(18) THE EFFECT OF SOURCE DEPTH AND LOCAL SITE TO THE ATTENUATION CHARACTERISTICS OF RESPONSE SPECTRA

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INTRODUCTION

The attenuation of earthquake ground motion has been one of the well-studied aspect of seismology and earthquake engineering. They are especially important in the evaluation of the seismic hazard and/or risk of a given site. Most attenuation studies were developed using earthquake ground motion from shallow events (up to 30 to 60 km depths). However, deep events like the 1993 Kushiro-Oki earthquake can produce very strong ground motion at the surface. Thus, the inclusion of deep events is important for a realistic evaluation of seismic hazard and risk for subduction zone regions like Japan.

To address this need, the authors developed attenuation equations for the peak ground acceleration and velocity from ground motion of events with depths of up to 200 km [1]. In this paper, the results of regression analysis of response spectra, specifically, the absolute acceleration and relative velocity response of single-degree-of-freedom systems with damping of 5 percent of critical are presented using the same data and regression technique.

DATA

Acceleration time histories from August 1, 1988 to December 31, 1993 recorded at 76 JMA stations using the new JMA-87 type seismometers are used in this study. Many attenuation relationships in Japan are based on ground motion recorded by older SMAC-B2 seismometers which suppress high frequencies. Because of this, their use requires correction procedures [2] which are not required for the new records used in this study. The acceleration time histories includes those of recent earthquakes like the January 15, 1993 Kushiro-Oki, the February 7, 1993 Noto Peninsula, and the July 12, 1993 Hokkaido Nansei-Oki earthquakes. Due to the resolution (± 0.03 cm/s^2) of the recording instrument, only records whose peak ground acceleration (PGA) are greater than or equal to 1.0 cm/s^2 for both horizontal components are used. Events whose focal depth are reported by the JMA as zero and those greater than 200 km are omitted from the analysis. A total of 2,166 records are used in the analysis.

Figure 1 shows the distribution of the magnitude, depth, and distance for the data set. A correlation between the magnitude and distance can be observed which is common for Japanese earthquake data.

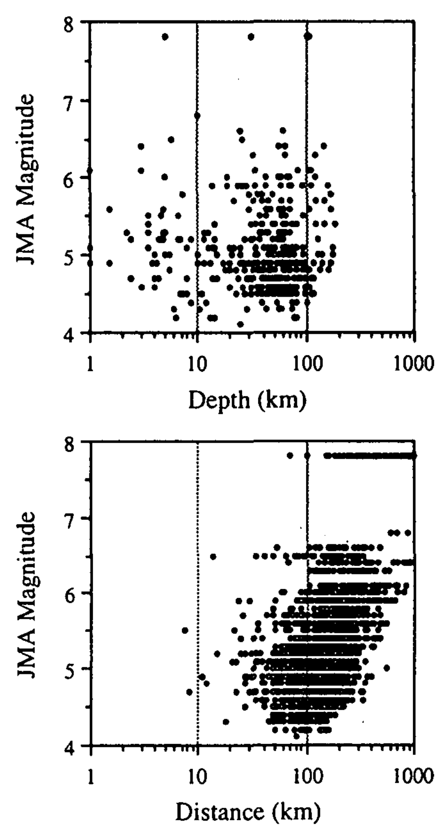

Figure 1. Distribution of magnitude, depth, and distance of the data used in this study

ATTENUATION MODEL

The attenuation model considered in this paper is based on the theoretical attenuation of body waves in an elastic medium from a point source [3]. Since the number of records for each recording station is adequate (Figure 2), we can separate the site effect of the recording station in the regression. Preliminary regression has shown that the effect of the source depth and local site are significant. Additional regressor

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variables are then added to consider the source depth and local site effects. The model is given by:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T)R + b_3(T)\log R + b_4(T)h + \sum_{i=1}^{N} c_i(T)S_i + \sigma P \qquad (1)$$

where $y(T)$ is the response spectra ordinate under consideration (larger of the two horizontal components), M is the JMA magnitude, R is the shortest slant distance from the site to the fault plane in km, h is the depth in km, $S_i = 1$ for station i, 0 otherwise and $b_i(T)$'s and $c_i(T)$'s are the coefficients to be determined. P is zero for 50-percentile values and one for 84-percentile values. However, from the results of the preliminary analysis, $b_3(T)$ is constrained to 1.0. The inclusion of the depth term, $b_4(T)$, and station coefficients, $c_i(T)$, are justified by the behavior of residuals and by the significant improvement of the regression fitting [1].

