EARTHQUAKE GROUND MOTIONS INFLUENCED BY IRREGULARITIES OF SUB-SURFACE TOPOGRAPHIES

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SUMMARY

The seismic responses of laterally varying layered structures are estimated by comparing the earthquake motions observed simultaneously on the soft ground and those on the rock outcrop. The effects of the surface topography on the seismic motions observed at the outcrop are examined by utilizing the spectral ratios of the vertical components to the horizontal components of P waves. The observed amplification characteristics of S waves' motions at the ground site are different depending on the directions of the seismic arrivals. The observed results are compared with the calculated values by the scattering theory and the ray theory.

1. INTRODUCTION

The effects of local ground conditions for seismic microzonings have been evaluated to depend only on the flat-stratified soil layers. However, the assumptions are far from real ground models underlying the site of interest, especially in basin areas and transitional areas of plain to mountain. Recently, numerous models have been proposed to calculate the effects of irregularities of surface and sub-surface topographies on ground motions (Aki and Larner, 1970; Trifunac, 1971; Wong, et al, 1977; Sabina, et al, 1978; Sesma, 1978). Their validity and range of applicability have not been determined yet, because only few examples are obtained of topographical effects on earthquake ground motions.

Direct estimations of seismic responses in laterally varying layered structures are attempted by observing earthquake motions on a soft ground and on a rock outcrop in the eastern part of the Kyoto basin in Japan. The grounds in this area are reported to be underlain by surface layers which are thicker towards the west direction. The first procedure to obtain the responses at the ground site is to estimate the characteristics of incident seismic waves at the bed rock. The effects of the surface topography on the seismic motions observed at the outcrop are examined by utilizing the spectral ratios of the vertical components to the horizontal ones of P waves. The relation between S waves' motions on the outcrop and those at the bed rock is studied by evaluating numenically the scattered wave fields when SH and SV waves are incident to irregular surfaces. As the second procedure, the seismic responses of the ground structures due to S waves are estimated by comparing the S waves' motions observed on the soft ground and those on the rock outcrop. The ground responses obtained here are compared with the theoretical values using scattering theory developed by Aki and Larner and ray theory devised by authors to calculate multiple reflections within dipping layers when SH plane waves are incident from the bed rock.

2. OBSERVATIONAL PROGRAM

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The study area is located at the eastern side of the southern part of Kyotobasin. Simultaneous recordings are made at the ground site, Co, underlain by soil layers (alluvium near surface and biluvium) and at the rock site, O_1, where paleozoic strata are outcropped. The locations of the observational sites and the underground profile from east to west are shown in Fig.1. The profile is determined by the seismic exploration using the refraction method of P waves (Kitsunezaki, et al, 1971). The distributions of S waves' velocities down to the depth of 50m at Co site are measured by well-logging (Goto, et al, 1972).

3. THE TOPOGRAPHIC EFFECT ON THE EARTHQUAKE MOTIONS AT THE ROCK OUTCROP

Observed Data. In order to estimate the input motions at the bed rock from the data observed on the surface of the rock outcropped, it has to be considered how the motions on the outcrop are influenced by the surface topography. In this study, the topographical effects are discussed in the method of examining the natures of the particle motions of P waves obtained at the single observational point, to make a comparison of the observed data with theoretical calculations. This is close to Phinney's method (Phinney, 1964), to interprete crustal structures by computing the spectral ratios of the vertical components to the horizontal ones of P waves. If the crustal structures have almost no azimuthal variations in the study area, P waves, obtained on a flat surface, from the events having the distances and depths of the same order should display much the same apparent angles for any directions of the seismic arrivals. The variations of the apparent angles as a function of the azimuth are considered to be mostly influenced by the local topographies near the site.

