 is negligible in the range of an annual probability of exceedance greater than about 10^{-4}. As stated in Section 2.2 the randomness of the attenuation equation, at least within the range of three standard deviations, can be represented by the log-normal distribution. Therefore, as far as an annual probability of exceedance greater than about 10^{-4} is concerned, the distribution of randomness outside the range of three standard deviations has almost no influence on the results.

Variation of hazard curves by changing β from 0.0 to 0.4 at Tokyo is shown in Fig.9. The truncation factor k is fixed to be 3. An annual probability of exceedance becomes higher with increasing β. The effect of β is more remarkable than that of k.

3.2 *Effect of minimum magnitude*

The minimum magnitude of 5.5 was used in the previous analysis of Annaka and Nozawa(1988). It was based on the fact that few disastrous earthquakes with magnitude less than 5.5 have been observed in the metropolitan area of the Kanto district because of low seismicity in the upper crust. In order to validate this assumption, the effect of minimum magnitude is examined. Variation of hazard curves by changing minimum magnitude from 5.5 to 4.0 at Tokyo is shown in Fig.10. The tectonics model and attenuation equation (1) were used. The standard deviation β and the truncation factor k are fixed to be 0.20 and 3 respectively. The difference of hazard curves becomes smaller with increasing PGA.

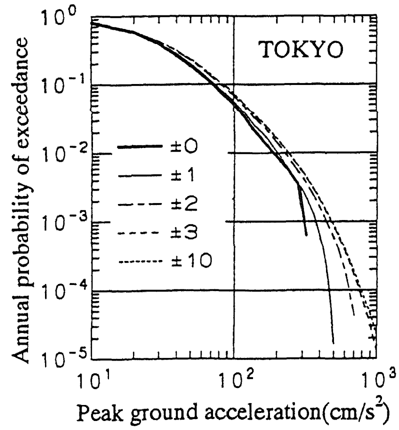

Fig.8 Variation of hazard curves by changing k from 0 to 10 at Tokyo.

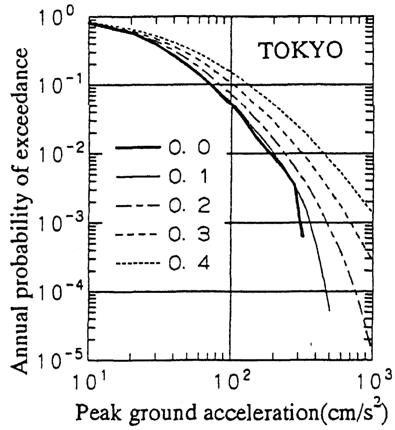

Fig.9 Variation of hazard curves by changing β from 0.0 to 0.4 at Tokyo.

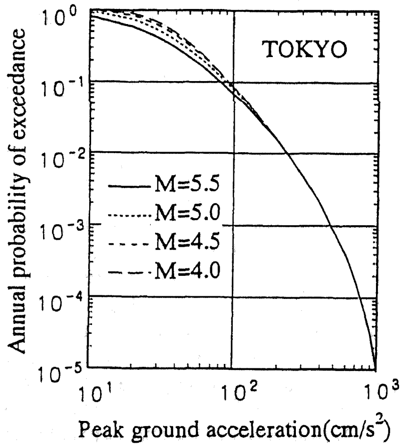

Fig.10 Variation of hazard curves by changing minimum magnitude from 5.5 to 4.0 at Tokyo.

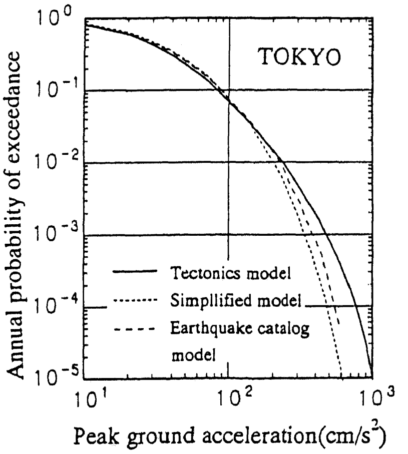

Fig.11 Variation of hazard curves among the three earthquake occurrence models at Tokyo.

The range of an annual probability of exceedance being important for determining an input ground motion is usually considered to be from about 0.02 to about 0.001. Within this range, considerable difference of hazard curves is not observed. The minimum magnitude of 5.5 can be practically used for the Kanto district.

3.3 *Effect of earthquake occurrence model*

Attenuation equation (1), the minimum magnitude of 5.5, the standard deviation β of 0.20, and the truncation factor k of 3 were used. Variation of hazard curves among the three earthquake occurrence models at Tokyo is shown in Fig.11. The difference of hazard curves becomes larger with increasing PGA. However, the three curves agree with each other in the range of an annual probability of exceedance greater than about 10^{-2}.

The contour maps of expected PGA for a return period of 75 years for the three earthquake occurrence models are shown in Fig.12. Spatial variation of expected PGA for the earthquake catalog model is more rapid than those for the other two models. This is because the hypocenter of an earthquake is fixed at a specified point in the earthquake catalog model, whereas that in the other two models is uniformly distributed on a plane of a seismic source zone. However, as a whole, the differences among the results from the three models are not large and the contour patterns are similar to each other.

Although many subjective judgments were necessary to determine the tectonics model, they have practically little influence on the probabilistic estimates in the range of an annual probability of exceedance greater than about 10^{-2}. The effect of subjective judgments naturally becomes greater as PGA increases. The tectonics model can be considered more reasonable than the other two models because it was essentially derived by smoothing and extrapolating the earthquake catalog model on the basis of the recent investigation on the seismotectonics of the region.

