11 WCEE
Copyright © 1996 Elsevier Science Ltd
Paper No. 1585. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

A STOCHASTIC SEISMIC HAZARD MODEL WITH TEMPORAL AND SPATIAL DEPENDENCE

S .SUZUKI* and R. NAKAMURA*
*Tokyo Electric Power Services Company Limited.
Iino Building 1-1 Uchisaiwai-cho 2 chome Chiyodaku Tokyo Japan

ABSTRACT

A stochastic site hazard model is presented for estimating probabilities of exceeding site ground motions. The multidisciplinary approach to the seismic hazard and the stochastic model for site ground motions are combined to develop the seismic hazard map. The model is applied to Kanagawa prefecture in Japan and the seismic hazard map is developed based on the multidisplinary information such as geology, geodesy, space geodesy, observational seismology, paleoseismology and seismic gap. The results indicate that the multidisplinary information to seismic hazard can be used to estimate the seismic hazard potential in the area where all types of earthquake sources are distributed.

KEYWORDS

seismic hazard, geodetic measurement, observational seismology, time predictable model, Kanto earthquake
space geodesy, global positioning system, seismic gap

INTRODUCTION

A stochastic site hazard model is presented for estimating probabilities of exceeding site ground motions. The multidisciplinary approach to the seismic hazard (Ward 1994) and the stochastic model for site ground motions (Kiremidjian and Suzuki 1987) are combined to develop the seismic hazard map.

The model includes information on the geological slip rate, the strain accumulation rate, the observational seismology and the seismic gap. In particular, the regional strain rate is used to estimate the seismic hazard in the area where locations and slip rates of faults are unknown.

The Poissonian or the time independent model is used to estimate the probabilities of small and frequent earthquake occurrences in this study, because the model can apply to regions characterized by small or local earthquakes. However, the stochastic time predictable model, which reflects the hypothesized dependence of the time of last earthquakes, is used to estimate the probabilities of occurrences for subduction earthquakes. The model is applied to Sagami area in Japan and the seismic hazard map in Sagami area is developed based on the geodetic information. A crustal strain accumulation rate in the triangular zone has been repeatedly measured from the precise geodetic observation in the area. These strain data are used to assess the seismic hazard from faults including obscure and blind faults. However, the time predictable model is applied to estimate the seismic hazard from the subduction earthquake along Sagami trough, because the seismic gap is particularly important to estimate the probability of the earthquake occurrence.

TECTONIC SETTING IN SAGAMI AREA

In Sagami area the Philippine Sea Plate subducting beneath the Japanese Islands is colliding with the Pacific plate at the depth of 50km to 80km as shown in Fig. 1 and Fig. 2. Complexities in tectonics in and around the Sagami area are caused by the convergence of three lithospheric plates. These are the Pacific, the Eurasian and the Philippine plate. A reverse fault with the horizontal E-W compression is predominant for subduction earthquakes in the Pacific side, and it is directly related to the convergence of the Pacific Plate underneath the Eurasian Plate. Most of earthquakes in this region are thrust events at a angle of of about 30° The earthquake occurred inside a boundary layer with a thickness of about 50km. The epicenters and magnitudes of the historical large earthquakes in the Sagami area are shown in Fig.3. The source areas of the 1605,1703,1923, and 1953 earthquakes in and around Sagami area are also shown in Fig.3. Fig.4 shows the location of active faults in and around Sagami area. In this study the seismic hazard ion Sagami area is estimated

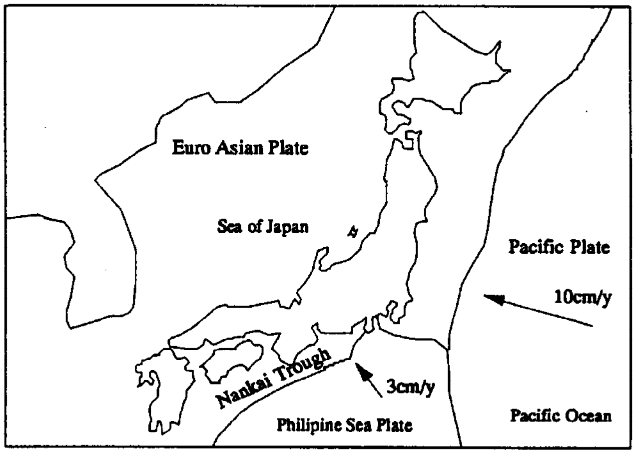


Fig 1 Tectonic setting around Sagami area and The slip velocity in Pacific and Philippine Sea Plate

