ATTENUATION RELATION OF RESPONSE SPECTRA IN JAPAN CONSIDERING SITE-SPECIFIC TERM

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SUMMARY

Since May 1996, the National Research Institute for Earth Science and Disaster Prevention (NIED) of the Science and Technology Agency, Japan has been operating a strong motion network that contains 1000 stations throughout in Japan. In this study to investigate the characteristics of the ground condition and site-specific response, attenuation relations of absolute acceleration and relative velocity response spectra for the thirty-five structural periods are developed, using accelerograms from Kyoshin Network (K-NET). The selected acceleration records consist of 6,017 three-component sets from 94 earthquakes, which recorded by K-NET95-type accelerometers at 823 free field sites in the period of May 1996 to December 1998. Using obtained regression coefficients for each structural period, the spectra of station coefficients and the site-specific response spectra for K-NET stations were presented. The predicted horizontal and vertical acceleration and velocity response spectra from the K-NET data were compared with those from JMA (Japan Meteorological Agency) data set that contains 3,990 records from 1,020 earthquakes recorded by JMA-87-type accelerometers at 77 stations.

INTRODUCTION

Earthquake strong ground motion indices such as peak ground acceleration (PGA), peak ground velocity (PGV) and JMA instrumental seismic intensity have been studied for developing their attenuation relationships. These strong motion indices are often used to estimate damage to buildings and civil infrastructures. In this study, to investigate the characteristics of the ground condition and site-specific response, which are highly frequency dependent, and to have a more comprehensive description of strong ground motion in terms of frequency contents, attenuation relations of absolute acceleration and relative velocity response spectra for thirty-five structural periods are developed, using the recent K-NET95-type accelerometer records. Note that there are limited numbers of proposed models for response spectra, and especially for velocity response spectra [Joyner and Boore, 1982; Lee, 1993; Bozorgnia et al., 1995; Ambraseys et al., 1996]; Molas and Yamazaki, 1996]. As an attenuation model, the three-stage iterative partial regression method, proposed by Molas and Yamazaki [1995], and used by Shabestari and Yamazaki [1998], is employed in this study. The results of attenuation relation for the response spectra using the K-NET data set are compared with the results of the previous study on the attenuation relation of response spectrum using JMA data recorded by JMA-87-type accelerometers at 77 JMA free field stations. The spectra of station coefficients represent the site amplification characteristics of each recording station. Considering this, the predicted site-specific response spectrum ratio that represents predominant period of each recording station is introduced for K-NET sites. The resulting attenuation relations are useful for seismic hazard analysis and damage assessment in highly seismic subduction zones.

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EARTHQUAKE RECORDS

The acceleration records used in this study consist of 6,017 three-component sets from 94 events, with the JMA magnitude equal or greater than 5.0. These data were recorded by K-NET95-type accelerometers [Kinoshita, 1998] at 823 free field sites from May 1, 1996 to December 31, 1998. The summary of the data is described in Table 1. The data set includes records for some moderate magnitude events, such as the 19 October, and the 3 December 1996 Miyazaki earthquakes (M=6.6 in JMA scale for the both earthquakes), the 26 March (M=6.3), and the 13 May (M=6.2) 1997 Kagoshima earthquakes, which caused slight to moderate damage to structures and lifelines. Since we have near source records for the above mentioned events and the 25 June 1997 Yamaguchi Prefecture earthquake (M=6.1), and the 3 September 1998 Iwate Prefecture earthquake (M=6.1), the shortest distances to the fault planes were calculated based on aftershock distributions [Seismo, 1997; Committee on Natural Disaster Study of Kagoshima University, 1997]. Earthquakes whose focal depths are greater than 200 km were excluded and the earthquakes whose focal depths are zero in the JMA report were assumed as 1.0 km. Records with PGA less than 1.0 cm/s^2 in vectorial composition of the two horizontal components were omitted. The data from the stations which have less than 2 records were omitted since they were not enough in number to determine the station coefficient. Figure 1 shows the locations of the K-NET stations and the epicenters of earthquakes used in this study. The distribution of JMA magnitude with the shortest distance, depth, and PGA with JMA magnitude and histogram of number of records per each station for the current data set are shown in Figure 2.

