An Observed Effect of Topography on Seismic Ground Motions

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Abstract

An observation of local earthquakes occurring in the Kinki district was carried out at the Osakayama hill, situated in the southwestern part of Shiga Prefecture, in order to obtain data pertaining to effects of topography on seismic ground motion. Two sets of 3-component seismometers were installed respectively at the ridge crest of the hill and in a disused railway tunnel running through below the hill.

Analyzing some good quality records obtained simultaneously at the both observation points, a frequency-dependent amplification of motion at the crest relative to motion in the tunnel was clearly discerned for the component perpendicular to ridge strike. Horizontal particle motions and temporal variation of amplitude ratios were examined in detail with the use of bandpass filtered seismograms, and then it was found that the motions at the crest are polarized in the direction perpendicular to ridge strike compared with those in the tunnel. It was also found that the linearity of particle motion increase gradually with time. Judging from the fact that all the above mentioned phenomena are observed independently of either azimuth or wave type, they were attributed to resonance of the hill.

1. Introduction

It is well known that seismic damages often concentrate near and around the ridge crest of mountains. Therefore, a detailed understanding of the effects of topographic feature upon seismic ground motion is of obvious value to seismoengineering and numerous papers aimed at investigating the effects have been published. For instance, Davis and West (1973)[1] and Griffiths and Bollinger (1979)[2] performed field experiments and showed that frequency-dependent amplification of the motion at the crest relative to the motion at the base was observed. Boore (1972)[3] and Bouchon (1973)[4] were concerned with this problem theoretically and also demonstrated that the surface displacement appears to be very much influenced by surface irregularities and in the case of ridge, a zone of amplification takes place near the top. In most cases, however, investigation of topographic effects was based mainly on amplitude spectrum ratios and behavior of ground motion was not examined in detail. In this paper, making use of some records of local earthquakes observed simultaneously at the ridge crest of a hill and in the tunnel running through below it, we examine particle motions and time-dependent amplification of ground motions, in addition to the amplitude spectrum ratios, for the purpose of investigating not only the steady-state response to seismic excitation but also the concrete process of amplification.

2. Instrument Description and Seismic Data

Fig. 1 shows a topographical map and vertical sections of the Osakayama hill,

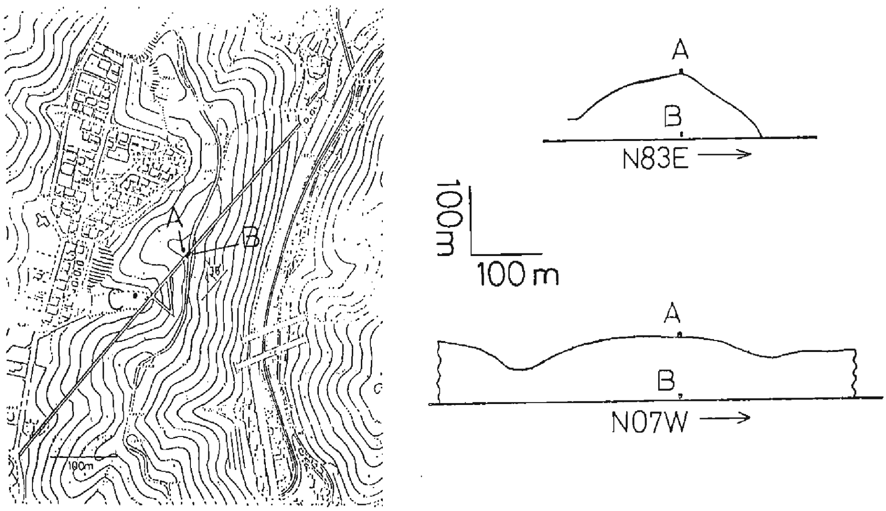

Fig. 1 Topography and station locations; A, at the ridge crest; B, in the tunnel; C, at the foot. Direction: N83E, perpendicular to the ridge; N07W, parallel to the ridge.

situated in the southwestern part of Shiga Prefecture, where the seismic observation was performed. The Osakayama hill provides a favorable condition for our study because the shape of the hill extending nearly from north to south lends itself raedily to two-dimensional modelling and because a disused railway tunnel running through below the hill could be utilized as an underground reference point where seismic motions may be free from any topographic effects.

