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ESTIMATION OF PEAK ACCELERATIONS AND RESPONSE SPECTRA ON ROCK FOR THE 1995 HYOGOKEN-NANBU EARTHQUAKE, JAPAN

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ABSTRACT

An attenuation relation of response spectra to magnitude, source-to-site distance, and soil classification is obtained by performing regression analysis on strong-motion records of California earthquakes. The attenuation relation is applied to the 1995 Hyogoken-Nanbu earthquake, and it is found that the estimates for pre-Quaternary sites agree well with the observed values. Peak ground accelerations on the pre-Quaternary stratum are estimated as about 350 cm/s^2 at Kobe and 750 cm/s^2 at Awaji Island. Amplification factors of Quaternary stratum during the Hyogoken-Nanbu earthquake are estimated by taking ratios between observation records from Quaternary sites and estimates for sites on the pre-Quaternary stratum. As the estimated amplifications at the observation sites in the heavily damaged area are large at around the natural period of a wooden house (0.4-0.5 seconds), such short-period amplifications might be one reason Kobe suffered extensive damage.

KEYWORDS

Attenuation Relation; Near-Field; Hyogoken-Nanbu earthquake; Soil Amplification

INTRODUCTION

Many researchers have modeled strong-motion spectra by attenuation formula as a function of magnitude M, source-to-site distance X, soil classification, etc., and have estimated coefficients by performing regression analyses on observation data. Major advantages of this empirical estimation are: 1) the number of parameters is small; 2) the method can be applied to almost any location; and 3) the results are stable (variance is small) despite the small number of parameters. On the other hand, this method has some disadvantages: 1) it cannot be used to predict complicated site-dependent phenomena such as the effects of local topography; and 2) when it is applied beyond the data range (*e.g.*, for the near-source region), the validity of the results decreases because the regression coefficients are determined empirically and are strongly dependent on the data distribution.

Recently, to overcome the latter problem, the form of the attenuation formula has been investigated from a physical point of view (Takemura *et al.*, 1987) and the validity of the method for estimating regression coefficients has been discussed (Joyner and Boore, 1993). However, the problem of evaluating the effect of fault size in the near-source region has not been solved. Although the shortest distance from a fault to an observation site X_{sh} (often termed fault distance) has been most commonly used as source-to-site distance X for the near-source region, this is considered unreasonable because strong motions in the near-source region are influenced not only from the nearest point but also from other points on the fault plane. To solve this problem, a new distance measure Equivalent Hypocentral Distance (X_{eq}) was proposed. X_{eq} is derived from the short-period approximation of the energy spectrum of strong motion based on the fault model theory (Ohno *et al.*, 1993).

In this paper, first an attenuation relation of response spectra is evaluated by regression analysis on strong-motion records from California, which include many near-source data. Second, the evaluated attenuation relation is applied to the 1995 Hyogoken-Nanbu earthquake in order to estimate the regional distribution of strong motion on the pre-Quaternary stratum. Third, the amplifications of ground motion due to the Quaternary stratum are estimated by comparing observation records on the Quaternary stratum with estimates on the pre-Quaternary stratum. The relation between the amplification of ground motion on the Quaternary stratum and the severe earthquake damage in and around Kobe is also discussed.

ATTENUATION RELATION OF ACCELERATION RESPONSE SPECTRA

Equivalent Hypocentral Distance

Equivalent Hypocentral Distance X_{eq} is derived from short-period approximation of the energy spectrum of strong motion based on the fault model theory by Ohno *et al.* (1993). X_{eq} is calculated using the following formula:

$$X_{eq}^{-2} = \sum_{i=1}^{n} M_{oi}^{2} X_{i}^{-2} \Big/ \sum_{i=1}^{n} M_{oi}^{2}, \tag{1}$$

where n is number of segments on the earthquake fault plane, M_{oi} is seismic moment density on the i-th segment and X_i is the distance between the i-th segment and the site. X_{eq} can take into account the effects of fault size, fault geometry, and inhomogeneous slip distribution on the fault plane. X_{eq} is hypocentral distance from a (virtual) point source that provides the same energy to the site as does a finite-size fault, which can be used in evaluating a near-source strong-motion spectrum without changing the form of the attenuation formula based on the point source theory.