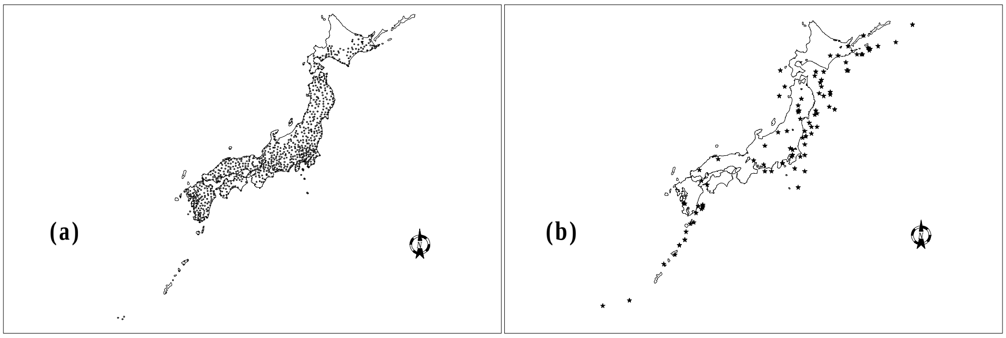

Figure 1: Location of the (a) K-NET stations and (b) epicenters of earthquakes.

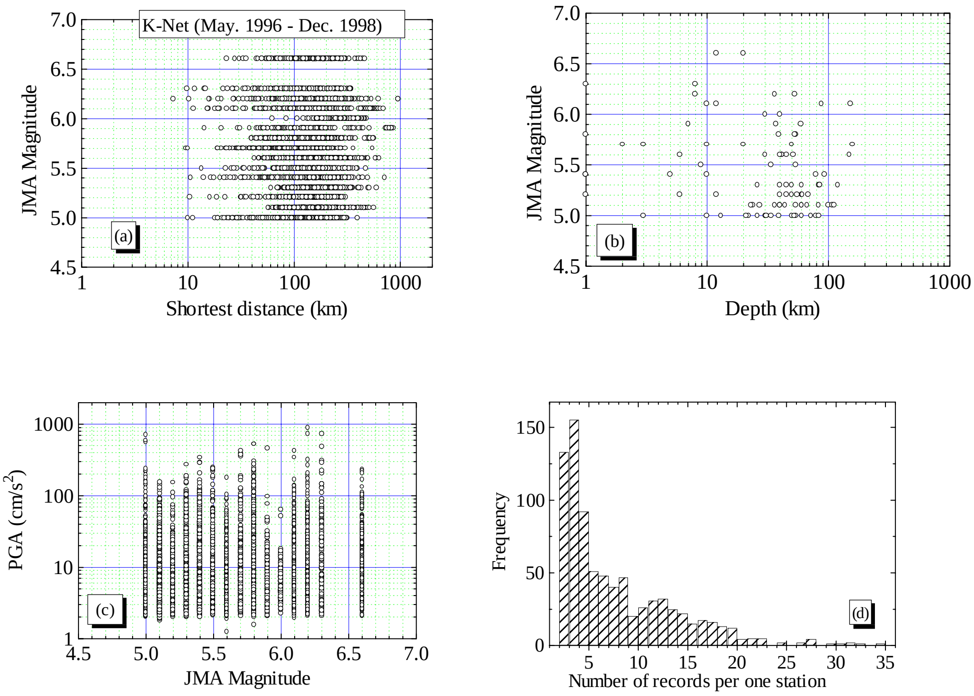

Figure 2: Disribution of the JMA magnitude with (a) shortest distance, (b) depth, and PGA with (c) JMA magnitude and (d) the histogram of the number of records per station for the current data set.

