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ENGINEERING PROPERTIES OF LONG-PERIOD STRONG MOTION EVALUATED FROM DISPLACEMENT SEISMOGRAPH RECORDS

Izumi SHINO[1] and Tsuneo KATAYAMA[2]

[1]Engineering Research Institute, Faculty of Engineering, University of Tokyo, Bunkyo-ku, Tokyo, Japan
[2]Institute of Industrial Science, University of Tokyo, Minato-ku, Tokyo, Japan

SUMMARY

Ninety-one strong motion records obtained by the displacement type seismographs of the Japan Meteorological Agency's Network during six earthquakes (M=7.0-7.9) were digitized and analyzed statistically to investigate the engineering properties of long-period (2-20 s) strong motion. Both earthquake magnitude and epicentral distance were found to have small effect on spectral amplitude in the intermediate period range. It was found that the horizontal response spectral amplitudes of 2-4 s period components estimated from the Japanese accelerograms are about 1.7 times greater than those estimated from the displacement records.

INTRODUCTION

In order to make more reasonable the method of earthquake-resistant design of structures with natural periods longer than several seconds, it is needed to clarify the engineering characteristics of long-period strong earthquake ground motion. The long-period strong motion here means that having the period components between 2 and 20 s.

This paper attempts to elucidate the engineering characteristics of the long-period strong motion by statistically analyzing the JMA's low-magnification displacement seismograph records obtained at over fifty observation sites during six earthquakes with magnitudes larger than 7.0. The displacement type seismograph has the most suitable instrumental characteristics in the period range of interest: magnification factor of unity and natural period of 5-6 s.

RECORDS FOR ANALYSES

Ninety-one records (178 horizontal and 87 vertical components) of the displacement type seismographs obtained at 55 JMA stations with epicentral distances between 46 and 691 km during six earthquakes in the northern part of Japan as shown in Table 1 were digitized for analyses. Each of the 55 stations provided one to four records digitized in the present study. The digitized records were instrumentally corrected as well as treated with a 2-20 s bandpass filter to eliminate distortions caused by digitization. Fourteen out of the 91 digitized records have already been analyzed preliminarily (Ref. 1).

Table 2 shows the distribution of the data set for horizontal component in each of the combinations of arbitrarily chosen ranges of earthquake magnitude and epicentral distance and classes of subsurface structure. The subsurface structure classes are the recording site categories based on amplification effects of subsurface structures around sites expressed by the "Most Probable Amplification Factor of seismic ground motion" (MPAF) defined and obtained by Okada and Kagami (Ref. 2). Amplification due to subsurface structure is largest for subsurface structure class SC3 and smallest for SC1. The data are far from sufficient in number nor uniform in distribution.

ENGINEERING PROPERTIES EXTRACTED FROM DIGITIZED RECORDS

Among the factors affecting properties of strong ground motion, effects of earthquake magnitude M (the magnitude determined by JMA), epicentral distance Δ, and subsurface structure around a recording site were taken into account in the statistical analysis as independent variables.

Peak Amplitude In order to examine the dependence of peak amplitude upon the affecting factors, statistical analysis was made by assuming the following form of equation:

$$\log_{10} Pes = \alpha - \beta \log_{10} \Delta + \gamma M \quad (1)$$

where Pes is the estimated peak amplitude of displacement (cm), velocity (cm/s) or acceleration (cm/s^2) time history obtained from the displacement record, and Δ is in kilometer. The above relation was derived regardless of the class of subsurface structure, because the value of MPAF was determined empirically from the ground motions with period components shorter than about 6 s. The values of the coefficients α, β and γ determined from regression analysis are listed in Table 3. From the values of β, it is seen that the attenuation with distance is fastest for the maximum acceleration and slowest for the maximum displacement. The effect of magnitude, coefficient γ, is found greater on the maximum displacement than on the maximum velocity or acceleration.