Table 1. List of earthquakes with number of components used in this analysis

No.	Earthquake Name	Origin Time (UTC)	Magnitude	Slip on the Fault for Calculating Xeq	Number of Comp. pre-Q.*	Q.*
1	Imperial Valley	05/19/1940	Mw=7.0	Uniform	0	2
2	Kern County	07/21/1952	Mw=7.5	Uniform	0	2
3	San Francisco	03/22/1957	ML=5.3	(hypocentral distance used)	2	0
4	Parkfield	06/28/1966	Mw=6.1	Uniform	2	7
5	Borrego Mountain	04/09/1968	Mw=6.5	Uniform	0	2
6	Lytle Creek	09/12/1970	Mw=5.3	(hypocentral distance used)	4	2
7	San Fernando	02/09/1971	Mw=6.6	Nonuniform	16	14
8	Hollister	11/28/1974	ML=5.2	(hypocentral distance used)	2	4
9	Coyote Lake	08/06/1979	Mw=5.8	Nonuniform	4	12
10	Imperial Valley	10/15/1979	Mw=6.5	Nonuniform	2	46
11	Imperial Valley	10/15/1979	ML=5.0	(hypocentral distance used)	0	32
12	Coalinga	05/02/1983	Mw=6.4	Uniform	46	50
13	Morgan Hill	04/24/1984	Mw=6.2	Nonuniform	12	22
14	North Palm Springs	07/08/1986	Mw=6.1	Nonuniform	10	24
15	Whitter Narrows	10/01/1987	Mw=6.0	Nonuniform	12	59
16	Loma Prieta	10/18/1989	Mw=7.0	Nonuniform	42	42
17	Landers	06/28/1992	Mw=7.3	Uniform	6	16
				Total	160	336

* pre-Q.: pre-Quaternary, Q.: Quaternary.

Data

The data used in estimating the attenuation relation comprise 496 horizontal components of strong-motion records from 17 California earthquakes which occurred from 1940 to 1992. Table 1 lists the earthquakes and the number of components for each earthquake. Moment magnitude M_w is used for earthquake magnitude M, but local magnitude M_L is used if M_w is not estimated. For each record, the portion after the initial S-wave arrival is used for calculating response spectrum. X_{eq} for each record is calculated using the slip distribution of the fault model, on the assumption that M_{oi} is proportional to slip on the i-th segment (Ohno *et al.*, 1993). The fault models used in calculating X_{eq} are listed in Ohno *et al.* (1995). When the slip distribution is not estimated, uniform distribution is assumed. For the small earthquakes (Nos. 3, 6, 8 and 11), hypocentral distance is used because the event is small enough to be treated as a point source. Magnitude M ranges from 5.0 to 7.5, and X_{eq} ranges from 7 to 100 km (fault distance X_{sh} from 0.4 to 90 km). Figure 1 shows M-X_{sh} and M-X_{eq} distributions of the data.

The sites are classified as pre-Quaternary or Quaternary stratum by the classification scheme shown in the upper part of Table 2, based on descriptions of site geology in CDMG and USGS reports. There are 160 pre-Quaternary and 336 Quaternary sites. Sites with very soft soil such as bay mud or artificial fill were excluded because the number of records was small and ground motions at such sites might have been strongly affected by soil nonlinearity. Figure 2 is a histogram of S-wave velocities (V_s) of the sites where the seismic surveys were performed. The velocity of underlying rock is used for pre-Quaternary sites with a shallow surface Quaternary layer. S-wave velocities at pre-Quaternary sites are distributed above 600 m/s.