Table 1: Summary of K-NET data set used in this study

Number of events	94
Number of records	6,017
Number of recording stations	823
Recorded period	May 1, 1996 to December 31, 1998
Instrument	K-NET95-type accelerometers
Recording Institution	Science and Technology Agency
Magnitude range	5.0 to 6.6 (JMA scale)
Depth range	1 to 158 km

Although, the summary and distribution of the JMA data set are not shown here, the description of the JMA (Japan Meteorological Agency) data set, which used in this study to compare with the result from the K-NET data set, are given in brief as follows:

The JMA data records consist of 3,990 three-component sets from 1,020 events [Shabestari and Yamazaki, 1998]. These data were recorded by the JMA-87-type accelerometers at 77 stations throughout Japan from August 1, 1988 to March 31, 1996. The data set includes records for some major events, such as the 1993 Kushiro-Oki (M=7.8 in JMA scale), the 1993 Hokkaido-Nansei-Oki (M=7.8), the 1994 Hokkaido-Toho-Oki (M=8.1), the 1994 Sanriku-Haruka-Oki (M=7.5), and the 1995 Hyogoken-Nanbu (M=7.2) Earthquakes. Records with peak ground acceleration (PGA) less than 1.0 cm/s^2 in one horizontal component were omitted. Events whose focal depths were zero or greater than 200 km were also excluded from the analysis.

ATTENUATION MODEL AND METHOD OF ANALYSIS

The attenuation model used is based on the attenuation of body waves in an elastic medium from a point source [Joyner and Boore, 1981; Ohno, et al., 1993; Molas and Yamazaki, 1995]. The model considers the attenuation of seismic waves in a continues medium with a geometric spreading term, an anelastic attenuation term, a depth term, and a site-effect term as follows:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T)r + b_3(T) \log r + b_4 (T)\, h + c_i(T) \qquad (1)$$

where $y(T)$ is the maximum amplitude of the response spectra under consideration. For the two horizontal components, $y(T)$ is taken as the larger maximum amplitude of these, M is the JMA magnitude, r is the shortest distance between the source and recording station, h is the source depth of earthquake in kilometers, and $b_i\,(T)$'s are the coefficients to be determined for each structural period T. The term $b_2(T)r$ represents anelastic attenuation and the term $b_3(T) \log r$ represents geometric spreading. The geometric constant b_3 is assumed to be –1, representing the far field. The term $b_4\,(T)$ represents the effect of the focal depth for each period. The term $c_i(T)$ represents the station coefficient, which reflects the relative site effect for each period, assuming a zero mean for all the stations. The three-stage iterative partial regression method [Molas and Yamazaki, 1995] is used to obtain the regression coefficients.

The absolute acceleration and relative response spectra are calculated for the two horizontal and vertical components. The acceleration response spectrum $S_A(\zeta,T)$, and velocity response spectrum $S_V(\zeta,T)$, used in this study are defined as the maximum response of single-degree-of-freedom system with a damping coefficient five percent of critical for varying structural period, T. Newmark's direct integration method was employed in obtaining the response from the acceleration records. After calculating acceleration and velocity response spectra for the two horizontal components, the larger of the two in each period, $S_{AH}(\zeta,T)$ and $S_{VH}(\zeta,T)$, also the maximum response of the vertical component for acceleration $S_{AV}(\zeta,T)$ and velocity $S_{VV}(\zeta,T)$ responses are used in the regression analysis. Thirty-five structural periods from 0.04s to 10s are selected and a regression analysis is performed separately for each structural period.

RESULTS AND DISCUSSIONS

Regression Coefficients

The results of iterative partial regression for the attenuation of absolute acceleration and relative velocity response spectra are shown in Figure 3, that shows the comparison of the structural period dependent regression coefficients for the K-NET data and also the similar result for the JMA data set. The regression intercept shows that the mean response and has its peak at about 0.1s-0.2s for the horizontal component of the acceleration response spectra and about 0.15s-0.25s for the horizontal component of the velocity response spectra. The magnitude coefficient has an increasing trend as the structural period increases at the same period range. Note that for each structural period the b_0 coefficients for the K-NET data set are larger than those for the JMA data set while the magnitude coefficients for the K-NET data are smaller than those for the JMA data. For the depth coefficient b_4, K-NET gave larger values than JMA.