For this analysis, are used the seismic data through 5 Hz low-pass filter at the rock site, O_1, from shallow events having the focal depths within crust. The apparent angles of incidence of P waves are evaluated from particle motions diagrams in the vertical plane when the horizontal motions are divided into the radial components and the transverse ones to the directions of P waves' arrivals. Fig.3 displays the apparent angles as a function of the epicentral direction. Open circles and solid ones show the apparent angles from the events of 15 sec$> t_{s-p} >$ 8 sec and 8 sec$> t_{s-p} >$ 3 sec, respectively. For the apparent angles from the further-distance events (15 sec$> t_{s-p} >$ 8 sec), there are significant trends with respect to the directions of the seismic arrivals. The apparent angles of P waves arriving from the eastern directions appear to be larger than those from the other directions. The angles from near-distance events (8 sec$> t_{s-p} >$ 3 sec) show little trend

Comparison with Theoretical Models. A practical method is devised to calculate the elastic wave field in a half-space with an irregular free surface by Bouchon (1973). The scattered field is repressented as a superposition of plane waves with descrete horizontal wave numbers. The surface profiles near O_1 site on the outcrop are suitable to two dimentional modelling as illustrated in Fig.2. The theoretical predictions of the seismic motions at O_1 site as a function of the wave frequency are shown in Fig.4 for oblique incidence of the same angle (30°) from the opposite directions from each other. The plus sign of the incident angle means the seismic arrival from the east, i.e. basin to mountain area and the minus sign means the arrival from the opposite directions. The P waves' arrivals from mountain to basin area tend to show the larger apparent angles than do those from the opposite direction. The theoretical predictions of the topographical effects shown in the apparent angles of P waves' motions (Fig.4) have the same trends as the observed results (Fig.3), although the comparisons between the absolute values are not available. The theoretical predictions of the amplitude variations of S waves' motions are summerized for oblique incidence (30°) from the opposite directions in Fig.5. The amplitudes of SH waves at O_1 site are amplified by factors from 5 % to 8 % in the case of the seismic arrival from mountain to basin, and on the other hand, they are attenuated by factors from 0 % to 13 % in the opposite directions. The amplitudes of SV waves are more influenced by the surface topography than are those of SH waves.

4. SUB-SURFACE TOPOGRAPHIC EFFECTS ON GROUND MOTIONS

Spectral Ratio of S Waves' Motions between the Ground Site and the Rock Site. Comparisons are made between Fourier spectra of S waves' motions at the ground site, CO, and those at the rock site to examine the amplification characteristics by the soft surface layers underlying the ground site. Fig.6 and 7 display the spectral ratios of the ground motions to the rock motions. The data are analyzed from events having magnitudes of 3.5 to 4.6, shallow foci within crust and S-P times of 14 sec to 25 sec (epicentral distances of about 100 km to 200 km). For the computation of the spectra, the length of time window is 5.12 sec. To compare the same phases of S waves' motions between the two sites, the horizontal motions are divided into the radial components, R, and transverse ones, T, to the epicentral direction. The shapes of the spectral ratios of R and T components show large variances from event to event. This is much due to difficulties of separating SH and SV phases. To reduce the scatters found in the ratios of R and T components, the ratios of $\sqrt{Es}$, given by $\sqrt{R^2 + T^2}$, are computed. $\sqrt{Es}$ means the square root of energy spectra. When the S waves' velocities of surface layers are remarkably low in comparison with the velosity of the bed rock, the ground responses due to SV waves are like to those due to SH waves. Thus the ratios of $\sqrt{Es}$ might be considered to approximate the ground responses due to SH waves. The lowest peak frequencies of the $\sqrt{Es}$ ratios are around 0.5 Hz in the case of the arrivals from the west (Fig.6), i.e. basin to mountain, and on the other hand, larger than 1 Hz in the case of the arrivals from the east (Fig.7). The amplitudes at the peak frequencies range from factors 3 to 5 in both cases. These show a lack of any dependence on the directions of the arrivals because of the large scatter found in the individual ratios. The SH motions at the rock site, O_1, are not so much subjected to the topographical effects in the frequency range of lower than 1.5 Hz (see Fig.5). Thus the azimuthal variances of the predominant frequencies of the spectral ratios are considered to be caused to the effects of irregularities of sub-surface topographies on the seismic motions.

