SOME PROBLEMS IN DETERMINING EARTHQUAKE GROUND MOTIONS ON BASE ROCK

by

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Synopsis

The effects of the source, path and site conditions on the earthquake motions on the base rocks were separately discussed in the southern parts of Kyoto, through the observations of local small earthquakes and moderate ones. From the spectra of local small events, the source effects in this area seem to vary regionally, dependent on the seismic activity. The seismic waves obtained at the adjacent points on the base rock were spatially filtered by the surface topography and the local fine geology in relation to the wave-lengths.

1. Introduction

Most of the previous models proposed for idealizing earthquake ground motions have consisted of stochastic processes in which the physical properties of earthquak motions have hardly been taken into account because of complexity of recorded accelerograms. As the number of recorded accelerograms has increased and the physical interpretations of earthquake motions have made progress, it has been found that the Gaussian random accelerograms did not always resemble actually recorded accelerograms, so it has become necessary to develope a method of synthesizing the realistic ground motions on basis of the physical properties of strong motions.

Recently the data processing techniques of seismic waves have been developed to obtain various available seismological informations from recorded accelerograms. Then, assuming the effects of source, path and recording sites on earthquake motions, investigations on methods of synthesizing input seismograms appropriate to a given structure site were tried (Rascon and Cornell[2] 1968; Trifnuc[3] 1972; Lastrico, Duke and Ohta[4] 1972). However, few discussions based on observational results have been made on availability of various significant assumptions such as reappearence and regional characteristics of source, path and site effects on base rock motions.

Strong earthquakes occur infrequently, and therefore it is difficult to examine whether the motions at a given site that will be generated by a future earthquake are same, even if a strong motions were recorded. In this paper, some problems are discussed about the estimation of the characteristics of the strong earthquake motions on the base rocks in the southern parts of Kyoto, through the observations of local small earthquakes and moderate ones. This is examined from the following two points of view: First, reappearence of base rock motion and regional variation of source effects are discussed through the analysis of local small earthquakes occuring in the source region where a disastrous earthquake may be generated in future. Secondly, the spatial variation of spectral characteristics at adjacent sites in a drift and in an outcrop are discussed

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through the observations of nearby and further earthquakes.

2. Observational points, recording system and summary of analysed data

The observational points and the vicinity map are shown in Fig.1. The recording system consists of three component seismometers (1 Hz, 3 V/kine), DC amplifiers and magnetic data recorders. The overall instrumental response is shown in Fig.2. Before digitizing of seismograms analysed, analog high cut filters were operated to remove disturbance of higher frequency noises and to avoid aliasing errors. The epicenters of local small earthquakes analysed are plotted on the map shown in Fig.1. In the vicinity of Kyoto, small events occur concentratedly in the belt-like zone running south-west from the west coast of Lake Biwa to Osaka Bay and not so frequently in the southern region of the zone. Almost all of the observed small events have the focal depths of 5 - 20 km in the crust and the distributions of push-pull of P waves are considered to be similar.[5] The observed facts that the events occur in the bounded region seem to suggest that the physical properties such as strength and shear modulus vary regionally in the crust.

3. Variation of spectra of local small earthquakes observed at one site

Spectral characteristics of body wave from local small earthquakes in the vicinity of Kyoto were investigated in relation to the effects of source and propagation path. The intervals of analysis for spectra were selected to be 0.64 sec after initial motions for P waves and 1.28 sec for S waves. In most of the seismograms obtained, later phases with large amplitude seldom appeared within this interval and so the truncation errors in calculation of Fourier spectra were considered to be small. And also the analysed portions of the seismograms were considered to be relatively uncontaminated by surface waves generated secondarily during propagation and to travel from the source with less disturbance. Fourier spectra of the signals were then calculated by using the Cooley-Tukey algorithm, referred to velocity by correcting for instrument response. Amplitude characteristics of P waves of the small events analysed were predominant in frequency range of 10 - 20 Hz and those of S waves in frequency range of 5 - 15 Hz.