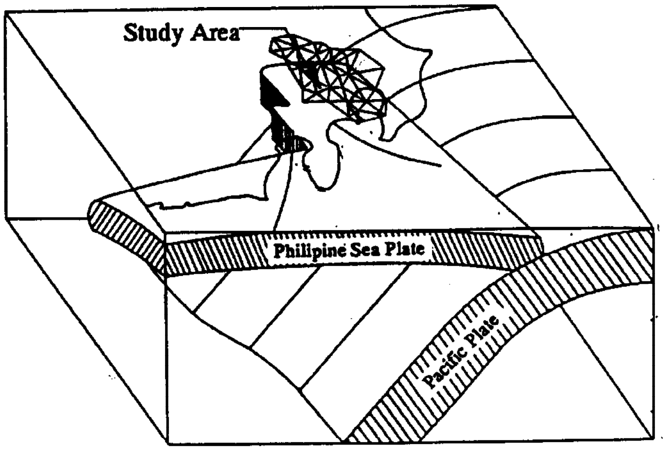


Fig 2 The section of the subduction zone along the Sagami trough

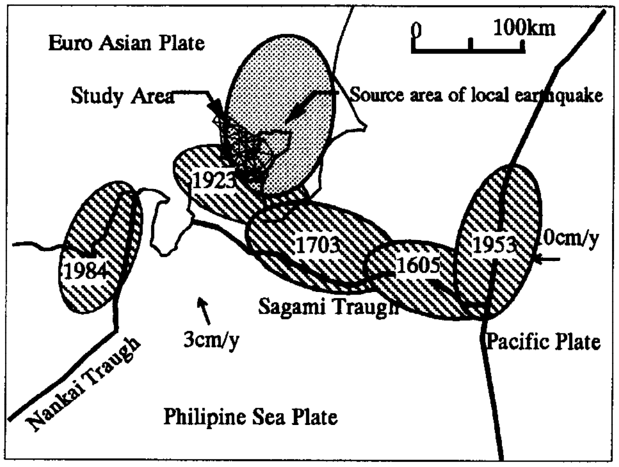


Fig 3 Location of historical earthquakes in Sagami area and source area of local earthquakes

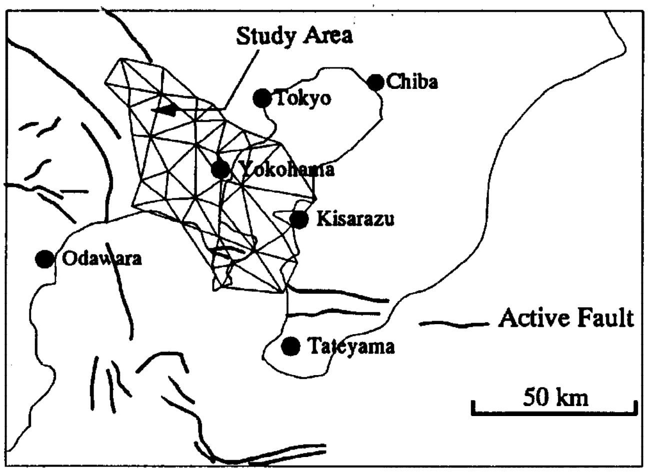


Fig 4 Location of active faults in Sagami area and and the small earthquakes

It is important to observe the crystal strain accumulation processes because earthquakes are sudden mechanical failures caused by the gradual strain accumulation. Many techniques have been developed to measure horizontal and vertical strains in time and space. These techniques are useful for the long and short term earthquake prediction. The geodetic survey has been operated to predict earthquake occurrences since 1883 in Japan. The levering survey also has been operated since 1870. The triangulation method has been used to measure changes in length between survey lines.