Seismic Response of Layered Media with Irregular Bed Calculated by Scattering Theory. The practical method are devised by Aki and Larner (1971) to calculate the surface motions of a layered medium with an irregular interface due to incident plane SH waves. The elastic field is assumed to be two dimentional. This method is valid for wavelengths which are larger than the magnitudes of the irregularities. In this paper, the calculations of the seismic response are made for multiflat-layered media underlain by an irregular bed rock, based on their method. It is cut down to present the techniques for numerical calculations. The ground site, C_1, is located near the eastern edge of Kyoto basin (see Fig.1). The ground structures beneath C_0 site are determined by the well-logging of S waves down to the depth of 50 m, as shown in model IV of Table 1, and inferred with respect to the depth of more than 50 m on the basis of boring data and geological formations. The surface motions are calculated for 4 ground models shown in Table 1, where the shape of the bed rock is approximated to be a cosine form for one cycle as shown in Fig.8.

Fig.9 displays examples of the horizontal distributions of the surface amplitudes for two frequencies (0.5 and 0.75 Hz) in the case of the incident angle of 30° from vertical. The amplitude distributions are not symmetric unlike the case of flat layers. This means the local amplifications by the ground structures are dependent on the directions of the wave arrival for oblique incidence. The C_0 site correspond to the location indicated by the arrow mark in Fig.8. Fig.10 shows the amplitude characteristics for incidence of 30° from the opposite directions from each other. The amplitude variations with the directions of the arrivals are the most remarkable in model I which have no flat surface layers and less in model III and IV which have thicker flat layers. The peak frequencies, appearing about 0.5 Hz, in the case of the arrival from the west are well consistent with the observed, but those from the east are not so. The azimuthal variations of the peak frequencies in any theoretical models tend smaller than those in the observed results. In this study area, the interfaces of the near surface layers as well as the bed rock are inferred to be not flat from the examination of the stratified soil formations (Kitsunezaki, et al, 1971). This is considered to cause the discrepancies between the theoretical values and the observed ones.

Seismic Response of Dipping Layers Calculated by Ray Theory. The ground structures in the immediate vicinity of C_1 site might be assumed to consist of dipping layers. The near-surface layers as well as the bed rock dip to the west. Several authors have considered the two-dimmensional problem of plane waves impinging under a dipping layer (Kane, 1966; Ishii and Ellis, 1970). We have extended their results to the structures involving two dipping layers.

When the SH phane waves impinge below dipping structures with the arbitrary incident angles, a computer algorithm is introduced for calculating systematically the timing and amplitude of every ray phase generated by refraction and reflection at the interfaces and the surface. The diffracted waves which are generated at the vertex of the wedge are ignored. The spectral characteristics of seismic responses of dipping structures are computed by Fourier inversion of the impulse responses in time domain obtained by this method. A shematic configulation of the layers and rays for calculation is shown in Fig. 11. When plane SH waves $u_0(t)$ are incident to the media at the angle θ_0, the surface displacement u(t) is given by the partial ray expansions in the following formulation,

$$u(t) = \sum_{m=1}^{M} \sum_{i=1}^{I} Q_{i,m} \cdot u_0(t), \quad I = 2\cdot(m-1) \qquad (1)$$

where $Q_{i,m}$ is given by the timing and amplitude for each ray. A ray procedure for the calculation is presented by authors' paper (Irikura, 1976).