Spectra of the events recorded at the sites in a drift (site 1 and site 3 of Amagase) are subjected to the site effect due to interference of incident waves and reflected ones from the free surface. To discuss mainly in this section the effects of source and path, it is nacessary to remove the effects of the fine geological structure from the spectra. The site effects are discussed in a later section. For the site correction, smoothings were carried out by taking the mean of the spectra in the sub-range of 6 Hz width shown in Fig.3, and thus the smoothed response due to the site effect became nearly flat.

Regional variation of smoothed spectra -- analysis of the events observed at Amagase site

Magnitudes of the events analysed ranged from 1.0 to 2.5 and S-P time from 1.0 sec to 5.0 sec. The wave forms from the events occurring at the same location showed similar motions at the same recording sites as long as magnitudes of the events were not so different. However, the wave forms appeared to vary in correspondence to the source location.

The spectra of the events obtained were classified into four groups from their peak frequencies on the whole as shown in Fig.4. The events of A type with the peak frequencies in the lower range occurred most in the north-east region of the belt-like zone (A block in Fig.1); those of B type with relatively higher ones, occurred most in the south-west region (B block), while the events of C type with the highest peak frequencies occurred most in the southern region (C block).

In Fig.5 are shown the smoothed spectra of the transverse component of S waves; each group was classified from P waves' spectra. Although the spectral shapes of S waves were not so consistent in the same group, the mean spectra obtained from all events belonging to each group had the similar tendency of variation of the peak frequencies of P waves.

Regional variation of the spectral shapes depends on source and propagation path. The dependency of spectrum on these two factors is examined in following two ways; (1) Q values of propagation path and (2) coda spectra.

Evaluation of Q values of propagation path

Assuming that the spectral characteristics due to source effects are same and Q values are constant in the frequency range concerned, we tried to evaluate Q values of propagation path by means of the least mean square method for the frequency range of 10 - 25 Hz, from the relations of the spectral ratios $U(\omega_1)/U(\omega_2)$ to the S-P times as shown in Fig.6; for the northern region where events of A-type occur mainly, $Q= 510$ in the median $280 < Q < 3{,}100$ in the 75 % confidence limit and for the western region $Q = 770$ and $390 < Q < \infty$. Large scatterings of the ratio in Fig.6 are considered to show that a meaningful difference in the Q values of the two regions do not almost exist but the assumption of the source spectra may be unreasonable. From these results the regional variation of the spectra seems to be attributable to the source effects rather than the path effects.

Coda spectra

Coda waves obtained at a station near epicenters are regarded as back-scattered waves due to lateral heterogeneity in the wide area with the radius sufficiently large as compared with the distance between origins and the recording site, and hence coda spectra are considered not to be directedly dependent on propagation path, but on source. From the analyses of seismic coda parts from larger events (M= 2.5 - 3.5), the low frequency amplitude (1 - 2 Hz) depended on the fact, in which blocks the source location was contained, as well as on magnitude. That is, the amplitudes in A and B blocks were obviously larger than the ones in C block, when eliminating the effects of magnitude.

The smoothed spectra at another site -- analysis of the events observed at Kameoka site

Kameoka site is about 26 km in the north-west of Amagase sites and near the center of the belt-like zone noted above. The smoothed spectra of the events observed at Kameoka site seemed to vary regionally in similar tendency of variation of the spectra of P waves obtained in Amagase.

4. Difference of base rock motions recorded at adjacent sites from the same earthquake

The earthquake motions obtained on base rock are filtered spatially by the topography of base rock, underlying configulation, horizontal heterogeneity and so on. In this section, based on the comparative observations at adjacent sites on base rock, the effects of site conditions were examined. The surface topography around Amagase (two recording sites are in a drift) and Ohbaku (one recording site in an outcrop) is shown in Fig. 7. The velocity of P waves of this area is found to be 4.6 - 4.7 km/sec to depth of about 1 km from the data of explosion observations. Amagase sites in a drift and Ohbaku site in an outcrop are considered to be involved together in the surface layer formed of paleozoic strata V_p=4.6-4.7 km/sec.

Comparison of spectra of local small earthquakes

The intervals of the calculation of Fourier spectra shown in Fig.8 for the comparison among the wave forms at the 3 sites were 1.28 sec for both P waves and Swaves.