In the last several decades space geodetic techniques have been developed to study the development of strain in plate boundaries where most destructive earthquakes occur. Three principal techniques of the space geodesy include very long baseline interferometer (VLBI), Satellite Laser Ranging (SLR) and Global Positioning System (GPS) .

The satellite laser ranging (SLR) uses short pulses of light from lasers at a network of ground-based stations toward reflectors on the surface of a satellite. Relative station locations can be determined by the precise time of the round-trip travel of the pulses and knowledge of the orbit. The other technique, very long baseline interferometer (VLBI), uses stations equipped with radio antennas to observe a fixed celestial radio source. As the earth rotates, the varying signals received at the stations can be electronically corrected to determine the delays in arrival times and thus the relative station positions. The concept of the space geodesy by GPS is shown in Fig 5 schematically.(Kato 1991)

In the 1970s the space-based geodetic technique enables to measure of relative horizontal and vertical position changes of earth stations separated by thousands of kilometers with an accuracy of a few centimeters. The results of these large-scale measurements have largely confirmed our knowledge of plate motions during the past several million years derived from earth-based measurement, and may provide rapid and frequent monitoring of the strain field over a large region.

A more recently developed technique, the global positioning system (GPS) uses orbiting transponders as signal sources and smaller portable receiver systems on the ground. The the global positioning system technique can measure distances over baselines of 150km or less with an accuracy of about 1 cm. This technique is frequently used to monitor movements in a complex region with many blocks and faults by frequent measurements over a dense network of station. Of the three space geodesy techniques available to the earthquake prediction, GPS geodesy appears to be the most useful in terms of surveying speed, density and cost.(King 1989)

The global positioning system was first used to measure tectonic strains in California in 1986. This satellite system, originally for the military navigation, now allows extremely accurate and cost effective geodetic measurements. There is no need for line of sight observations between a site and a site and no limitation on

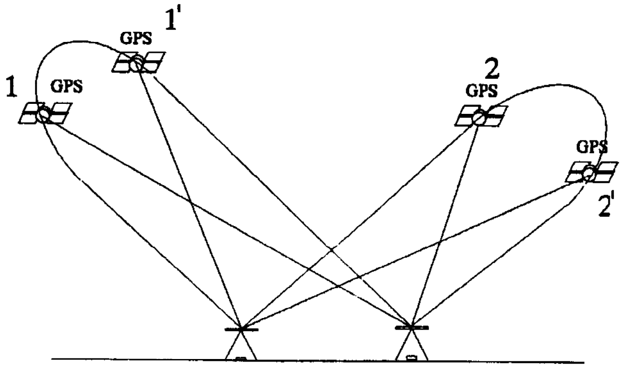


Fig 5 Concept of the space geodesy by GPS

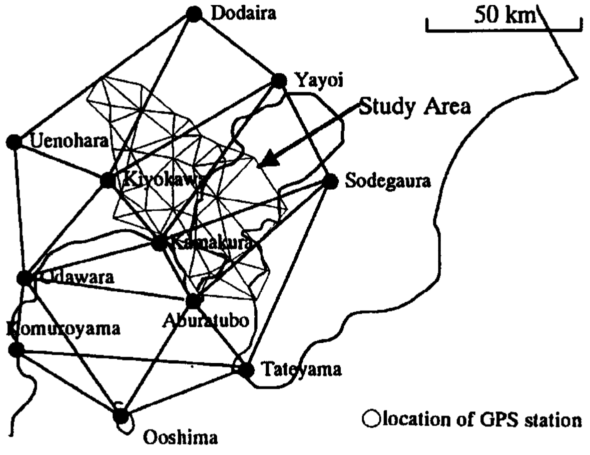


Fig 6 Location of GPS station in Sagami area

baseline length. The global positioning system network, which consists of 110 stations in Kanto and Tokai area has been operated since 1994. The GPS network in and around the Sagami area is shown in Fig.6. In this study the stress accumulation rate obtained by the triangulation and the slip accumulation rate obtained by GPS survey are used to estimate the probabilities of earthquake occurrences in the subduction zone.