Table 2 Site classification schemes for observation stations

Data	Classification	Description of geology
California data	Pre-Quaternary	• Rock (sandstone, siltstone, shale, granite, mudstone, etc.) • Thickness of surface soil overlying rock is less than 10 m. • Shallow soil or thin alluvium
	Quaternary	• Soil (alluvium, clay, sand, silt, loam, gravel, etc.)
	(Very soft soil)	• Bay mud or artificial fill (not used for analysis)
Hyogoken Nanbu earthquake data	Pre-Quaternary	• Rock- granite, sandstone • Tertiary or older in geologic map
	Diluvium	• Diluvium • Pleistocene in geologic map
	Alluvium	• Alluvium; Silt, sand, gravel, etc. • Holocene alluvium in geological map

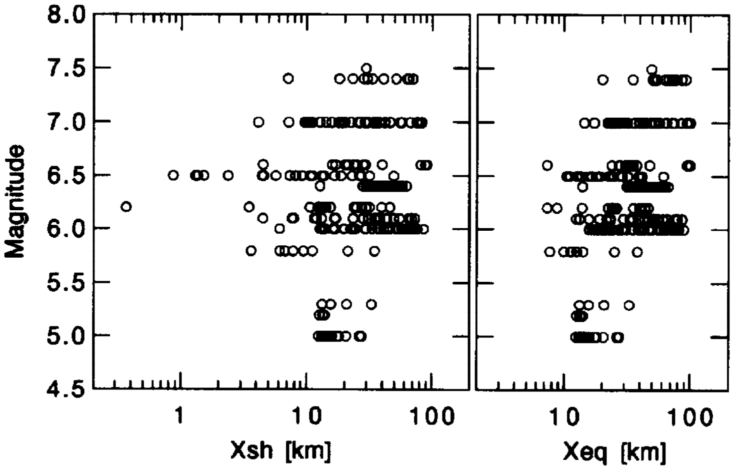

Fig. 1 Relationships between magnitude and distance of the California data.

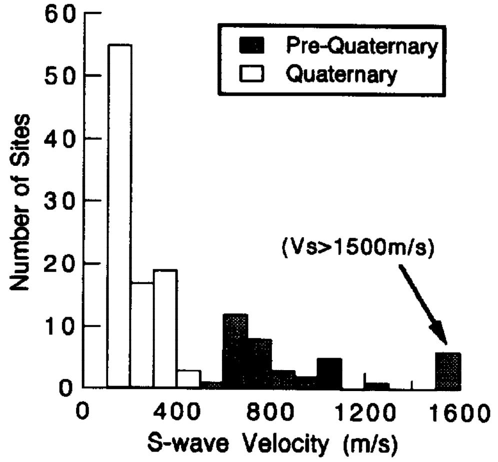

Fig. 2 Distribution of S-wave velocities of the California data.

Regression Analysis

Following the random-effects model of Joyner and Boore (1993), we modeled 5%-damping acceleration response spectrum $S(T)$ as:

$$\log S(T) = a(T)M - \log X_{eq} - b(T)X_{eq} + c(T) + k\Delta s(T) + \varepsilon_R(T) + \varepsilon_E(T) \tag{2}$$

where T is period, M is magnitude, k is a dummy variable to stratify the site as pre-Quaternary or Quaternary (value of 0 or 1, respectively), and $\varepsilon_R(T)$ and $\varepsilon_E(T)$ are Gaussian random variables whose averages are 0 and variances are σ_R^2 and σ_E^2, independent of record and earthquake, respectively. The variance of the estimated attenuation relation is calculated as $\sigma_R^2 + \sigma_E^2$. The coefficients $a(T)$, $b(T)$, $c(T)$, $\Delta s(T)$, σ_R^2, and σ_E^2 were estimated using the maximum likelihood two-stage regression procedure (Joyner and Boore, 1993) at periods from 0.02 to 2.0 seconds. The estimated regression coefficients are shown in Fig. 3.

$b(T)$ is related to the Q-value Q_s along the source-to-site propagation path of S-waves by the relation: $b(T) = \pi[\ln(10)\cdot T\cdot V_s\cdot Q_s(T)]^{-1}$ (Takemura *et al.* 1987). The broken line in the chart of $b(T)$ in Fig. 3 is the value of $b(T)$ calculated from Q_s in California obtained by Chin and Aki (1991) where V_s=3.5 km/s. This value approximately agrees with the regression coefficient of $b(T)$.