Response Spectrum For clarification of the characteristics of the long-period strong motion in the frequency domain, the undamped velocity response spectra were computed and analyzed statistically. They were employed for analysis because of being approximately identical to Fourier acceleration spectrum and the relatively small damping of long-period structures.

Statistical analysis was performed at 49 discrete natural periods from 2 to 20 s by assuming that the estimated response spectral amplitude, SVes cm/s, has the following form:

$$\log_{10} SVes = \alpha - \beta \log_{10} \Delta + \gamma M + \delta D_1 + \varepsilon D_2 \quad (2)$$

where D_1 and D_2 are dummy variables representing subsurface structure class as shown in Table 4, and α, β, γ, δ and ε are the regression coefficients to be determined by the least squares method. Figure 1 shows response spectra for a SC2 site at Δ = 290 km (mean of the recorded distances) estimated by using the equation (2) for different magnitudes. The spectral shape of a large earthquake (M=7.9) is found almost flat. The period such as the corner period of source spectrum is seen for the spectrum of small earthquake, more clearly for vertical motion.

Figure 2 shows the influence of magnitude in terms of the regression coefficients γ of equation (2). The effect of magnitude is seen to wane with increasing period to about 9 s. However, in the period range longer than about 9 s it becomes generally stronger with period. The tendency in the shorter period range may be due to the use of the magnitude of JMA as earthquake magnitude, which was determined mainly from maximum amplitudes of horizontal components with a period of 5 s and shorter obtained by seismographs with periods of about 5 s. The greater influence of magnitude at the longer periods may result from the existence of the period such as the corner period of source spectrum (see Fig. 1). The effect of epicentral distance is illustrated in Fig. 3 in terms of β of equation (2). It is seen that the distance has relatively small effect in the approximate period range between 7 and 17 s. The slow attenuation at a period around 10 s is found very pronounced. Both magnitude and distance have relatively little effect on spectra in the intermediate period range; whereas, the extent of their influence on peak amplitudes varies systematically in the following order: displacement, velocity and acceleration as seen in Table 3. These results suggest that the maximum velocity is not always an appropriate parameter for describing the properties of the intermediate period components.

Figure 4 presents the effect of subsurface structure around a recording site in terms of the ratio of spectral amplitude at a SC2 or SC3 site (SVes(SC2) or SVes(SC3)) to that at a SC1 site (SVes(SC1)). The spectral amplitude ratios can be estimated by the following equations:

$$\frac{SVes(SC2)}{SVes(SC1)} = 10^{(\varepsilon-\delta)}, \quad \frac{SVes(SC3)}{SVes(SC1)} = 10^{-\delta} \qquad (3)$$

where δ and ε are the regression coefficients of equation (2). The ratio of SVes(SC3) to SVes(SC1) decreases gradually with increasing period in the period range longer than about 7 s. This may imply that the classification of site according to the MPAF value is ineffective in estimating the extent of amplification of the longer period motion by subsurface structure. It is, therefore, inferred that the information on deeper and broader underground structure is indispensable to properly interpret the influence of subsurface structure on the ground motion with the longer period components, though such information is hardly available for all the sites under investigation up to the present. The spectral amplitude of horizontal motion at a SC3 site is about 4 times greater than that at a SC1 site in the period range from 2 to 8 s, and the ratio is about 2 in the period range from 8 to 14 s.