METHOD FOR THE EARTHQUAKE PREDICTION

The geographic distribution of earthquake potential is one of the best representation in terms of the seismic moment accumulation rate in unit area. If the crystal strain in a region is purely elastic within an upper brittle layer of thickness H and purely inelastic below that depth, then strain in the layer can be estimated by the accumulation of seismic moments. The accumulation of the seismic moment in the area can be obtained by the equation 1

$$Mj^{box} = 2 \mu HA \varepsilon^{box} = \mu HAs^{box} \qquad (1)$$

where M is the rate of seismic moment accumulation. A is the area of the region and H is the seismogenic thickness. μ is the average rigidity of the crust. ε and s are strain and slip rate in the area respectively. With the seismic moment rate per box Mj^{box}, the recurrence interval for an earthquake larger than M is computed. The recurrence interval for earthquakes larger than M < Mmax is obtained by the equation 2.(Ward 1994)

$$Tj = [bj /1.5+bj] [10^{(1.5+b)Mj+9.05}]/Mj[10^{bMmax}-10^{bM}] \qquad (2)$$

In the next step, the acceleration level in jth box is computed by the empirical attenuation relationships, when an earthquake occurs in the kth box . In our analysis, segments are considered as separate earthquake sources. With the assumption of spatial independence of segments, the composite probability of exceedence of the acceleration levels in X site is computed by the following equation.

$$Pt = 1.0 - \pi_{i=1}^{N} (1.0 - p_i) \qquad (3)$$

where Pt is the probability of exceedence of a given acceleration level, when an earthquake occurs in box 1 to N. The probability p_i is the probability of exceedence of the acceleration level, when an earthquake occurs in segment i.

APPLICATION OF THE HAZARD MODEL

The seismic hazard model is applied to the Sagami area in Japan to estimate probabilities of earthquake occurrences and the probabilities of exceeding accelerations in the specified area.

In order to estimate the spacial seismic hazard distribution in the Sagami area by the model, the area is divided into 49 boxes in accordance with the geodetic observation data. The box map of Sagami area is shown in Fig. 7. The strain accumulation rate ε^{box} in Sagami area has been observed since 1925. The strain accumulation between 1990 and 1925 obtained by the geodetic observations is shown in Fig.8. (Report of the coordinating committee for earthquake prediction 1991). In this study the seismic moment accumulation rate between 1984 and 1990 is used to estimate the strain accumulation rate after eliminating strain changes due to local earthquakes. The strain change between 1990 and 1984 in the area are shown in Fig.9. The accumulation of the seismic moment is estimated by the equation 1 based on the geodetic observation. Then the seismic moment accumulation rates are obtained by the equation 1.

Probabilities of Small earthquake occurrences

In the first step the return period of small earthquakes, whose sizes are greater than or equal to magnitude 5.0 are obtained from the equation (2) based on the geodetic data. The return periods of the small earthquake for each box are shown in Fig.10.