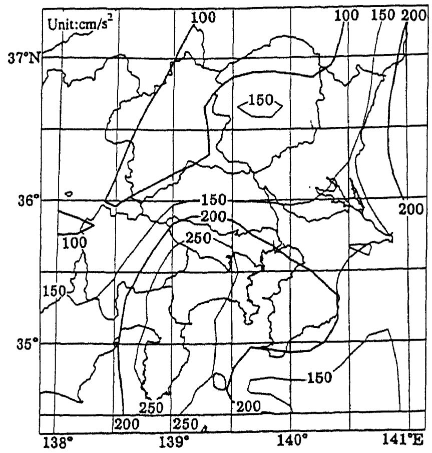

Fig.12 (1) Contour map of expected PGA for a return period of 75 years by a tectonics model.

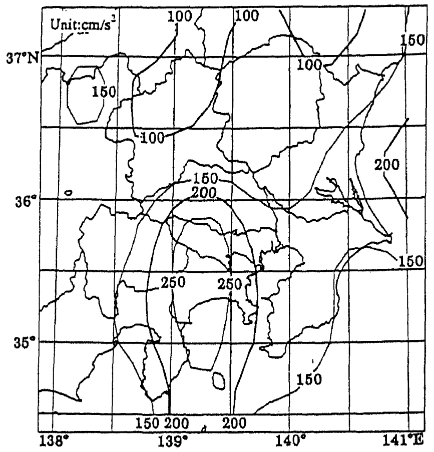

Fig.12 (2) Contour map of expected PGA for a return period of 75 years by a simplified model.

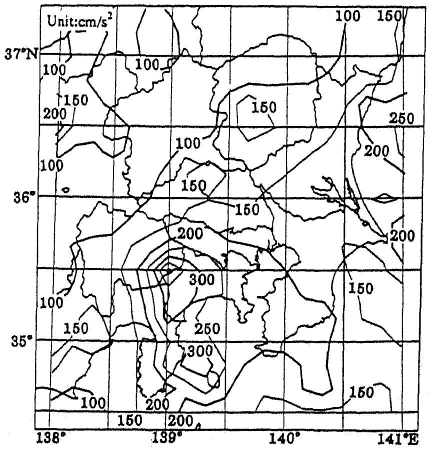

Fig.12 (3) Contour map of expected PGA for a return period of 75 years by an earthquake catalog model.

3.4 *Effect of focal depth term in attenuation equation*

The contour maps of expected PGA for a return period of 150 years between attenuation equations (1) and (2) are compared as shown in Fig.13. The tectonics model was used. The other conditions are identical with those in Section 3.3. The two contour patterns of expected PGA were quite different in and around northern Chiba and southern Ibaragi prefectures. The zone with high expected PGA in Fig.13 (2) is extended to north-eastward compared with Fig.13 (1). This difference is caused by the high seismic activity of the uppermost mantle beneath northern Chiba and southern Ibaragi prefectures. Attenuation equation (2) predicts the same PGA for these deeper earthquakes as those for shallower earthquakes because it does not include the effect of focal depth. The level of expected PGA by attenuation equation (2) is much higher than that by attenuation equation (1).

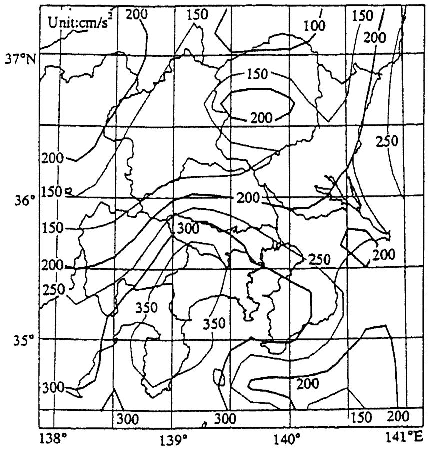

Fig.13 (1) Contour map of expected PGA for a return period of 150 years by a tectonics model and attenuatin equation (1).

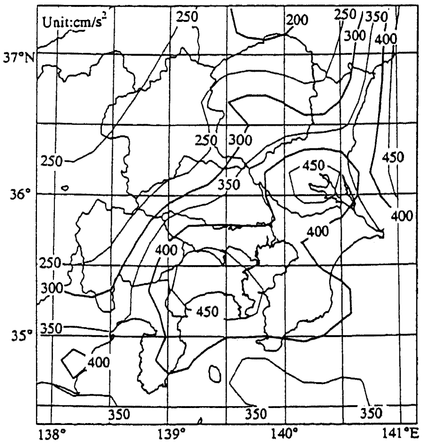

Fig.13 (2) Contour map of expected PGA for a return period of 150 years by a tectonics model and attenuation equation (2).

4 CONCLUSIONS

The sensitivity of seismic hazard estimation was evaluated for the Kanto district. Variation of seismic hazard curves for a selected site and contour maps of expected peak ground acceleration for several return periods were examined. Subjective judgments required for determining an earthquake occurrence model have practically little influence on the probability estimates if common earthquake data are used to determine the seismicity parameters of the model. The minimum magnitude of 5.5 can be practically used for the Kanto region. The randomness of an attenuation equation, at least within the range of three standard deviations, can be represented by a log-normal distribution. As far as an annual probability of exceedance greater than about 10^{-4} is concerned, the distribution of randomness outside the range of three standard deviations has almost no influence on the results. The effects of an attenuation equation and its randomness are very large. An agreement on the attenuation equation is needed for reducing the difference of the probabilistic estimates.

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