Fig.12 shows the seismic responses for the ground models of two dipping layers illustrated in the bottom figure. Plus sign of the angle θ_o from the vertical indicate incidence of the up-dip case and minus sign, that of the down-dip case. That is, the plus angle θ_o corresponds to the seismic arrival from the east, mountain to basin. The chained curve in the same figure shows the response calculated by the flat layer model. The calculated responses in the cases of arriving from up-dip direction are found to be have lower predominant frequencies than do those from down-dip direction. The responses calculated for the ground model of θ_{d1}= 2.5° and θ_{d2}= 9° are comparatively consistent with the observed values. Thus the azimuthal variations of the amplification characteristics observed at the ground site, Co, are considered to cause to dipping of near-surface layers as well as dipping of the bed rock.

5. CONCLUSION

Direct estimations of seismic responses in laterally verying layered structures are attempted using the simultaneous recording data of earthquake motions on a soft ground and on a rock outcrop in the area near the eastern edge of Kyoto basin. The spectral ratios of S waves' motions between the ground site and the rock site are found to be different with the directions of seismic arrivals. The surface topographic effects at the rock site are found not to be so much as the azimuthal variations of the ratios, from the theoretical predictions using Bouchon's method. The seismic responses of flat near-surface layers underlain by bed rock of an irregular shape, calculated by Aki's method, tend always not to be consistent with the observed results. Supposing that not only the bed rock but also near surface layers are slightly dipping, the theoretical predictions of the seismic responses using ray theory tend to be comparatively consistent with the observed ones.

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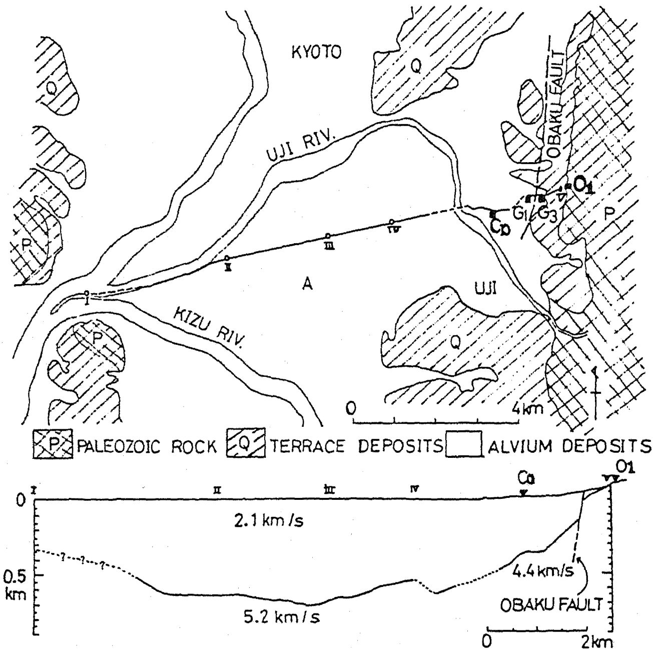

Fig. 1. Locations of the observational site C_0 and O_1, and the vertical profile of the ground structure.

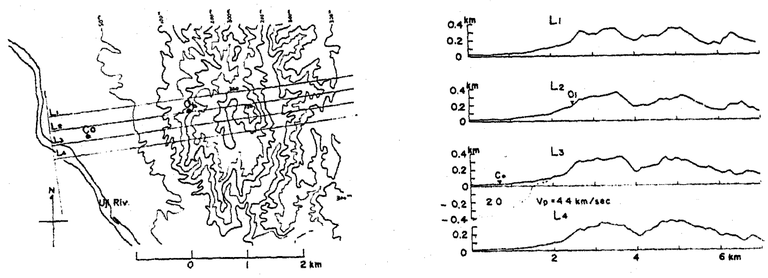

Fig. 2. Topographical map and cross sictions in vicinity of the rock site, O_1.