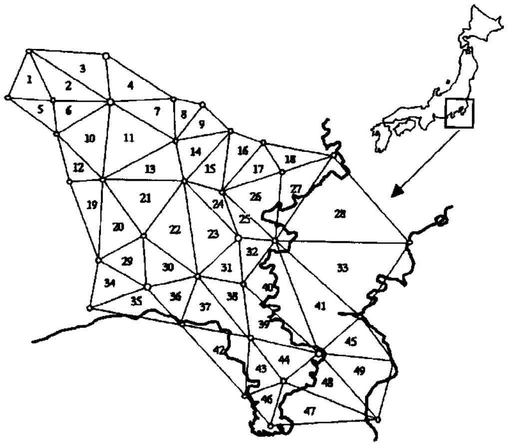


Fig. 7 Box map in Sagami area based on the geodetic survey area

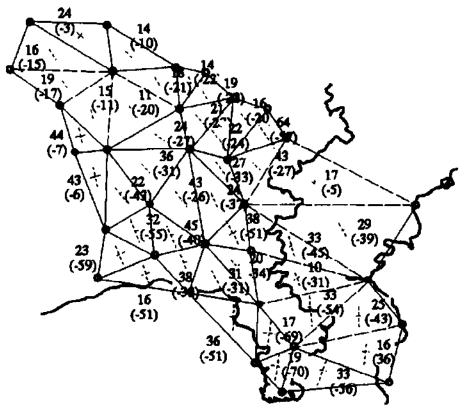


Fig. 8 Distribution of the strain accumulation level in Sagami between 1990 and 1925

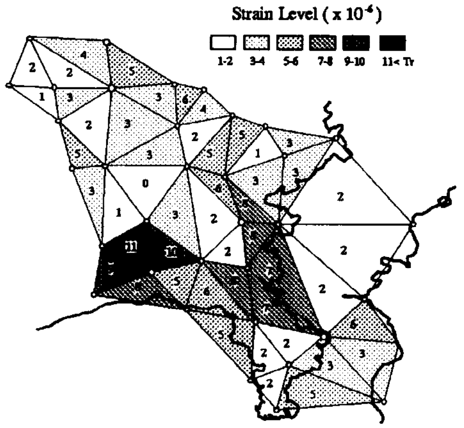


Fig. 9 Distribution of the strain acceleration level in each box

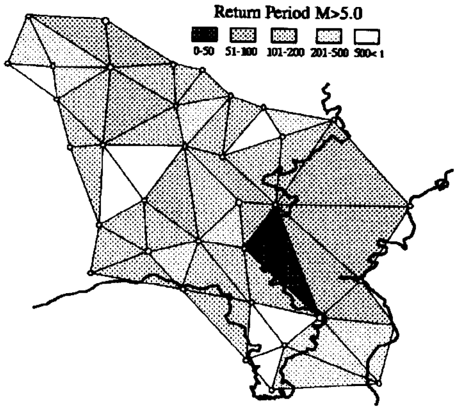


Fig. 10 The return periods of small earthquakes for each box.

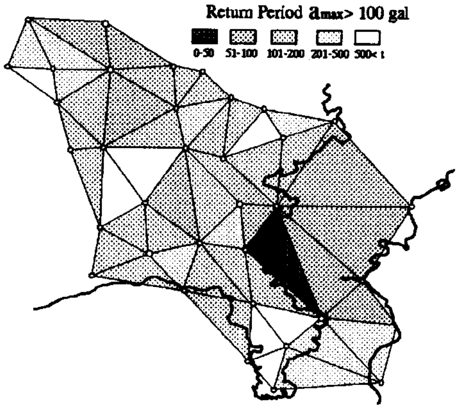


Fig. 11 The return period of exceeding the peak ground acceleration greater than 100gal for each box

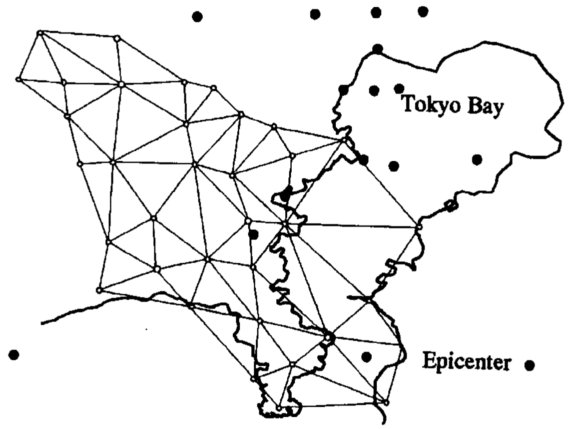


Fig. 12 Location of earthquakes directly under the metropolitan area

The probabilities of exceeding the peak ground acceleration of 0.1g due to small earthquakes are also estimated by the Poisson model and the empirical attenuation relationships. The probabilities of exceeding the peak groundacceleration of 0.1g are estimated by the Poisson model and the empirical attenuation relationships. The equation (4) is used to estimate the probabilities of exceedence of 0.1g. The results are shown in Fig.11.