Two sets of 3-component seismometers whose natural period is 1 second were installed in the tunnel and at the crest (and occasionally at the foot) of the Osakayama hill. In **Fig. 1**, A, B and C indicate the instrument locations. Site-A is on the ridge crest where elevation is the highest in the vicinity, site-B is in the tunnel and site-C is at the foot where topography is relatively flat. The heights of site-A and site-C above site-B are about 90 meters and 60 meters, respectively. Simultaneous observations were carried out usually at site-A and site-B and occasionally at site-B and site-C. The occasional observation was performed in order to resolve a question whether or not site-B can be considered to be an underground reference point free from topographic effects. At each site the horizontal seismometers were aligned respectively parallel and perpendicular to the direction of the tunnel, N38E–S38W.

Thus, 156 local events were recorded in the period from June 1980 to July 1981, and 18 good quality records were selected for processing and analysis, of which 14 records were observed at site-A and site-B and 4 records at site-B and site-C. The location of the sources of the selected events was given by the Regional Observation Center for Earthquake Prediction, Feculty of Science, Kyoto Univercity. The focal depths of the events range from 5 to 30 Km, the epicentral distances from 15 to 40 Km and the azimuths vary in a relatively wide range except for 110°–180°.

3. Analysis of Data

The original seismograms of horizontal components recording respectively in the direction of N38E–S38W and N52W–S52E were preliminarily examined by transforming them to several horizontal directions and then it was found that the effect of topographic feature of the hill could be most pronounced on seismograms corresponding to the direction parallel and perpendicular, respectively, to ridge strike. Therefore, preparatory to the following analysis, horizontal seismograms are transformed to the direction mentioned above and hereafter N07W component indicating the motion parallel to the ridge strike is referred to as L-component (longitudinal); N83E component indicating the motion perpendicular to the ridge strike is referred to as T-component (transversal).

Fig. 2 shows an example of seismograms recorded simultaneously at site-A and at site-B. Upper three and lower three components exhibit seismic ground motions at site-A and at site-B, respectively. It is noticeable that the amplitudes of short period motions are greater at site-A than at site-B throughout the seismograms. In particular, the amplitude of T-component recorded at site-A is remarkably large as compared with that of T-component recorded at site-B and the duration of S-coda signals in T-component is longer at site-A than at site-B. These features are common to all the records selected for analysis, regardless of focal depths, epicentral

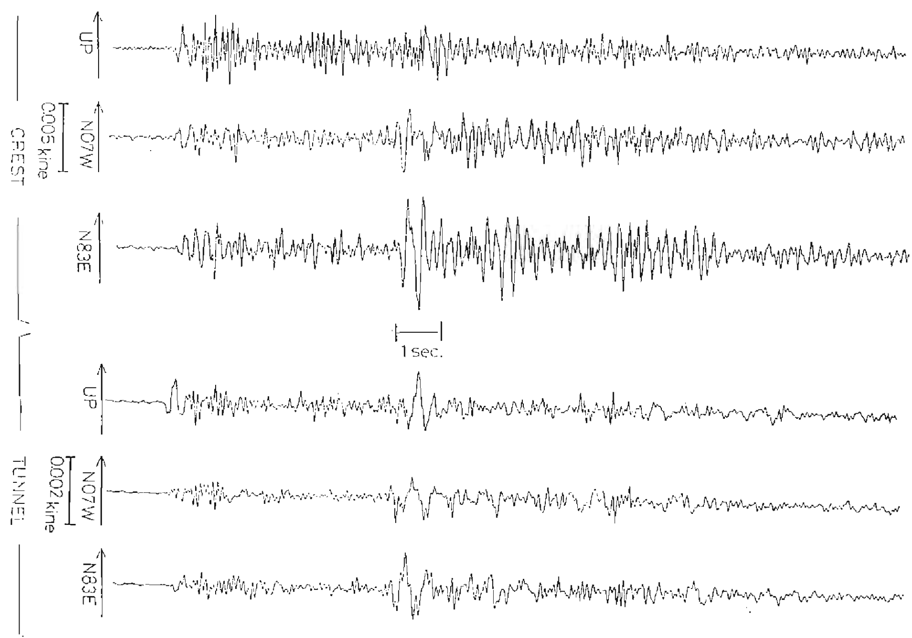

Fig. 2 Comparison of three-component seismograms recorded at the ridge crest (upper) and in the tunnel (lower). There is a noticeable difference in the predominant wave period and signal duration, especially for the N83E component.

distances and azimuths. It seems appropriate, therefore, to attribute the features to local site effects near around the hill.