Response Spectrum of Each Individual Earthquake Data To know the special properties of the ground motion of each earthquake, regression analysis was performed by using the relation expressed by the equation (2) without the term of magnitude. Figure 5 shows examples of estimated response spectra for horizontal motion at SC1 sites with the average distances of individual earthquake data. The estimated spectrum for the 1983 Nihonkai-Chubu earthquake (EQ5) has an obvious peak at a period around 10 s. Since such peaks can be seen for the spectra of EQ5 at any distances, the predominance of about 10 s period component seems to result from the property of the focal process of this earthquake. The attenuation properties of horizontal response spectral amplitudes for each earthquake are shown in Fig. 6 in terms of β. The attenuation rate in the shorter period range is very high for the 1983 Nihonkai-Chubu earthquake (EQ5). About 10 s period component is found to attenuate considerably slower during the aftershock of the 1968 Tokachi-Oki earthquake (EQ4), the main shock (EQ5) and the aftershock (EQ6) of the 1983 Nihonkai-Chubu earthquake. These three earthquakes provided more than 40 % of all the records. This prevalent result, therefore, may imply that the slower attenuation of about 10 s period component is caused by the selective amplification of this period component by deeper and broader underground structure such as crustal structure.

COMPARISON WITH JAPANESE ACCELEROGRAMS

It is examined whether or not the properties estimated from the displacement records are consistent with those known from the analysis of a large number of acceleration strong-motion records in Japan.

In the period range of 2 to 4 s in which the SMAC type accelerograph (typical accelerograph in Japan) is thought to precisely record earthquake ground motion, velocity response spectral amplitudes at a damping value of 5 percent of critical calculated from the horizontal records of the SMAC type accelerographs were compared with those computed in the present study from the displacement records. In the case of the records of the SMAC type accelerographs, the velocity response spectra were predicted using the Japanese empirical relation for the acceleration response spectra (Ref. 3) and the approximate relation between velocity response and acceleration one. Figure 7 shows the ratios of the average amplitudes between 2 and 4 s of the predicted spectra by the empirical relation from accelerograms to those of the observed spectra calculated from the displacement records. At the distance shorter than about 200 km, the predicted spectral amplitude is generally consistent with the observed one; however, at the longer distance, the former tends to be larger than the latter. The mean ratio of the predicted amplitudes to the observed ones is 1.75.

CONCLUSIONS

The engineering characteristics of the long-period strong motion were investigated by statistically analyzing the 91 records of the displacement type seismographs obtained at sites with Δ=46-691 km during six earthquakes (M=7.0-7.9). The major findings are summarized as follows:

1) The response spectral amplitudes at the intermediate periods were much less affected by earthquake magnitude and epicentral distance, although such tendencies were not found for peak amplitudes of acceleration, velocity and displacement. The slow attenuation of about 10 s period component was noticeable.
2) The subsurface structure around a recording site had the capability to cause significant amplification effect on the response spectral amplitude at least in the period range shorter than about 14 s.
3) The ground motion during the 1983 Nihonkai-Chubu earthquake, one of the six earthquakes, had marked properties such as the fast attenuation in the shorter period range and the response spectrum with an obvious peak at a period around 10 s.
4) The horizontal response spectral amplitudes in the period range of 2 to 4 s predicted by a Japanese empirical relation obtained from statistical analysis on acceleration strong-motion records were about 1.7 times greater than those estimated from the displacement records.

ACKNOWLEDGMENTS

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Table 1 Earthquakes and Displacement Records Analyzed

EQ No.	Earthquake	Date	M	No. of Sta.	No. of Components Hor.	Vert.	Total
EQ1	Kita-Mino	1961.8.19	7.0	12	24	11	35
EQ2	Niigata	1964.6.16	7.5	22	44	20	64
EQ3	Tokachi-Oki	1968.5.16	7.9	20	38	20	58
EQ4	Tokachi-Oki (AS)	1968.5.16	7.5	12	23	11	34
EQ5	Nihonkai-Chubu	1983.5.26	7.7	19	38	19	57
EQ6	Nihonaki-Chubu (AS)	1983.6.21	7.1	6	11	6	17
			Total	91	178	87	265