First, the comparison between the spectra at the two sites in a drift (site 1 and site 3 of Amagase) was made. The spectral shapes at the two sites were comparatively similar. However, there were some significant differences in the trough frequencies between the spectra of site 1 and the ones of site 3. That is, the remarkable troughs were seen around 8 Hz in the spectra at site 3, but around 9 Hz at site 1. And also the remarkable troughs (around 5 Hz) seen in the S waves' spectra at site 3 were lower than those (around 6 Hz) seen in the S waves' spectra at site 1. The trough frequencies were seen not to depend on the direction of the arrival.

The differences between the spectra at the two sites were found to be due mostly to the differences in the thickness of the overlying strata as shown in Fig.7. Theoretical responses of the site at depth of 140 m are calculated by means of the Thomson-Haskell matrix method with a half space model and one layer model as shown in Fig.9. The response of the vertical component of P waves is characterized by a large trough around 8 Hz independent of the incident angle. The trough moves to higher frequency when the depth of the site is shallower. The spectra of S waves are explained similarly.

The spectral shapes at Ohbaku site in an outcrop were different from those at the two Amagase sites in a drift for the frequency range of higher than 5 Hz, because of the absense of the overlying strata at Ohbaku site. And the spectra in the outcrop were seen to involve high frequency components more than those in the drift.

The peak frequencies of P waves' spectra at Ohbaku site were seen to vary from 8 Hz to 13 Hz, dependent on source location, as shown in Fig.8. The spectra of the events occurring in the north-east region of the belt-like zone had a peak around 8 Hz; the ones of the event in the south-west region had a peak around 10 - 13 Hz, while the ones of the event in the southern region had no remarkable peaks. This regional variation of the spectra was consistent with the tendency of the variation in the Amagase site, although the peak frequencies were different. This suggests that the variation of the peak frequencies of the events in each site is due to the source location, while the difference of the peak frequencies among each sites is influenced by the local geology.

Comparative observation of moderate earthquakes from further distances (> 100 km)

The spatial variation of the motions on base rock subject to site conditions such as the shapes of the base rock was discussed on the basis of the observational results of moderate earthquakes from further distances.

The response at the two sites in a drift and the site in an outcrop are nearly same in the frequency range less than 5 Hz, as shown in Fig.9, when theoretical calculations are made on assumption of a flat layer model . Then the low pass filtered seismograms (cut-off frequency, 5 Hz) in the three sites were compared.

Time domain

In Fig.10 were shown the examples of two earthquakes observed simultaneously at the three sites. The two events have nearly the same S-P time , but have extremely different focal depths, that is, the event No.248 has the very shallow focal depth, while the event No.246 has the deep ones. Similar wave forms were observed at the three sites for the event No.246, especially in P waves' portion, but this was not the case for the event No.248. The differences between these two events were considered to be due mostly to the differences of both the frequency components and the apparent incident angles.

From the comparison of several earthquakes, it was found that the wave forms at the 3 sites were similar when the apparent predominant frequencies were lower than 2 Hz and /or the incident angles were nearly vertical. On the other hand the wave forms with the apparent predominant frequencies of higher than 2 Hz have the less similarity among the three sites, as the incident angle became larger.

Frequency domain

The Fourier spectra of the initial portion (analyzed length, 5.12 sec) of P waves are shown in Fig.11. The epicentral distances of the earthquakes analyzed here are sufficiently large compared with the intersite distances.

First, the spectra at the two sites in a drift were compared. The spectral shapes at the two sites were comparatively consistent but the densities at every peaks were different. The deviation among the spectra at the two sites from the same earthquakea fluctuated about 50 % in the frequency range of 0.5 - 5.0 Hz.

Next the spectra at the sites in the drift and in the outcrop were compared. The spectral shapes of P waves in each site were similar in shape in the frequency range of lower than 2 Hz. And the densities at the site in the outcrop were about 1.5 times larger than those at the site in the drift. In the frequency range of higher than 2 Hz, the spectral shapes in the outcrop became complex in comparison with those in the drift and the peak frequencies were not so consistent. The densities in the outcrop were about 2 times larger than those in the drift as an average in the frequency range 2 to 5 Hz. This could not be explained from the difference of the responses between free surface and underground, based on the assumption of flat layer models. The actual response in the outcrop was considered to be amplified in relation to the local geology and topography around the site.[6]

The wave length of 2 Hz of P waves is about 2,000 m and this length is is comparable to the horizontal length of the relief in vicinity of these sites as shown in Fig.7. This is significant for estimating the amplification of soil deposites by comparing the records on allvium and on rock outcrop.