Peak ground acceleration A_{max} on the pre-Quaternary stratum is estimated as

$$\log A_{max} = 0.318M_w - \log X_{eq} - 0.00164X_{eq} + 1.597, \tag{3}$$

from the attenuation relation of 5%-damping response spectrum at a period of 0.02 second as an approximation of A_{max}. Hanks and McGuire (1981) derived the moment magnitude dependency of peak ground acceleration as $\log A_{max} \propto 0.31M_w$ based on the random vibration theory with the ω-square source model, and equation (3) is consistent with this. The estimated $\Delta s(T)$ indicates that only waves of periods longer than 0.2 seconds are amplified at Quaternary sites. This agrees with other estimates of the attenuation relation from California records. This phenomena probably occurs because attenuation of surface soil at short periods cancels amplification due to the impedance ratio between surface soil and underlying rock.

This attenuation relation is applied to records of the Hyogoken-Nanbu earthquake in order to investigate the strong-motion characteristics of the earthquake, because both the California and Hyogoken-Nanbu earthquakes were shallow inland earthquakes.

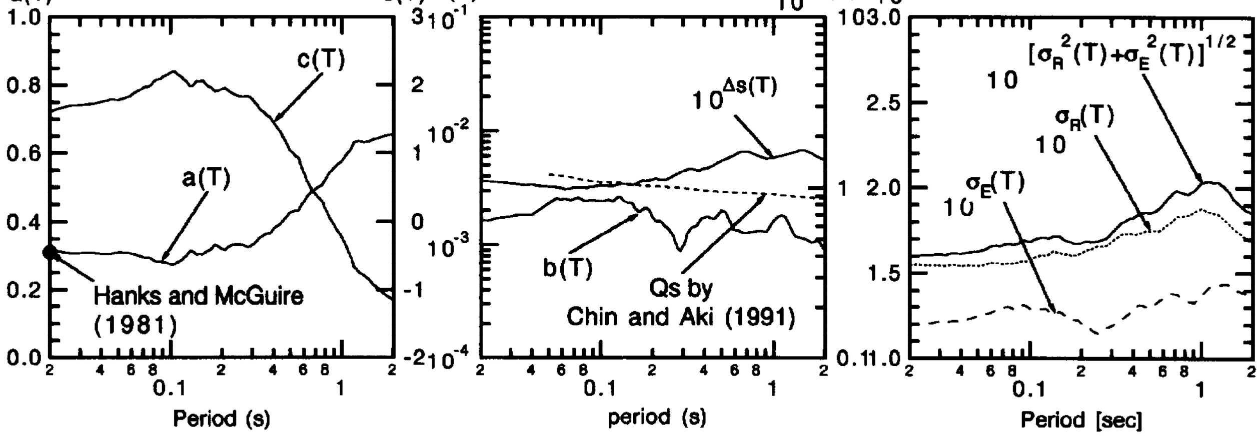

Fig. 3 Estimated regression coefficients

STRONG-MOTION CHARACTERISTICS OF THE HYOGOKEN-NANBU EARTHQUAKE

Source Process, Geology, and Observation Records

The Hyogoken-Nanbu earthquake, M_w=6.9, occurred on January 17, 1995. The location of the epicenter was estimated by the Japan Meteorological Agency to be at the northern edge of Awaji Island (34.6°N, 135.1°E), and the focal depth to be 14 km. The length and depth of the aftershock distribution were approximately 50 to 60 km and up to 20 km, respectively (DPRI, Kyoto University).

Many researchers have estimated the source process of the 1995 Hyogoken-Nanbu earthquake using the inversion method on seismic and/or geodetic records. Common features of the estimated source process are summarized as follows: 1) The rupture started from the hypocenter and propagated in NE and SW directions bilaterally. The duration of the main rupture was less than 10 seconds. 2) There were two regions of large slippage: one was shallow (0 to 5 km) on the Awaji Island side, and the other was deep (10 to 15 km) near the hypocenter on the Kobe side. 3) The slip vector over the fault plane indicates that right-lateral strike slip was predominant, which is consistent with the source mechanism estimated from initial P-wave motions. There were some dip-slip components on the Kobe side near the hypocenter.