The anelastic attenuation coefficient increases as the structural period increases for the both data sets although this trend becomes a bit flater for the relative velocity response spectrum, after period of 1.0s. Since the coefficients become positive, which is physically inadmissible, for S_{AH} in the long period range, it was set zero in the regression then recalculated.

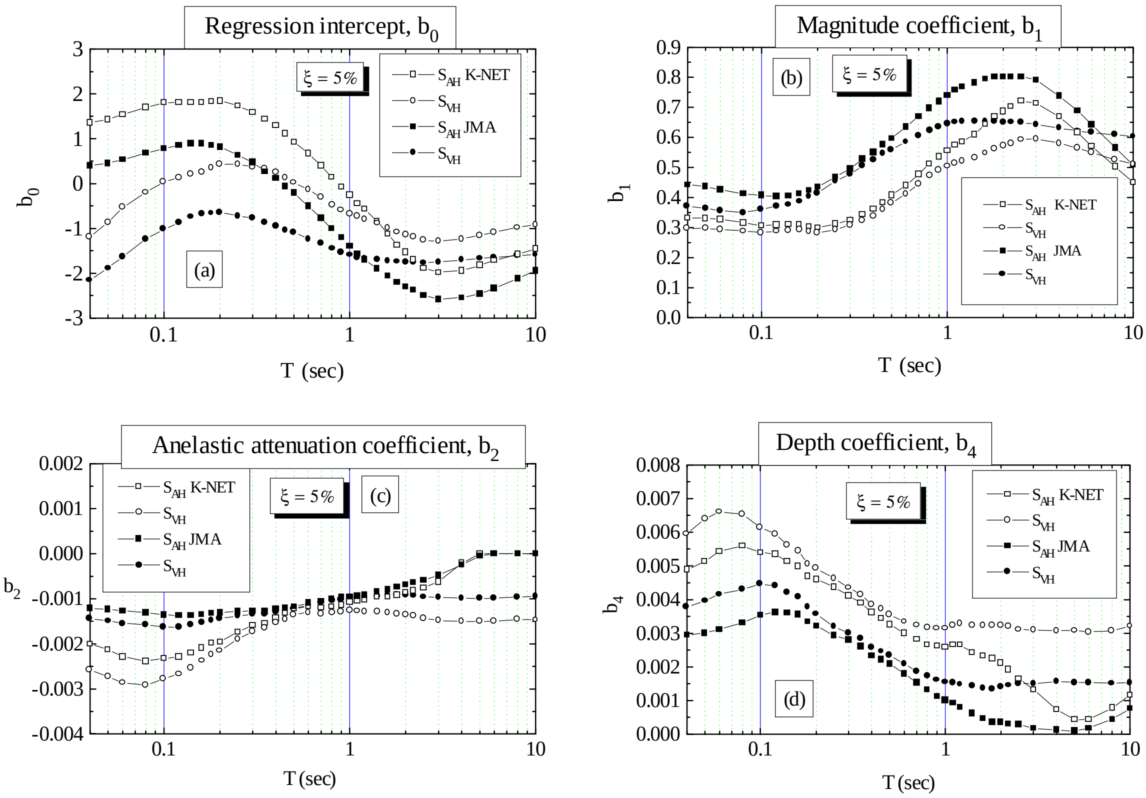

Figure 3: Regression coefficients for the absolute acceleration response spectra S_{AH} and relative velocity response spectra S_{VH} using K-NET and JMA data sets.

Spectral Shape

By taking iterative regression for several structural periods independently, it is not necessary to pre-determine the shape of response spectra. Figure 4 shows the predicted mean horizontal and vertical acceleration response spectra for the K-NET and JMA data sets, for a fixed distance and depth and for varying magnitudes. The shape of the response spectra is magnitude dependent as can be seen from this figure. The structural period where the peak occurs shifts to the higher period as the magnitude increases for the JMA data. But for the K-NET data, this shift cannot be observed. This is probably due to the lack of large magnitude events in the K-NET data.