5. Conclusion

1. The spectra from local small earthquakes in this area varied regionally, dependent on the source locations. The regional variation of the spectra was considered to correspond to the regional variation of the activity of the small events.

The peak frequencies of the seismic waves from earthquakes are generally considered to be dependent on source size. This result, however, shows that spectral shapes are influenced by local characteristics of the source region as well. The diameters of the regional blocks in this case are 30 - 50 km as shown in Fig.1.

2. From the observations at several adjacent sites (in a drift and an outcrop) on the same rock, the base rock motions generated by an earthquake were found to vary spatially, especially when the wave-length of the motion were comparable to the wave-length of the relief of the base rock. Then the motions in the outcrop were 1.5 - 2.0 times larger than those in the drift, even in the lower frequency ranges (lower than 5 Hz in this case) where the effects of the free surface were small.

The motions in the drift in the higher frequency ranges where the wave-length of the motions was relatively small as compared with the wave-length of the relief were strongly influenced by free surface effects explained by flat layer theorem.

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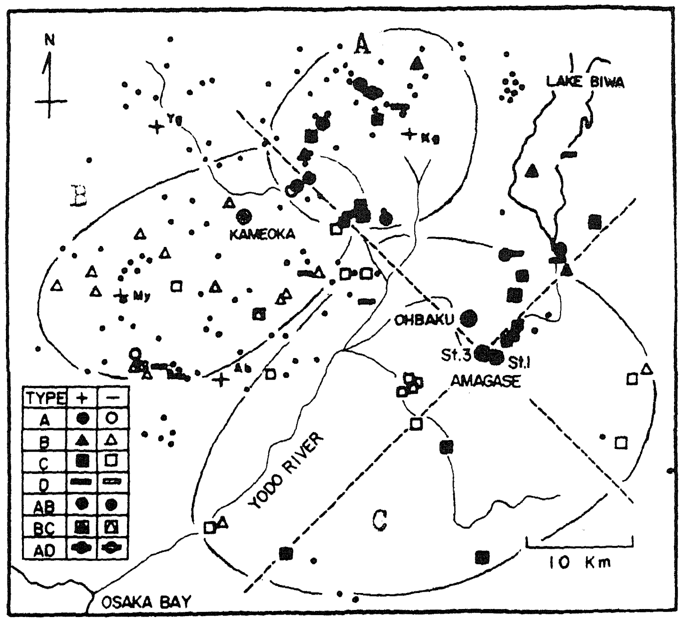


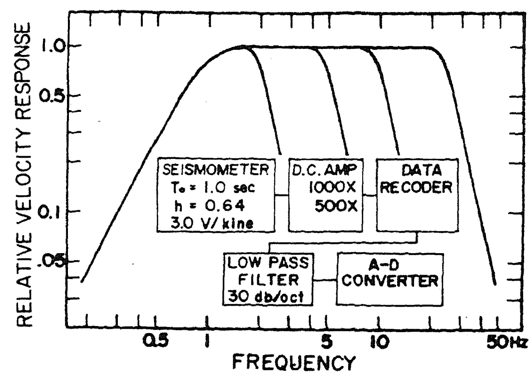
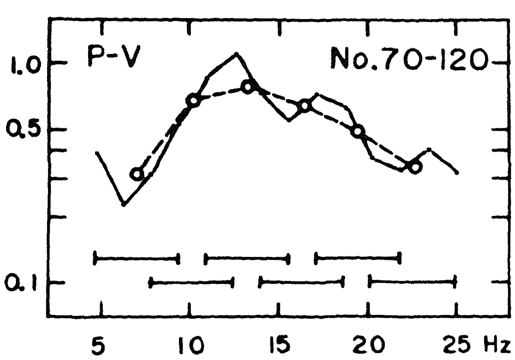


Fig. 2. Overall instrumental response curves.