The topography and geology of the Kobe area are consequences of activity of the Rokko fault system. The area can be broadly divided into two regions: the Rokko mountains, and the lowlands which is to the south of the mountains. Granite is widely distributed in the Rokko mountains. The lowlands can be topographically

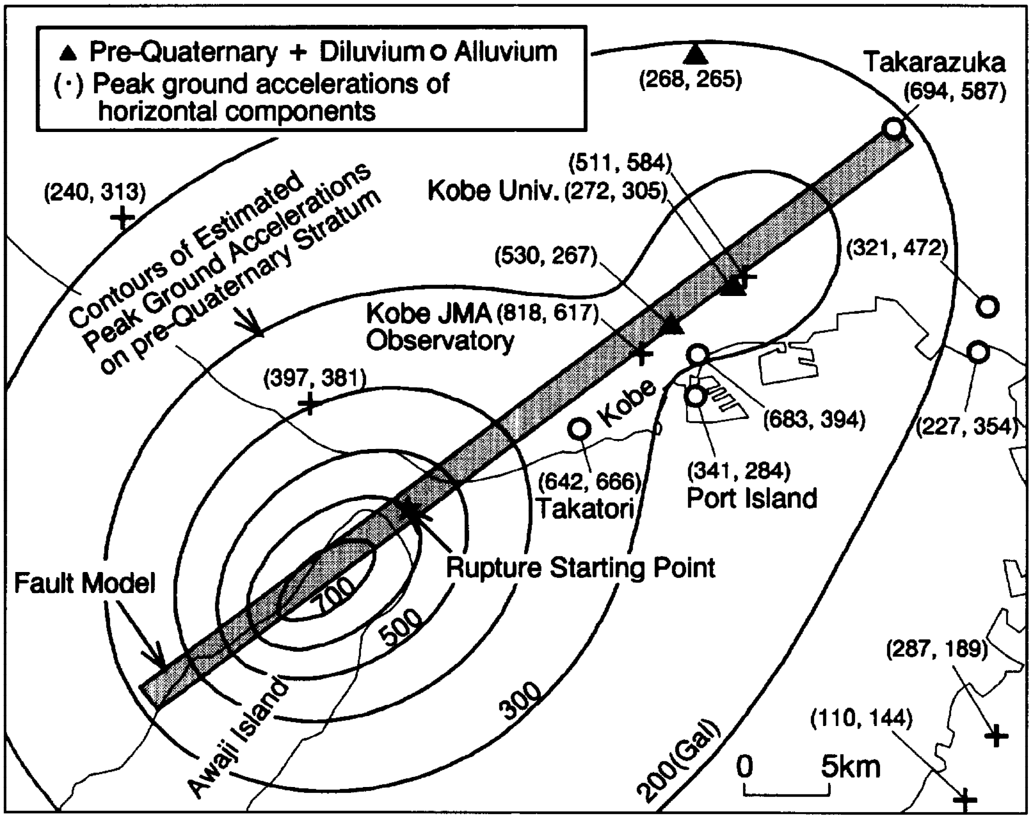

Fig. 4 Contours of the estimated peak ground accelerations on pre-Quaternary stratum.
Surface projection of the Hyogoken-Nanbu earthquake fault model of Kakehi et al. (1995); location of the strong-motion stations are also plotted.

divided into alluvial fans, seaside lowlands, and reclaimed land. These areas correspond geologically to fluvial sediments, alluvial plains (sandy soil at near surface), and soft and thick clay layers, respectively (Kobe City, 1985). The region which suffered severe damage is approximately coincident with the area of alluvial fans and seaside lowlands (Takemura and Tsuji, 1995). Damage was relatively light in the Rokko mountains and on the reclaimed land.

Many organizations observed strong-motion records of the Hyogoken-Nanbu earthquake. Figure 4 shows observation sites located near the epicenter. The observation sites are classified as pre-Quaternary, diluvium or alluvium according to the classification scheme shown in lower part of Table 2. Comparing the classification schemes in Table 2, the definitions of California and Hyogoken-Nanbu earthquake pre-Quaternary sites are nearly equivalent. Almost all diluvial and alluvial sites in the Hyogoken-Nanbu earthquake records correspond to Quaternary sites in the California data, except sites on reclaimed land. As mentioned above, records from sites on reclaimed land were excluded from the California data. The Hyogoken-Nanbu earthquake data includes records from sites on reclaimed land as alluvium sites.