Assuming that the ground motions recorded at site-B are free from topographic effects, we proceed to examine the amplitude spectrum ratios of the motions at site-A relative to the motions at site-B. **Fig. 3** shows the amplitude spectrum ratios obtained for P-wave and S-wave of each three component. For T-component, spectral ratio curves have a projecting value over a narrow range of frequency round 5 Hz, with the amplitude of about 15. For L-component, however, a noticeable change in the value of spectral ratios with frequency is never found. On the other hand, for vertical

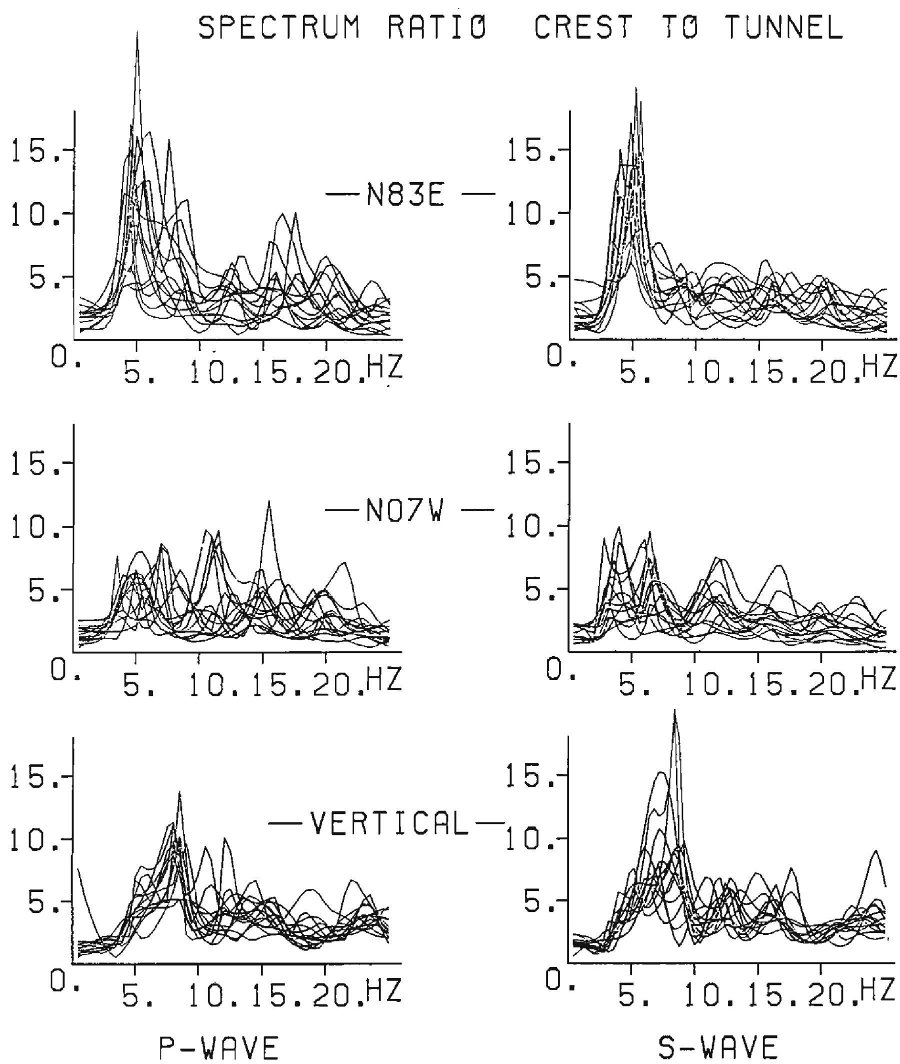

Fig. 3 Amplitude spectrum ratios

component, the manner in which the motions are amplified is different from that for horizontal components, that is, spectral ratio curves for vertical components peak over a range of frequency round 8 Hz. These features are recognized commonly in all the analyzed records and it is remarkable that the features mentioned above as to spectral ratios persist both for P-wave and for S-wave.