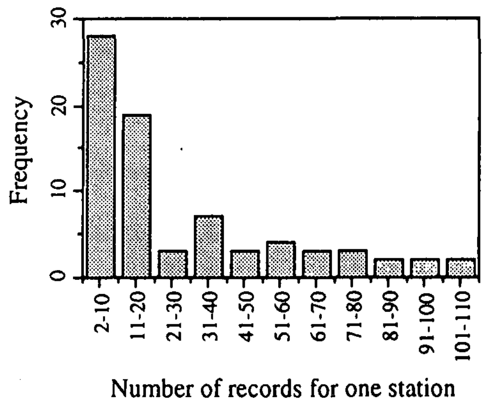

Figure 2. Histogram of the number of records per station

METHOD OF ANALYSIS

Fukushima and Tanaka [4] proposed that a two-stage regression procedure similar to Joyner and Boore [3] be used to eliminate systematic errors in one-stage regression due to the correlation of magnitude and distance. In this case, the first stage is the linear regression of

$$\log y(T) = \sum_{j=1}^{K} a_j(T)A_j + b_2(T)R + \log R + b_4(T)h + \sum_{i=1}^{N} c_i(T)S_i \qquad (2)$$

where k is the number of earthquakes and $A_j = 1$ for earthquake j; $= 0$ otherwise. The second stage is the weighted least-squares regression of

$$a_j(T) = b_0(T) + b_1(T)M_j \qquad (3)$$

where a_j is determined in the first stage and the weighing matrix is proposed by Joyner and Boore [5].

However, the use of station coefficients in the two-stage regression procedure results in singular matrices in the solution of the first stage. An iterative partial regression procedure is used to solve this problem. A detailed explanation of the procedure is given in reference [1]. In summary, the depth term and station coefficients are first estimated by one-stage regression of Eq. (1). The distance dependence is then determined from Eq. (2) but $b_4(T)$ and $c_i(T)$'s are constrained to the values determined in the previous step. The third step is to determine the magnitude dependence from Eq. (3) in which $a_j(T)$ is determined from the previous step. The first step is then