Strong Ground Motions on the pre-Quaternary Stratum

Kakehi *et al.* (1995) obtained a distribution of acceleration radiation intensity w_i, which indicates the relative contribution of the i-th segment of the fault plane to the amplitude of the acceleration envelope. We calculated X_{eq} by substituting w_i for M_{oi} in equation (1) and estimated peak ground accelerations on the pre-Quaternary stratum using equation (3) with M_w=6.9. Figure 4 shows contours of the estimated peak ground accelerations together with a surface projection of the fault model. Because energy did not radiate homogeneously on the fault plane, there were two areas of large acceleration: one on Awaji Island and the other in Kobe. The estimated maximum for Awaji Island is about 750 cm/s^2, which is much larger than the estimated maximum for Kobe of about 350 cm/s^2.

Figure 5 shows the relation between observed peak ground accelerations and X_{eq}, together with curves indicating the estimates for the pre-Quaternary stratum and the estimates plus and minus the standard

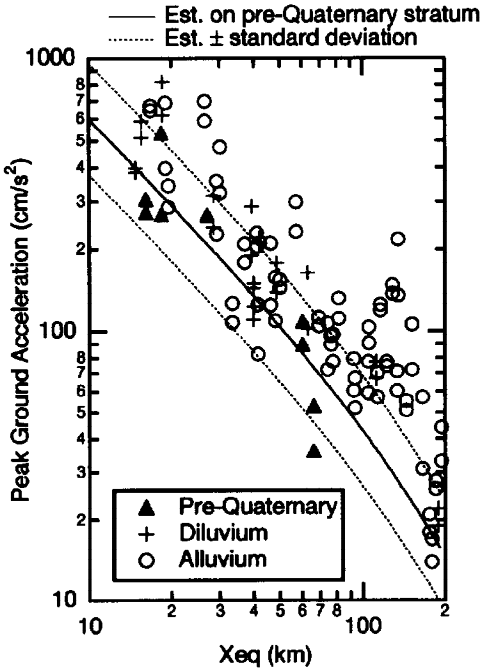

Fig. 5 Peak ground accelerations versus Xeq

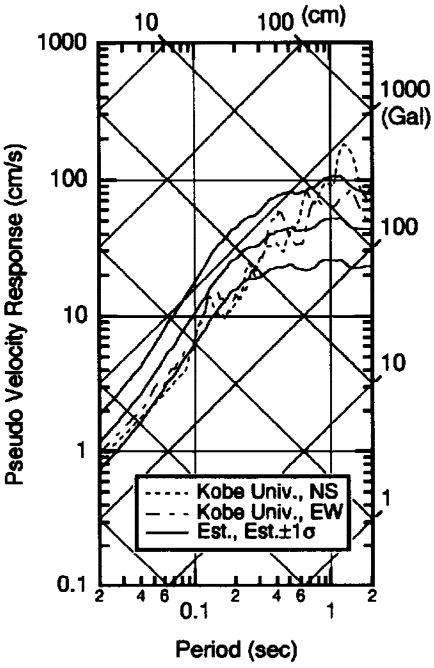

Fig. 6 Observed and estimated acceleration response spectra for the Kobe University site

deviation ($\sqrt{\sigma_R^2+\sigma_E^2}$). The values observed at the pre-Quaternary sites are within the range of the standard deviation. The values observed at the diluvial and the alluvial sites are 1.4 and 1.8 times larger, respectively on the average, than the estimates for the pre-Quaternary stratum, although the values observed at the alluvial sites vary widely. Figure 6 shows response spectra of the near-fault records of the Kobe University site together with the estimate for the pre-Quaternary stratum. The estimates agree with the observed values, as the observed values are generally within the range of the standard deviation. The results shown in Figs. 5 and 6 indicate that the amplitudes of incident waves on the pre-Quaternary stratum during the Hyogoken-Nanbu earthquake were similar to those in California earthquakes of M_w=6.9.