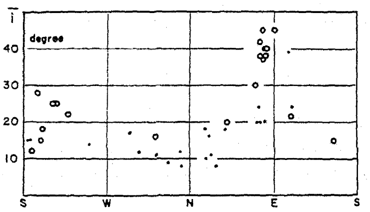

Fig.3. Azimuthal variation of apparent angles of incidence determined from particle motions of P waves in the vertical plane. Open circles and solid circles show apparent angles of incidence from events of $15 > t_{s-p} > 8$ sec and from events of $t_{s-p} < 8$ sec, respectively.

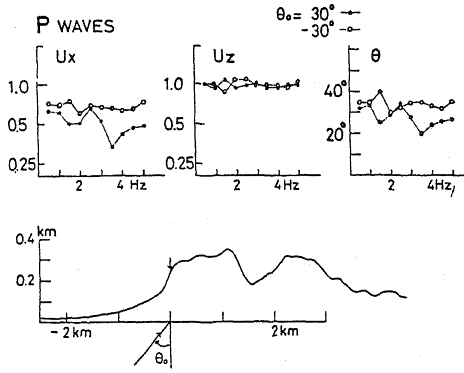

Fig.4. Amplitudes and apparent incident angles of surface motions at the rock site, O_1, for P waves arriving from different directions, θ_o=30° and θ_o=-30°.

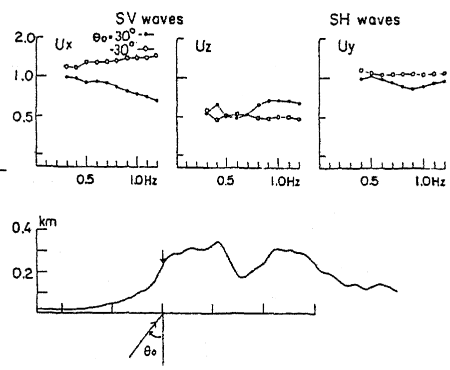

Fig.5. Amplitude-frequency characteristics of surface motions at the rock site, O_1, for SV and SH waves incident from different directions, θ_o=30° and θ_o=-30°

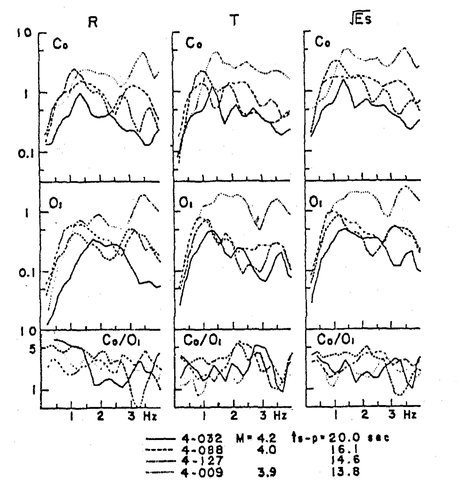

Fig.6. Fourier spectra of radial components and transverse ones of S parts and square roots of energy spectra, $\sqrt{Es} = \sqrt{R^2 + T^2}$, of seismic waves arriving from the west side.
Top: spectra at the ground site.
Middle: spectra at the rock site.
Lowerst: spectral ratios between the two sites. Window length for computation of spectra is 5.12sec.

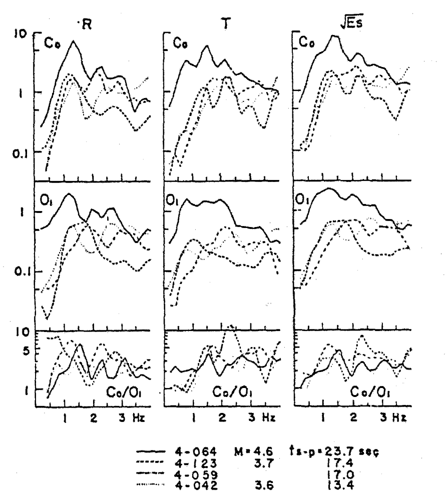

Fig.7. Fourier spectra of radial components and transverse ones of S parts and $\sqrt{Es} = \sqrt{R^2 + T^2}$, of seismic waves arriving from the east side.
Top: spectra at the ground site.
Middle: spectra at the rock site.
Lowest: spectral ratios between the two sites. Window length for computation of spectra is 5.12 sec.