AS: Aftershock

Table 4 Dummy Variables Representing Subsurface Structure Class

Cl.	Dummy Var. D_1	D_2
SC1	1	0
SC2	0	1
SC3	0	0

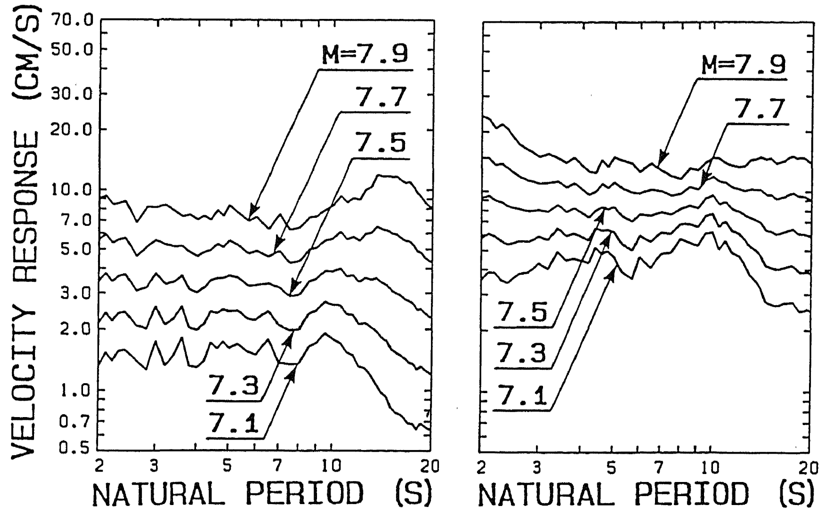
Table 2 Distribution of Data Set (Horizontal Component)

M	SC*	Epicentral Distance Δ (km) 0-100	100-200	200-300	300-400	400-500	500-600	600-700	Total	
|	SC1	4	2						6	35
|	SC2	8	2						10	
7.2	SC3	2	9	6	2				19	
7.3	SC1		8	4	2				14	67
|	SC2		7	12	6				25	
7.5	SC3		4	12	6	2	2	2	28	
7.6	SC1			14					14	38
|	SC2			2	2	4	2	2	12	
7.8	SC3			2	2	2	4	2	12	
7.9	SC1		2	8	7			2	19	38
|	SC2		1	2	6				9	
	SC3			2	2		2	4	10	
Total		14	35	64	35	8	10	12	178	

SC*: Class of Subsurface Structure

Table 3 Regression Coefficients of Equation (1)

Com.	Peak Amp	Regression Coef. α	β	γ
Vert.	Dis	-5.45	0.98	1.08
	Vel	-3.27	1.01	0.78
	Acc	-1.78	1.26	0.68
Hor.	Dis	-2.63	0.28	0.51
	Vel	-0.77	0.50	0.33
	Acc	0.31	0.84	0.31



(a) Vertical (b) Horizontal

Fig. 1 Estimated Response Spectra (SC2, Δ=290km)