Fig. 1. Location map of the observational points and regional variation of smoothed spectra of P waves. Area in the vicinity of Kyoto is divided into 3 blocks, A,B and C, by spectral shapes shown in Fig. 4. Dots denote epicenters of microearthquakes determined by the Abuyama Seismological Observatory (after Okano and Hirano [5]).



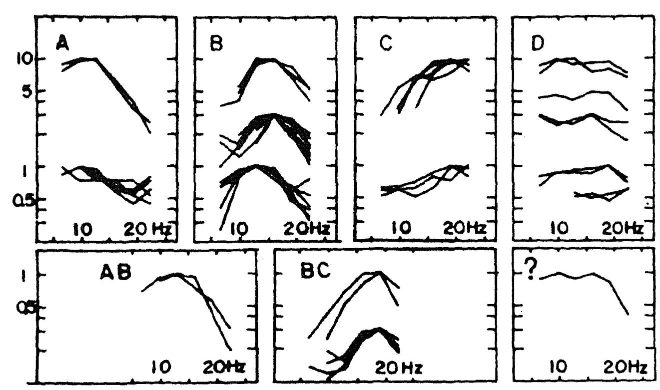


Fig. 3. Method of smoothing of spectra for site correction.

Fig. 4. Smoothed spectra of P waves from local small earthquakes, classified to 4 types, A, B, C and D on the whole.

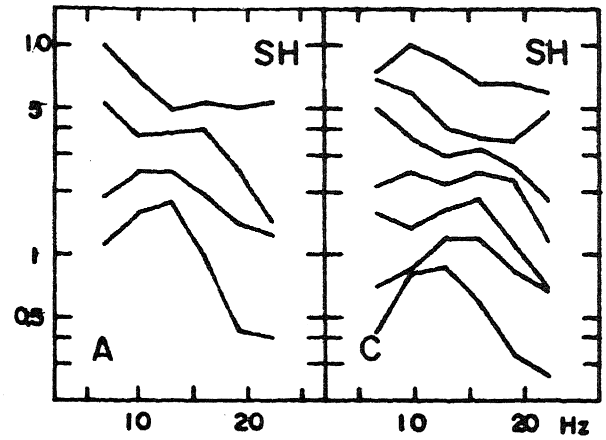


Fig. 5. Smoothed spectra of SH waves of the events those spectra of P waves are A type (left) and C type (right), respectively.

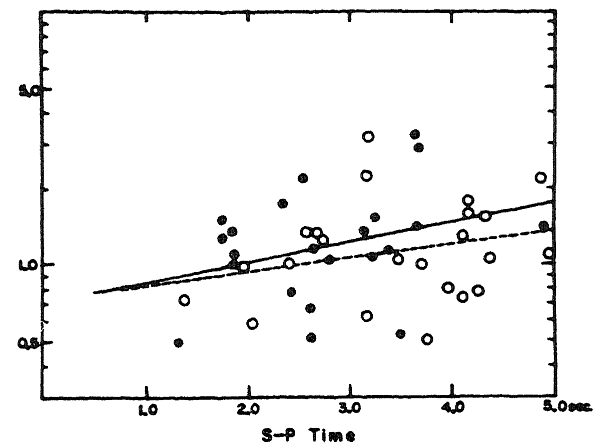


Fig. 6. Relations of spectral ratio U(12 Hz) / U(21 Hz) to S - P time. Closed and open circles denote the spectral ratios of the events occurring in the north and west regions, respectively. Inclinations of solid and broken lines indicate the Q values of the waves from the north and west regions.

Q value is determined from following equation:

$$\ln \frac{U(\omega_1)}{U(\omega_2)} = \frac{\omega_2 - \omega_1}{2\,Q\,v} \cdot r + \text{const.}$$