Amplifications on the Quaternary Stratum

Amplification factor for each observation site was calculated by taking a ratio between the observed response spectrum and the estimate for the pre-Quaternary stratum. Figure 7 shows the average amplification factors estimated for different site classifications. Similar to the peak ground accelerations shown in Fig. 5, the values observed at pre-Quaternary sites agree well with the estimates while the values observed at the diluvial and alluvial sites are consistently larger than the estimates. The estimated amplification factors for diluvial sites are not strongly dependent on frequency and are roughly 1.5 to 2. Amplification factors for alluvial sites are almost the same as those for diluvial sites for periods less than 0.5 seconds, but are larger for longer periods and reach approximately 5 for periods between 1 and 2 seconds.

Estimated amplification at each site is roughly consistent with average amplification for sites of that classification, although there are some exceptions such as Kobe JMA Observatory on diluvium and Port island, Takatori and Takarazuka on alluvium. The amplification factors at these sites are plotted in Fig. 7. The estimate for Kobe JMA Observatory is larger than the average for diluvial sites. As this site is located on the top of a hill, local topography may explain the large amplification. Tohdo (1995) calculated theoretical amplification including the effect of the hill, and Tohdo's result is similar to that of the present study. As for Port Island, estimated amplification is less than unity for short periods. This is probably due to large attenuation at short periods by the effects of soil nonlinearity, as observed in the vertical array records at this site (Kawase *et al.*, 1995). Takatori and Takarazuka are located in the heavily damaged area and the estimated amplifications at these sites are large not only for long periods of more than 1 second but also for shorter periods. Although it is difficult to investigate the cause of large amplifications at these sites because no soil data are available, the focussing effect due to the irregularity of basement (Motosaka and Nagano, 1995) might be one reason for Takatori. As the estimated amplifications at the observation sites in the heavily damaged area are large at around the natural period of a wooden house (0.4-0.5 seconds), such short-period amplifications might be one reason Kobe suffered extensive damage.

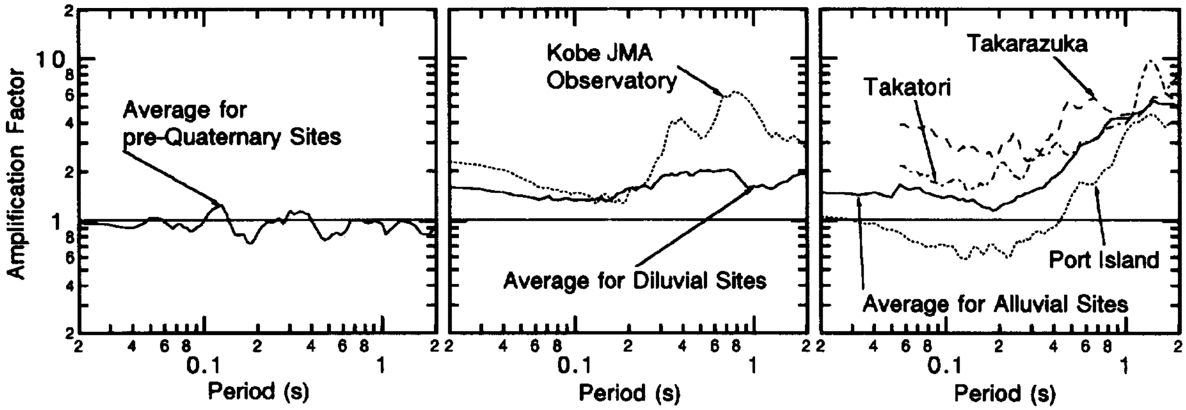

Fig. 7 Estimated site amplification factors (ratios between the observed and the estimated response spectra on the Quaternary stratum)

CONCLUSIONS

Amplitudes of incident waves on the pre-Quaternary stratum in the Hyogoken-Nanbu earthquake were similar to those of M_w=6.9 California earthquakes. Peak ground accelerations on the pre-Quaternary stratum are estimated as about 350 cm/s^2 in Kobe and about 750 cm/s^2 on Awaji Island. Strong motions at diluvial and alluvial sites were larger than those at pre-Quaternary sites. As the estimated amplifications at the observation sites in the heavily damaged area were large at around the natural period of a wooden house (0.4-0.5 seconds), such short-period amplifications might be one reason Kobe suffered extensive damage.

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