Probabilities of the earthquake occurring directly underneath metropolitan area

In the next step the probabilities of the earthquake occurring directly underneath metropolitan area are estimated based on the geodetic data, because Sagami area are expected to have severe damage by this type of earthquakes. The size of earthquakes in the bay area are between 6.0 and 7.5. The locations of this type of earthquakes are shown in Fig.12. Based on the source region of this type of earthquakes, the source region of the earthquake in Sagami area is divided into 3 blocks based on the rupture size of the earthquake as shown in Fig.13. The return period in each region is estimated to be about 300 to 370 years for all three blocks. The return periods of the earthquake occurrence in the three blocks are shown in Fig.13. The return periods of exceeding the peak ground acceleration of 0.1g and 0.2g in a rock site are estimated and results are shown in Fig.14.

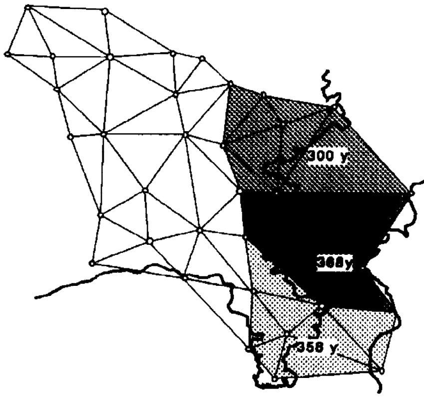


Fig. 13 Source area of earthquakes directly under the metropolitan area.

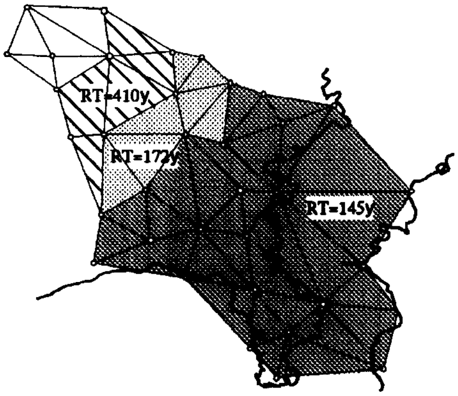


Fig. 14 Return periods of exceeding the PGA greater than 100 gal by the earthquake.

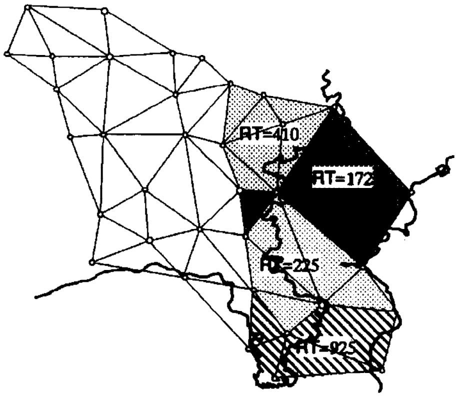


Fig. 15 The return period of exceeding the peak ground acceleration < 200gal by three type of eqs

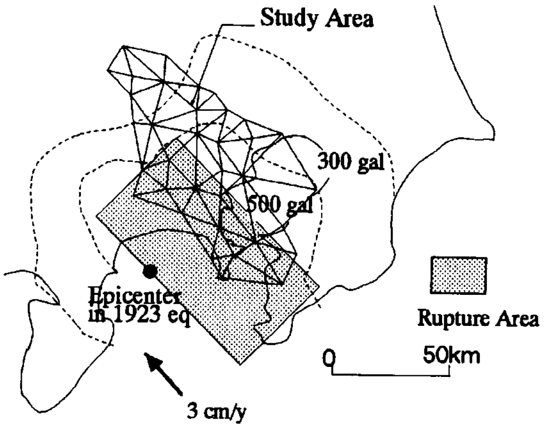


Fig. 16 The rupture area of 1923 Kanto Earthquake and the distribution of the acceleration

In the next step the return periods of exceeding the peak ground acceleration greater than 100gal and 200gal is estimated from earthquakes directly under the metropolitan area. The results are shown in Fig.15. and 16.