v : velocity
r : hypocentral distance

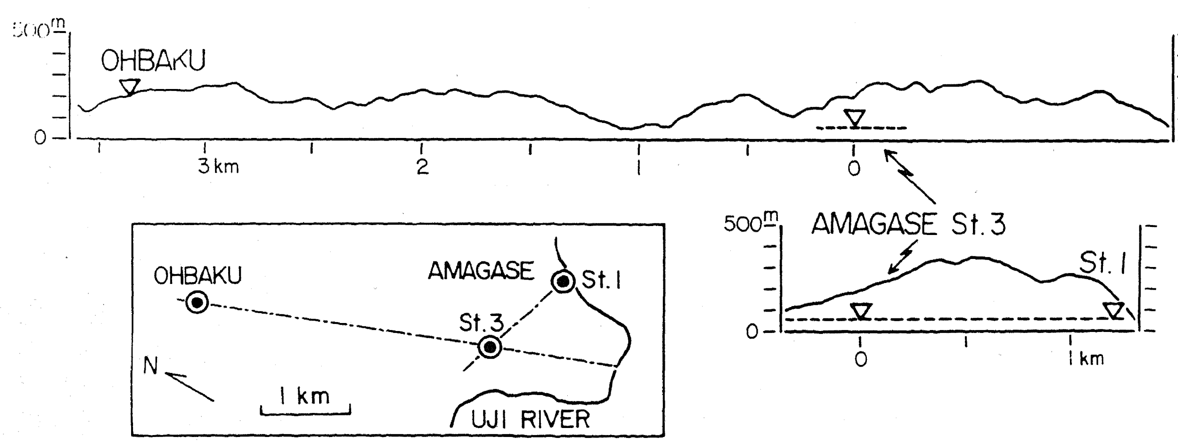


Fig. 7. Surface topography arround the observational points. Site 1 and Site 3 of Amagase are in a drift, while Ohbaku site is in an outcrop.