For each structural period the obtained depth coefficients are larger than those for the JMA data set as demonstrated in the previous study by Shabestari and Yamazaki [1999] are. Due to lack of large magnitude events in the current K-NET data set, the predicted acceleration response spectra become large for the small and intermediate magnitude events. This can be explained by increasing intercept coefficients and decreasing magnitude coefficient for the current K-NET set. Hence, as seen in Figure 5, the predicted acceleration response spectrum for the given magnitude 6.0 becomes large for the K-NET data set. Since the depth coefficient is always positive, the earthquake with a deep source depth has higher response than shallow one.

Local Site Effect

The obtained station coefficients represent amplification factors relative to the other stations. Since, site amplification is known to be frequency dependent, the spectra of station coefficients were employed for the determination of site specific amplification ratios. As seen from Figure 6, the shapes of the station coefficients for response acceleration and velocity spectra for each station are very similar, although the shapes are quite different from station to station. The dominant peak in both response spectra may represent the predominant period of the recording site [Molas and Yamazaki, 1996; Yamazaki and Ansary, 1997] although the obtained peaks are relative amplification of the site compared with the others.

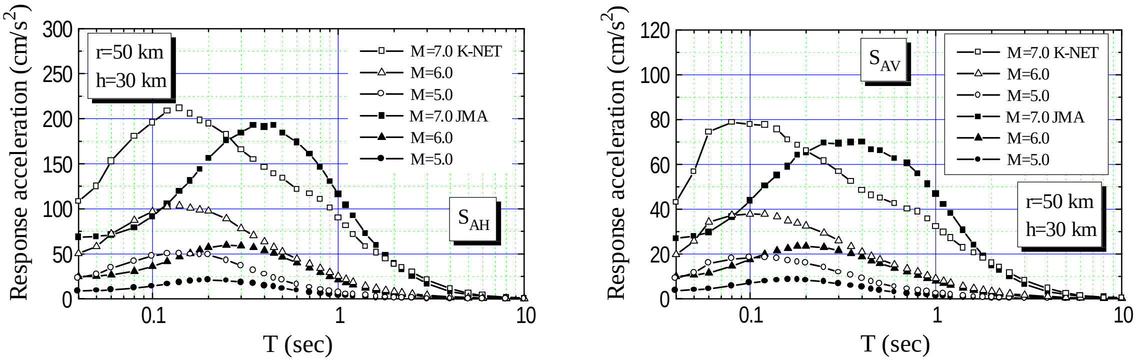

Figure 4: Predicted horizontal and vertical acceleration response spectra (S_{AH} and S_{AV}) for 5 percent damping and c_i=0.0, depth h=30 km, shortest distance r=50 km and different magnitudes for the K-NET and JMA data.

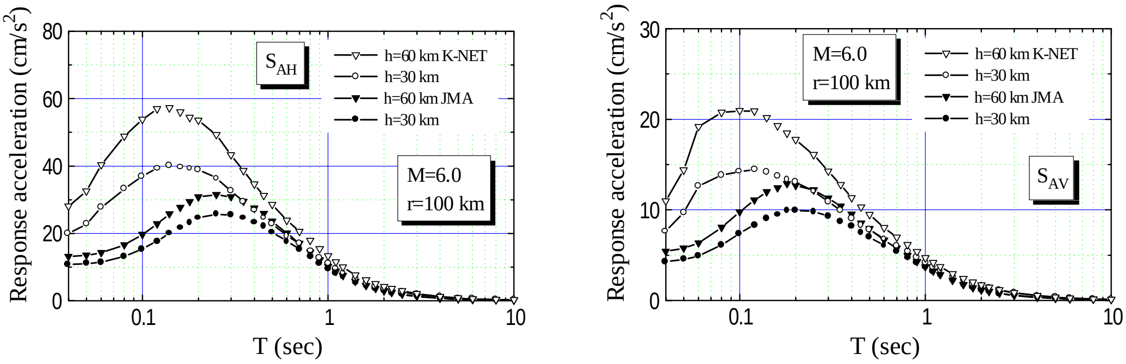

Figure 5: Predicted horizontal and vertical acceleration response spectra (S_{AH} and S_{AV}) for 5 percent damping and c_i=0.0, magnitude M=6.0, shortest distance r=100 km and different depths for the K-NET and JMA data.