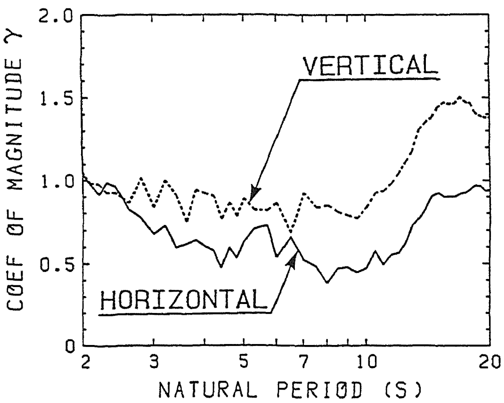


Fig. 2 Regression Coefficients γ for Earthquake Magnitude

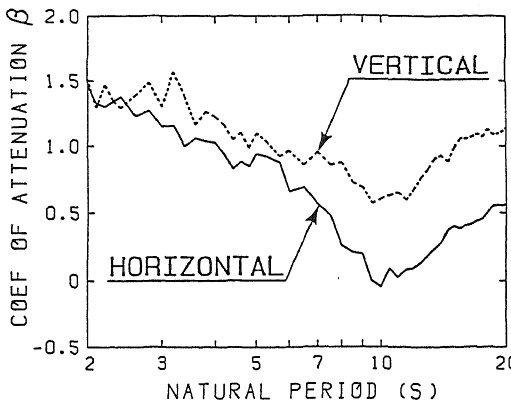


Fig. 3 Regression Coefficients β for Epicentral Distance

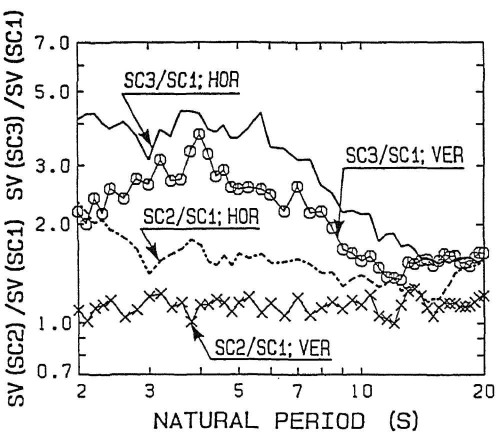


Fig. 4 Effect of Subsurface Structure on Response Spectra

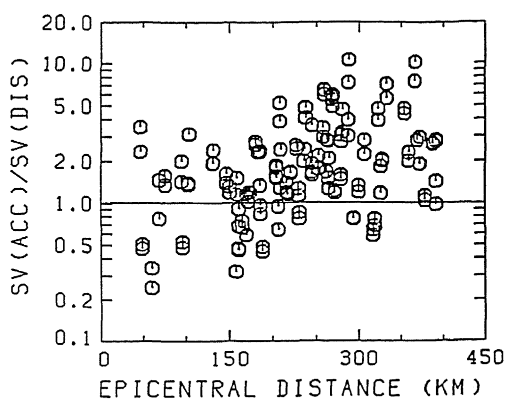


Fig. 7 Ratios of Average Horizontal Response Spectral Amplitudes (2-4 s) Estimated from Accelerograms to Those Estimated from Displacement Records

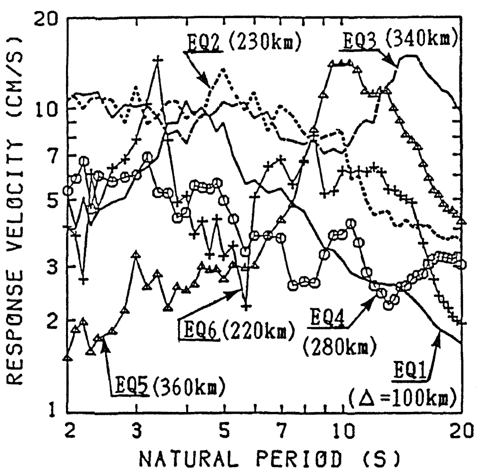


Fig. 5 Horizontal Response Spectra Estimated at SC1 Sites with Average Distances of Individual Earthquake Data

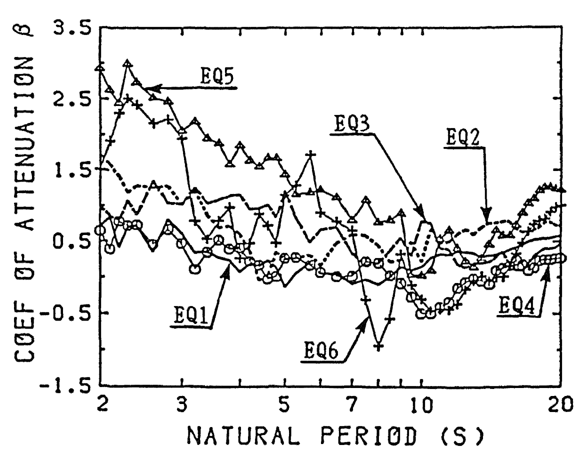


Fig. 6 Regression Coefficients β for Epicentral Distance (Horizontal Data of Individual Earthquakes)