Table 1. Parameters of layer modeal for the ground structure

Layer	Thicness (m)	S Velocity (m/sec)	Density (g/cm)	Layer	Thickness (m)	S Velocity (m/sec)	Density (g/cm)
MODEL I				MODEL IV			
1	0-750	800	2.0	1	3	250	1.7
2		2400	2.2	2	12	440	1.8
MODEL II				3	6	320	1.8
1	50	580	1.8	4	11	580	1.9
2	0-700	800	2.0	5	8	460	1.9
3		2400	2.2	6	60	580	1.9
MODEL III				7	0-650	800	2.0
1	100	580	1.8	8		2400	2.2
2	0-600	800	2.0				
3		2400	2.2				

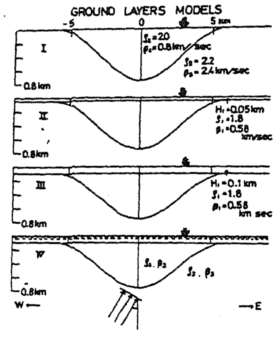

Fig.8.

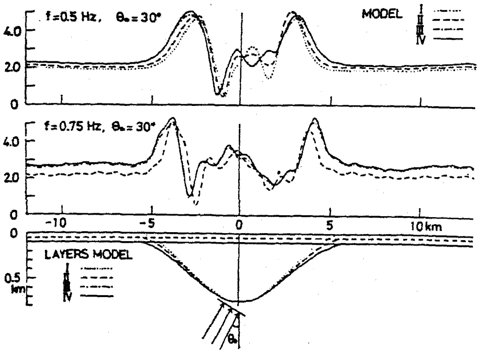

Fig.9. Horizontal distributions of surface amplitudes of 4 ground layers' models, shown by Table 1, for incidence of 30° of SH waves with unit amplitude, calculated by scattering theory using Aki's method.

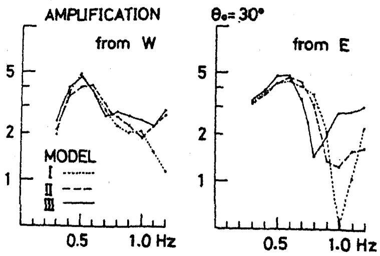

Fig.10. The variations of amplitude characteristics with the directions of the arrivals at the location of arrow marks in Fig.8.

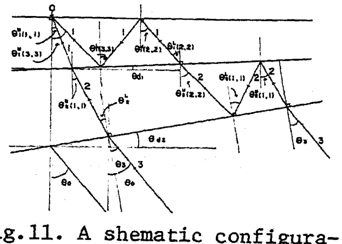

Fig.11. A shematic configuration of the layers and the rays generated by refractions and reflections at interfases and surface.

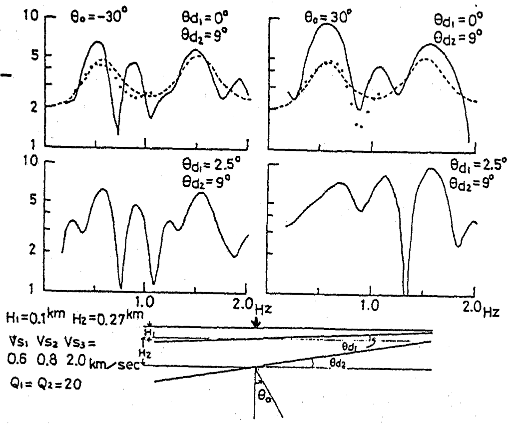

Fig.12. The seismic responses for the ground models of two dipping layers illustrated in the bottom. Chained curves, calculated by the flat model,and dotted curves,calculated by scattering theory, are plotted for comparison.