Site-specific Response Spectra

Combining the expected response spectra for the mean station (with c_i=0.0) and the spectrum of station coefficients, the site-specific response spectra can be introduced for K-NET stations. Figure 7 shows sample site-specific predicted response spectra for five K-NET stations those received more than thirty records in the current data set. As it can be seen from the figure, the shapes and amplitudes of spectra are different for the different sites. These site specific response spectra should be considered in design or damage assessment of structures. Using bore-hole logging and geotechnical information, it is possible to investigate the predominant period of each station and to compare the result with the proposed site-specific response spectra as demonstrated by Yamazaki and Ansary [1997].

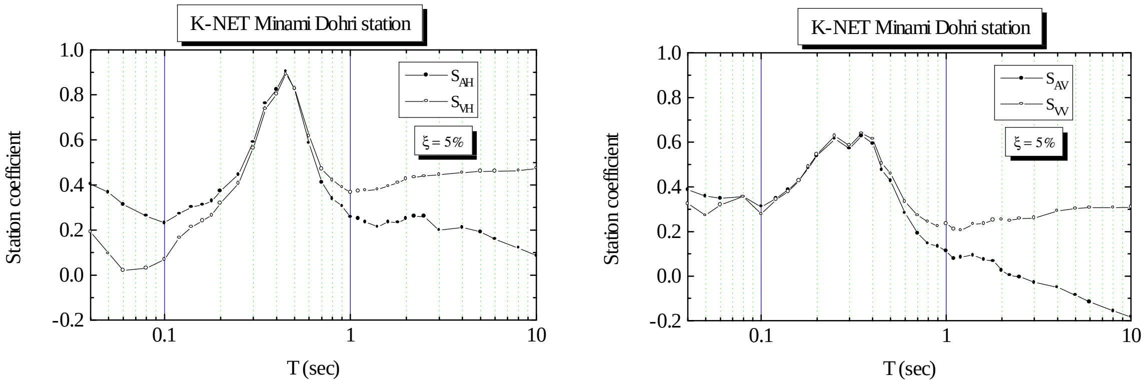

Figure 6: Spectrum of station coefficients for attenuation relations of $S_{AH}(0.05, T)$, $S_{AV}(0.05, T)$, $S_{VH}(0.05, T)$, and $S_{VV}(0.05, T)$ for the K-NET Minami Dohri station, which received more than thirty records.

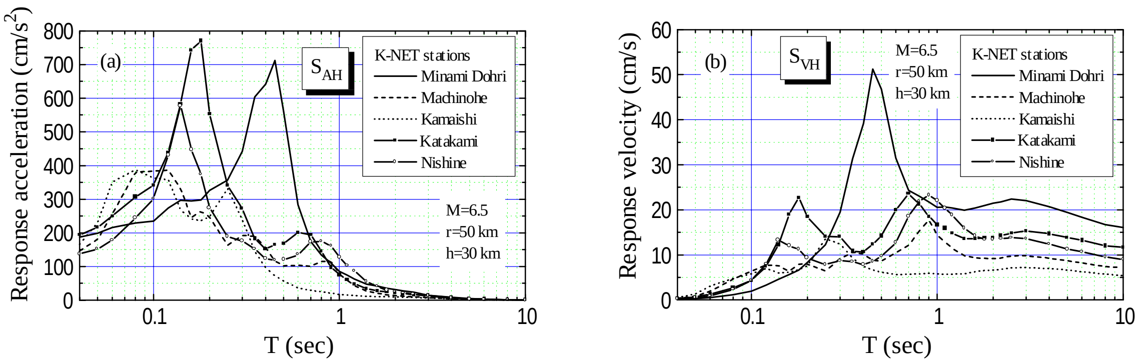

Figure 7: Predicted site-specific (a) acceleration response spectra and (b) velocity response spectra for the five K-NET stations with the same condition (M=6.5, r=50 km, h=30 km).