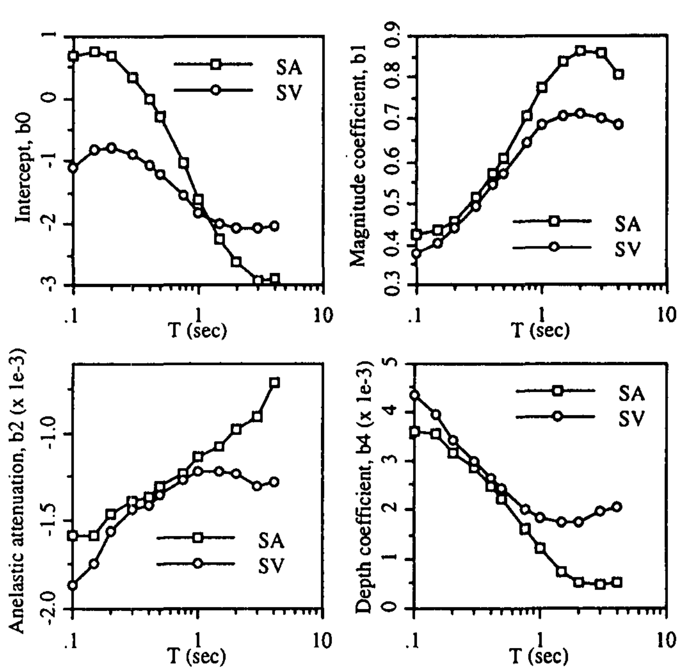

Figure 3. Regression coefficients for $S_A(T)$ and $S_V(T)$

Table 1. Regression coefficients for $S_A(T)$

T (sec)	b_0	b_1	b_2	b_3	b_4	σ
0.10	0.702	0.424	-0.00159	-1.0	0.00362	0.292
0.15	0.773	0.434	-0.00158	-1.0	0.00357	0.298
0.20	0.691	0.457	-0.00147	-1.0	0.00319	0.294
0.30	0.349	0.515	-0.00139	-1.0	0.00287	0.284
0.40	-0.004	0.570	-0.00136	-1.0	0.00246	0.275
0.50	-0.296	0.608	-0.00131	-1.0	0.00222	0.266
0.75	-1.028	0.707	-0.00124	-1.0	0.00161	0.263
1.00	-1.593	0.775	-0.00114	-1.0	0.00123	0.255
1.50	-2.240	0.838	-0.00107	-1.0	0.00073	0.247
2.00	-2.608	0.862	-0.00098	-1.0	0.00053	0.242
3.00	-2.929	0.858	-0.00091	-1.0	0.00048	0.235
4.00	-2.912	0.807	-0.00071	-1.0	0.00053	0.234

Table 2. Regression coefficients for $S_V(T)$

T (sec)	b_0	b_1	b_2	b_3	b_4	σ
0.10	-1.073	0.381	-0.00187	-1.0	0.00435	0.327
0.15	-0.794	0.404	-0.00175	-1.0	0.00396	0.321
0.20	-0.764	0.438	-0.00156	-1.0	0.00342	0.307
0.30	-0.883	0.495	-0.00144	-1.0	0.00301	0.290
0.40	-1.057	0.544	-0.00142	-1.0	0.00266	0.279
0.50	-1.182	0.572	-0.00135	-1.0	0.00243	0.268
0.75	-1.553	0.643	-0.00127	-1.0	0.00201	0.262
1.00	-1.812	0.685	-0.00122	-1.0	0.00182	0.256
1.50	-2.002	0.707	-0.00121	-1.0	0.00175	0.250
2.00	-2.068	0.711	-0.00123	-1.0	0.00176	0.249
3.00	-2.076	0.703	-0.00130	-1.0	0.00196	0.251
4.00	-2.018	0.686	-0.00128	-1.0	0.00205	0.250

repeated except that $b_1(T)$ and $b_2(T)$ are constrained to the values determined from the previous iteration. The cycle is then repeated until the coefficients stabilize. In this study, 10 iterations are enough for the coefficients to converge.

RESULTS

Figure 2 and Tables 1 and 2 show the frequency dependence of the regression coefficients. The regression intercept, b_0, decreases as the structural period increases while the magnitude term, b_1, increases as structure period increases for both $S_A(T)$ and $S_V(T)$. This is consistent with the results of other studies [6]. The anelastic attenuation coefficient decreases as the structure period increases. This is consistent with observations that high frequency seismic waves attenuate faster than low frequency waves. Figure 3 also shows that the effect of depth diminishes as the structure period increases. It can also be seen that the coefficients for $S_V(T)$ stabilize somewhat for structure periods 1 to 4 s.

A comparison of spectral shapes for $S_A(T)$ and $S_V(T)$ show that it is dependent on the magnitude (Figure 4) but not on distance, nor depth (not shown). The spectra of station coefficients have a distinct characteristic for each station and cannot be categorized by the soil type of the recording stations. However, the spectrum of station coefficients for $S_A(T)$ and $S_V(T)$ are similar (Figure 5). This suggests that it may be possible to use other ground motion parameters to estimate the frequency dependent amplification at a given site.

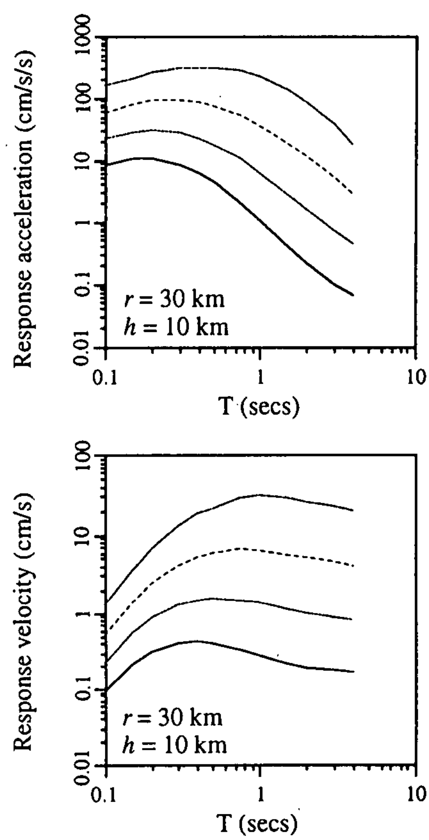

Figure 4. Predicted absolute acceleration response spectra (top) and relative velocity response spectra (bottom) for mean station (c_i = 0.0)