Probabilities of the subduction earthquake occurrences

In the last step the return period of subduction earthquakes in the Sagami bay area is estimated. For the subduction earthquakes along the Sagami Trough, Shimazaki and Nakata (1980) investigate the recurrence of large thrust fault earthquakes. Both historical and geomorphological data in the area indicate a dependence between successive earthquakes and event size. Therefore, time predictable model is applied to estimate the probabilities of earthquake occurrences along the Sagan trough. The holding time T is determined by the equation (3) based on the annual slip rate and the slip length /

$$T = D / d \qquad (3)$$

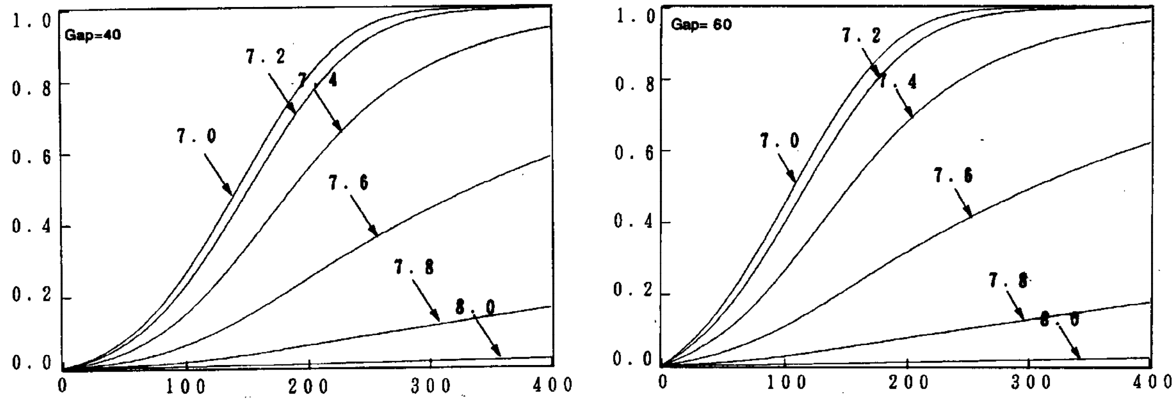
where D is the displacement of the fault plane and d is slip velocity in the subduction zone. The displacements are estimated the empirical relationships between the size of earthquake and the length of the displacement..(Sato 1965)

$$\log Ms = 1.5\,M + 16.2 \qquad (4)$$
$$\log D = 0.5\,M - 1.40 \qquad (5)$$

The holding time of subduction earthquakes is estimated by equation 3 and the results are shown in Table 2.

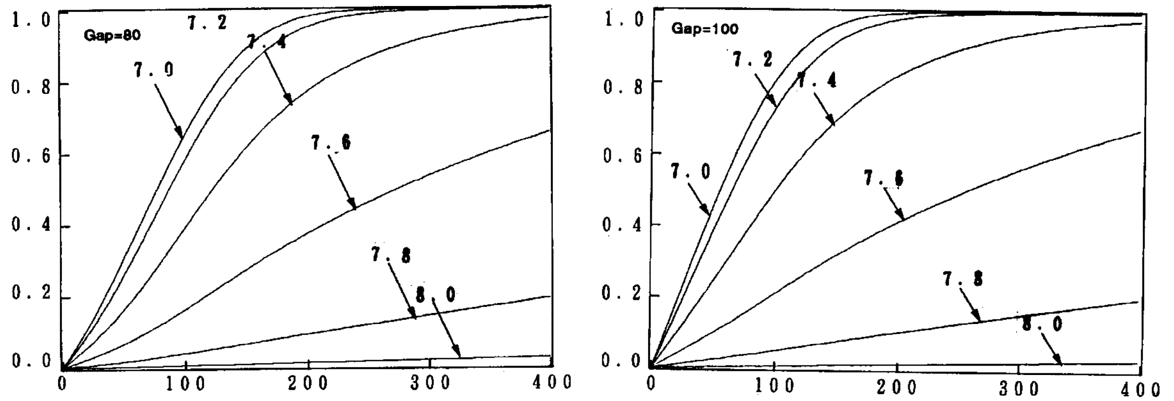
Table 2 Holding times of subduction earthquakes estimated by GPS observation in years