Spectral Ratio

Horizontal-to-vertical (H/V) acceleration and velocity response spectral ratios were calculated for the different magnitudes, source to site distance, and depths. Figure 8 shows the H/V ratios for the acceleration and velocity response spectra for a given shortest distance and depth with changes in the magnitude. The ratios are slightly affected by the magnitude. In the short-period range (0.06s to 0.3s) the ratio increases linearly with period (up to 2.8-3.0) for the acceleration and velocity response spectra. In the intermediate to long-period range (0.5s to 2s) the ratio decreases gradually, and the ratio becomes larger for the small magnitude events for the acceleration and velocity response, but for the long period (greater than 2.5s) the ratio becomes larger for large magnitude events only for acceleration response. Although the current data set includes some near field records [Shabestari and Yamazaki, 1999], it is consist of mostly intermediate to far field records. Therefore, as demonstrated in Yamazaki and Ansary [1997] for the JMA records, the H/V spectral ratios are almost independent of magnitude, distance and depth. The reason for this can be explained by the similarity of regression coefficients for the horizontal and vertical components.

Site-specific Response Spectrum Ratio

The station coefficients are frequency dependent, and the peak of the station coefficient spectrum for the horizontal response spectrum corresponds to the predominant period of S-wave propagation [Yamazaki and Ansary, 1997; Molas and Yamazaki, 1996]. Also the peak for the vertical component may indicate the predominant period of P-wave propagation. Combining the H/V response spectral ratio for the mean station (c_i=0.0) and station coefficients (c_{iH} and c_{iV}), the site-specific acceleration and velocity response spectral ratios can be introduced for each K-NET station. Figure 9 shows the site-specific acceleration and velocity response spectral ratios for K-NET Minami Dohri station, plotted for a given magnitude, shortest distance and depth. From the figure it can be seen that the response spectrum ratio is almost constant with the change of magnitude.

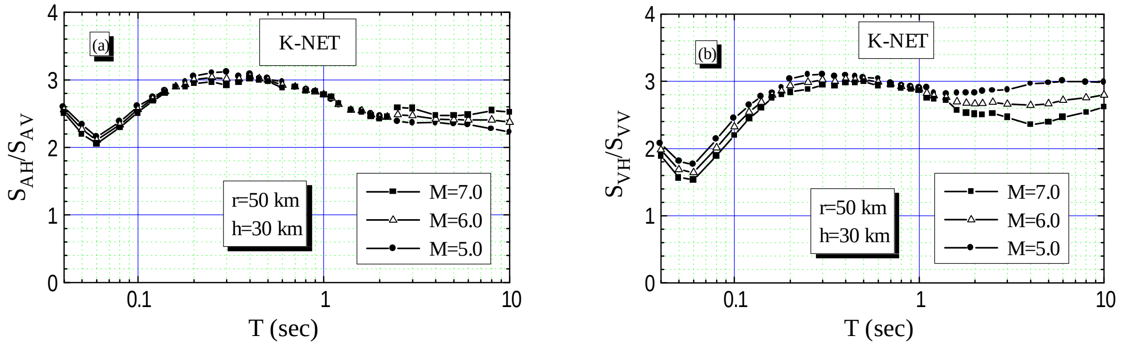

Figure 8: Predicted H/V ratios of (a) acceleration response spectra (b) velocity response spectrum for a given shortest distance and depth with changes in the magnitude (5 percent damping ratio and c_i=0.0).