By combining the spectrum of station coefficients and the mean predicted response spectra, a site-specific response spectrum can be predicted at a site given the magnitude, distance and depth of an event. Figure 6 shows the predicted response spectra for five JMA stations which have a large number of data (about 100). It can be seen that the resulting predictive equations give substantially different response spectra between sites in terms of amplitude and spectral shape. Sites with the same soil type classification have very different response spectra. This is significant in seismic hazard and risk studies where site-specific response spectra are needed. However, to use the attenuation equations for other sites, we must first find a reliable method to estimate the station coefficients.

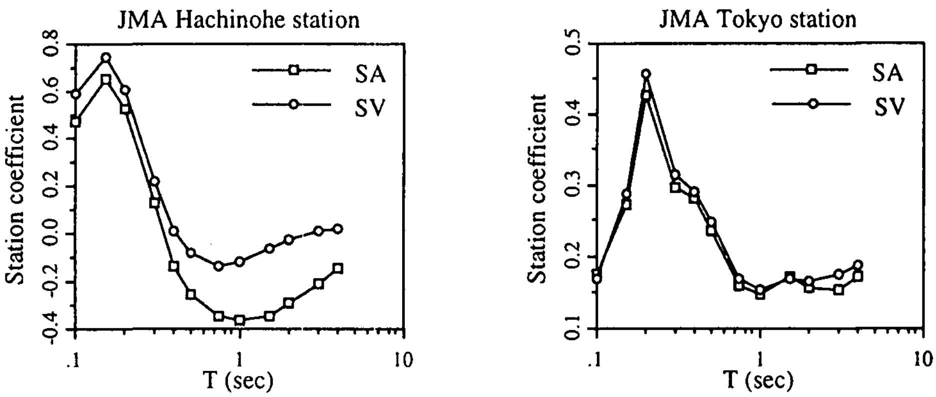

Figure 5. Spectrum of station coefficients, $c_i(T)$, for two JMA stations

CONCLUSIONS

Regression analyses of absolute acceleration and relative velocity response spectra are performed. The effect of source depth and local site are considered in the analysis. Due to a matrix singularity problem that occurs when the local site effect is considered with a two-stage regression procedure, an iterative partial regression procedure is used.

It was found that the effect of source depth diminishes as the structure period increases. However, in the case of the relative velocity response spectra, the regression coefficients stabilize for periods about 1.0s and above. The frequency dependence of the site effect for $S_A(T)$ and $S_V(T)$ are similar, however, it cannot be adequately represented by using soil type classification only.

The results can be used to predict site-specific response spectra at the JMA stations used in this study.

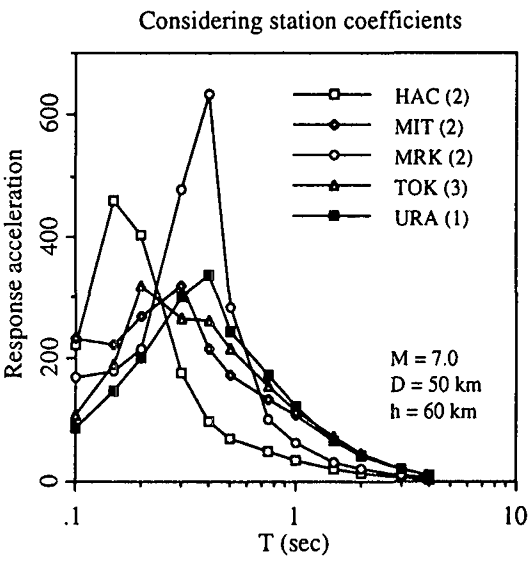

Figure 6. Site-specific predicted acceleration response spectra (soil types are enclosed in parenthesis)

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