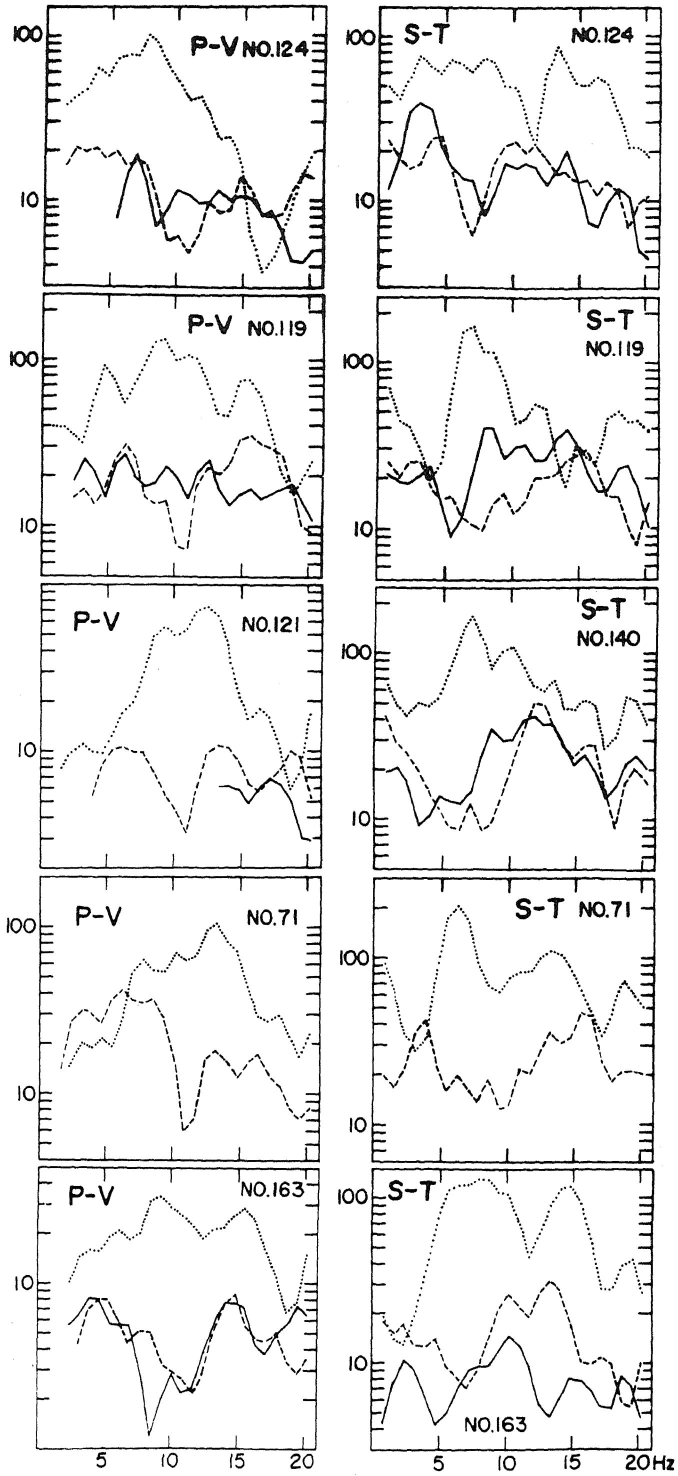


Fig. 8. Conparison of the spectra of P and S waves from local small earthquakes observed at the 3 sites.

———— Site 3 of Amagase
– – – – Site 1 of Amagase
········ Ohbaku site

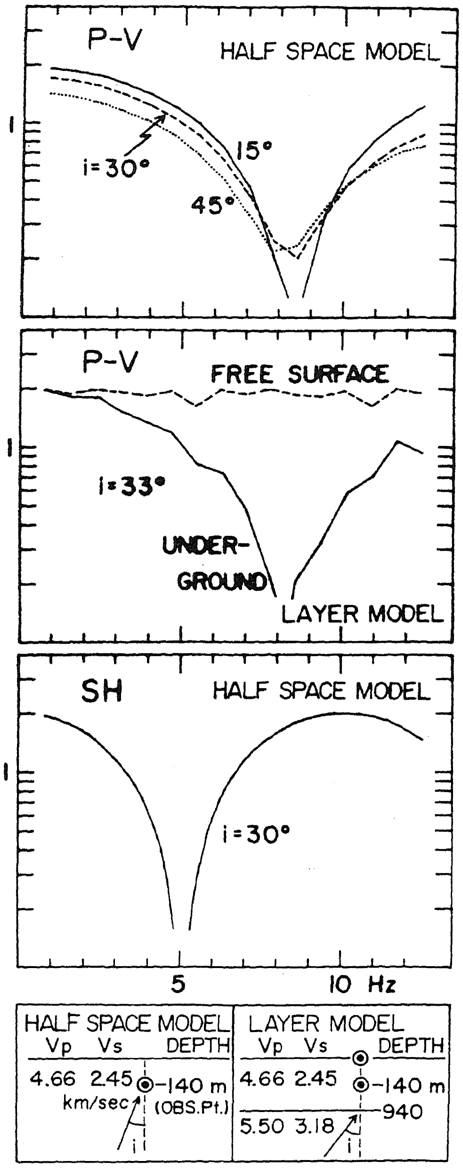


Fig. 9. Theoretical response of the underground.

No.	t_{s-p} sec	φ degree	Block
124	4.9	−11	A
119	3.24	−23	A
140	3.67	−58	B
121	3.02	−73	B
71	4.12	−86	B
163	2.20	+99	C