Magnitude	M=7.2	M=7.4	M=7.6	M=7.8	M=8.0
Return Period	160	200	250	320	400



(a)Seismic gap is 40 year

(b)Seismic gap is 60 year



(a)Seismic gap is 40 year

(b)Seismic gap is 60 year

Fig.10 The probabilities of earthquake occurrences in the subduction zone as a function of seismic gaps

The annual slip rate in this area is estimated to be 3 cm /year based on the geodetic observation by GPS. The return period of the subduction earthquakes are estimated based on the geodetic observation by GPS. The return periods are tabulated in Table 2 depending on the the size of the last earthquake. The slip velocity obtained by the GPS observation in Sagami area is shown in Fig.14. The same velocity is obtained by the precise geodetic measurement. The holding times of the subduction earthquake based on the GPS data are summarized in Table 2.

The stochastic time predictable model is applied to the Kanto-earthquake area, where data suggested time-predictable behaviors. The probabilities of at least one event of magnitude greater than or equal to 7 are estimated as a function the gap time.The holding time of Kanto earthquake is also determined by the GPS observation data for the time predictable model. The result is shown in Fig.15 depending on the gap length. The empirical attenuation relationship is used to obtain ground motions at a site. The fifty-year probabilities of exceeding accelerations of 0.2g from earthquake M>6 are obtained. It is found that the seismic gap is particularly important to estimate the probabilities of earthquake occurrences in the subduction earthquakes.The results also indicate that the expected peak ground acceleration strongly depend on the seismic gap and strain accumulation rate in the study area.

Conclusion

This paper presents an improved stochastic site hazard model based on the multidisplinary approach and the stochastic time predictable model. The seismic hazard model is developed by combining the multidisplinary model and time predictable model. The model is applied to Sagami area in Kanagawa prefecture,Japan.. The results indicate that the multidisplinary information to seismic hazard can be used to estimate the seismic hazard estimation in the area where an unknown active faults are distributed in space.

References

Chi Yu King (1989) Earthquake prediction techniques, Encyclopedia of the earthsystem science,vol.2

Dixon T.H.(1991) An introduction to the global positioning system and some geological application Reviews of Geophysics,29, May 1991

Hashimoto M.(1990) Horizontal strain rates in the Japanese Islands during interseismic period deduced from geodetic surveys (part I) Honshu,Shikoku and Kyushu Jishin No.43

Hydrographic Department Maritime Safety Agency (1995) GPS Observations around Sagami Bay area (February 1990 to May 1995)

Kato T. (1991) Recent developments in earthquake studies and global dynamics based on the crystal deformation studied Jishin vol.44 1991

Kiremidjian A. and S. Suzuki (1987) A stochastic model for site ground motions BSSA vol. 77 No4 1987.8

Bihilman R.

Report of the coordinating committee for earthquake prediction vol.46 1991

Shimazaki.K and T. Nakata (1980) Time-predictable recurrence for large earthquakes Geoph. Res. Lett. 7

Shimada S and Y.Bock (1992) Crustal deformation measurements in central Japan determined by a Global Positioning System fixed point network

Suzuki S and A.Kiremidjian(1991) A random slip predictable model for earthquake occurrences with Baysian parameters BSSA vol.81 No3.1991.6

Ward S.N. (1994) Multidisplinary approach to seismic hazard in southern Ca. BSSA vol.84 No5 1994.10