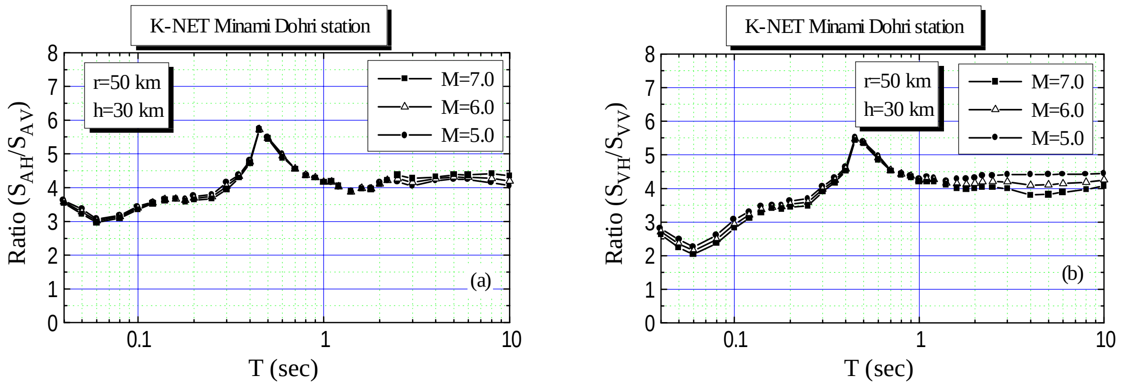

Figure 9: Predicted site-specific H/V ratios of (a) acceleration response spectrum and (b) velocity response spectrum for a given magnitude, shortest distance, and depth (5 percent damping ratio, Minami Dohri station).

Similarly, although not shown here, it is almost independent of the source-to-site distance and source depth. Hence the ratio is unique to the site, representing site amplification characteristics. Since K-NET sites are accompanied by geological data, a further study comparing the site-specific response spectral ratio and theoretical transfer functions is possible.

CONCLUSIONS

To investigate the characteristics of the ground condition and to have a more comprehensive description of strong ground motion in terms of frequency contents, attenuation relations of absolute acceleration and relative velocity response spectra for thirty-five structural periods are developed, using the recent accelerograms from the Kyoshin Network (K-NET), which was recently deployed throughout in Japan. The selected acceleration records consist of 6,017 three-component sets from 94 earthquakes, which recorded by K-NET95-type accelerometers at 823 free field sites in the period of May 1996 to December 1998. The obtained regression coefficients for each structural period and the predicted horizontal and vertical acceleration response spectra from the K-NET data were compared with those from JMA data set that contains 3,990 records from 1,020 earthquakes recorded at 77 stations.

From the result of the iterative regression analysis it can be observed that the spectra shape is a function of magnitude, shortest distance, and depth for the JMA and K-NET data sets. The structural period where the peak occurs shifts to the higher period as the magnitude increase for the JMA data. But for the K-NET data, this shift cannot be observed. This is probably due to the lack of large magnitude events in K-NET data. Also the predicted acceleration response spectra for the K-NET data were larger than those for the JMA data. This can be explained by increasing intercept coefficients and decreasing magnitude coefficient for the K-NET data. Using obtained station coefficients for each structural period, the spectra of station coefficients and combining the expected response spectra for the mean station and the spectrum of station coefficients, the site-specific response spectra were introduced for the K-NET stations. Since the spectra of station coefficients and site-specific response spectra represent the site amplification characteristics of each recording station, these should be used in design or damage assessment of structures in highly seismic subduction zones.

Although the current K-NET data set includes some near field records it is consist of mostly intermediate to far field records. Therefore, the horizontal-to-vertical (H/V) spectral ratios are almost independent of magnitude, distance, and depth. The shape of the spectra ratio is only a function of the average site and station coefficients with respect to the structural periods. The reason for this can be explained by the similarity of regression coefficients for the horizontal and vertical components. Combining the H/V response spectral ratio for the average station and station coefficients, the site-specific acceleration and velocity response spectral ratios can be introduced for each K-NET station. The site-specific acceleration and velocity response spectral ratios are almost independent of the magnitude, source-to-site distance and source depth. Hence the ratio is unique to the site, representing site amplification characteristics. Since K-NET sites are accompanied by geological data, a further study comparing the site-specific response spectral ratio and theoretical transfer functions is possible.

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