φ : Azimuth of epicenter

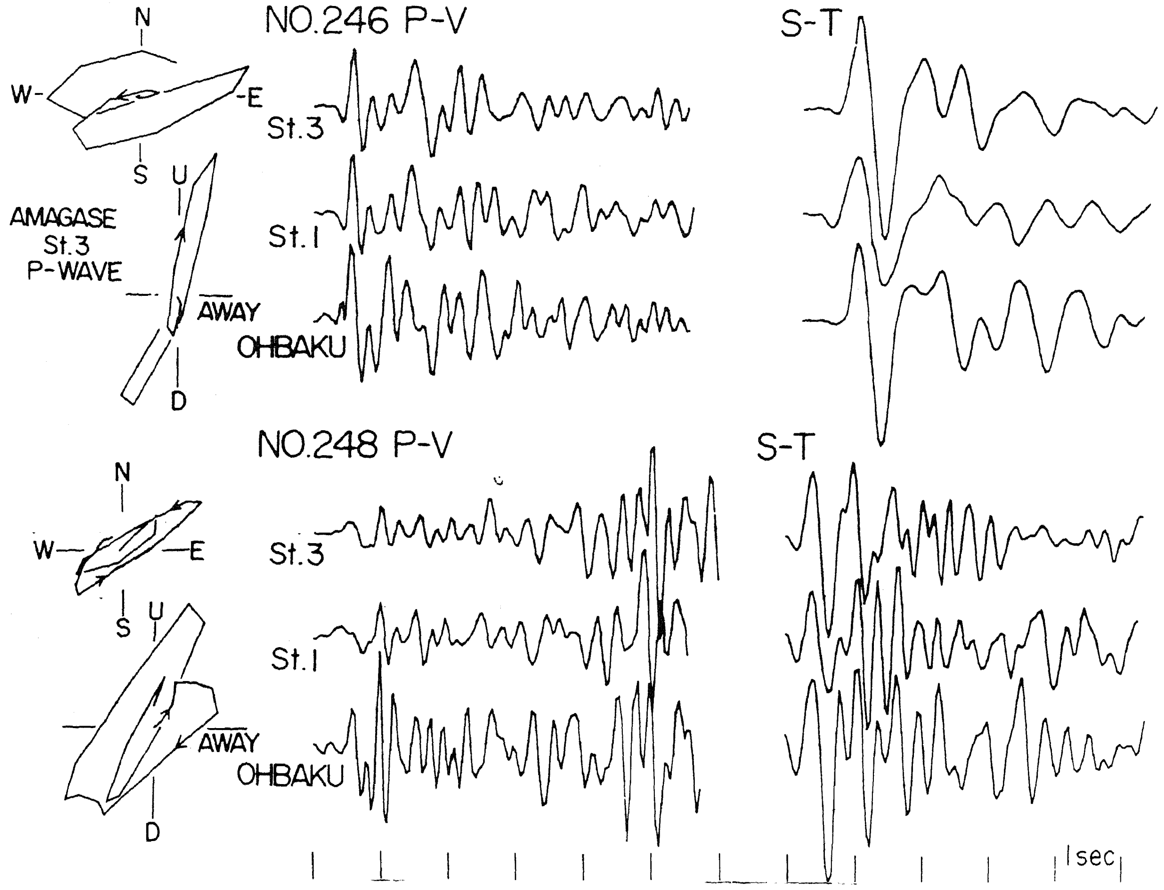


Fig. 10. Comparison of low pass filtered (5 Hz) seismograms of moderate earthquakes at further distances observed at the 3 sites and the loci of initial motions at Site 3 of Amagase. Amplitude scale factors are same for P portions but not same for S ones among the 3 sites.

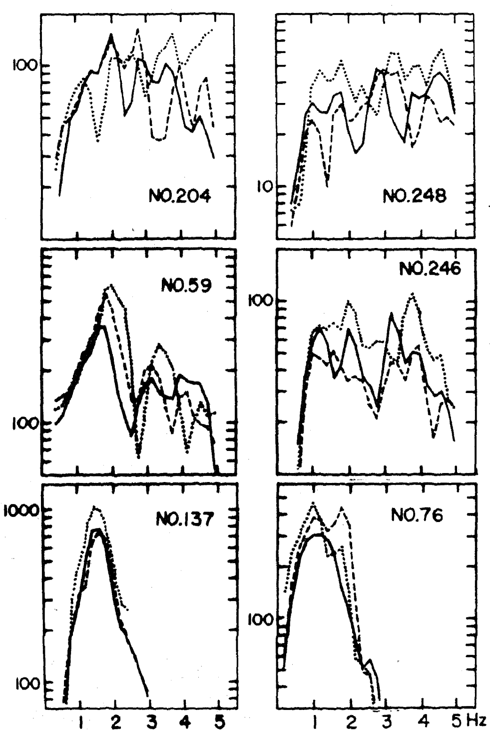


Fig. 11. Comparison of spectra of P waves from moderate earthquakes observed at the 3 sites. ——— Site 3 of Amagase; - - - - Site 1 of Amagase; .... Ohbaku site

No.	Δ	t_{s-p}	M	H	Azimuth	i
204		12.4			-132°	(36)
248	2.4°	33.8	3.7	20	49°	(40)
59	2.6°		5.3	10	75°	(34)
246		31.7		D	72°	12
137	8.9°		5.6	40	42°	33
76	39.3°		5.7	150	-169°	22

i : apparent incident angle
H : source depth   M : magnitude