By the way, we have assumed that site-B is an underground reference point free from topographic effects. However, a question arises whether the assumption is valid or not. In order to resolve the question, we analyzed 4 good quality records of the occasional simultaneous observation carried out at site-B and site-C. **Fig. 4** shows amplitude spectral ratios for T-component, solid curves indicating the foot-to-tunnel ratios and broken curve indicating an typical example of crest-to-tunnel ratios shown in **Fig. 3**. It is evident from the figure that the foot-to-tunnel ratio curves have no projection round 5 Hz and is fairly flat over a frequency range of 3 to 9 Hz. Examining the foot-to-tunnel ratios in detail, it is noted that the ground motions recorded at the foot are not amplified in the frequency range lower than 2 Hz, implying that, in this frequency range, site-B behaves just like a surface observation point. On the other hand, amplification factor in the frequency range of 3 to 9 Hz is about 2. This means that, for wave motions in a frequency range of 3 to 9 Hz, site-B fills the role of underground reference point, since the amplitude of body waves on the free surface is twice as great as that of waves propagating within a

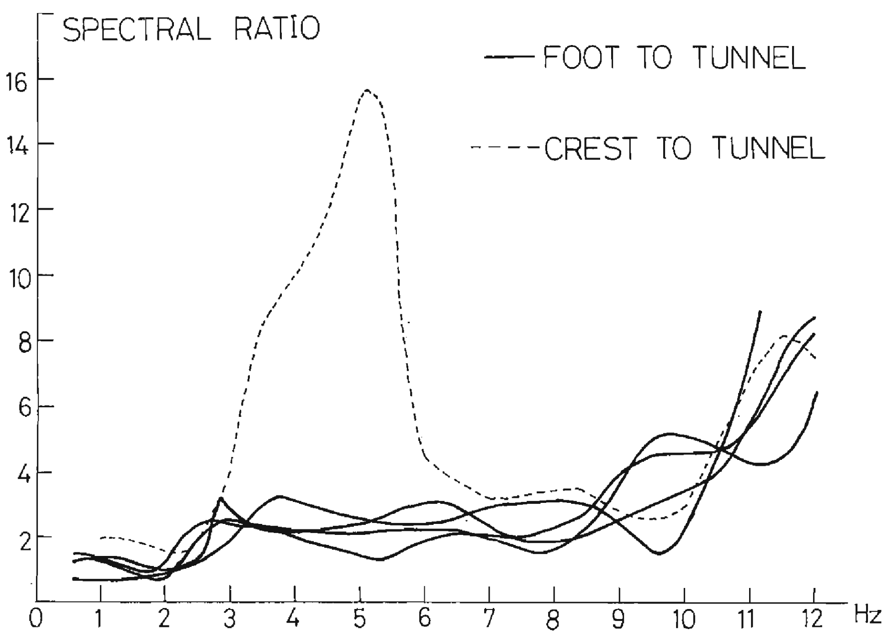

Fig. 4 Comparison of spectral ratio for the N83E component, solid curves showing the foot-to-tunnel ratio and broken curve showing a typical example of the crest-to-tunnel ratio.

homogeneous and isotropic half space. A fairly large amplification in a frequency range higher than 10 Hz would be caused by small geological structure (maybe thin surface layer). Therefore, our assumption seems verified as far as the motion in a frequency range higher than 3 Hz is concerned.

On the other hand, different from horizontal components, foot-to-tunnel ratio curves and crest-to-tunnel ratio curves of vertical component are similar in shape, both having a noticeable peak round 8 Hz, as shown in **Fig. 5**. This feature might be explained by means of effects of body-wave reflection and refraction within the local structure of layers. But, from this point of view, it seems difficult to explain the fact that spectral ratio curves for S-wave have a peak round 8 Hz in common with those for P-wave and there is no corresponding peak for horizontal components. Anyway, though the precise mechanism of amplification for vertical motion is presently not understood, it is certain that the cause of amplification for vertical component is different from that for horizontal components and topographic effects are more pronounced for horizontal than for vertical motion.

Accordingly, it can be concluded with confidence that on the ridge crest ground motions perpendicular to the ridge strike are very strongly affected by the topographic feature of the hill, amplitude ratios being more than 15 in a narrow range of frequency round 5 Hz.

In order to investigate the topographic effects in detail, we proceed to examine horizontal particle motions both at site-A and at site-B. **Fig. 6-a** shows an example of particle motions in a frequency range lower than 3 Hz. It is evident from the figure that locus of horizontal motion at site-A is similar in shape to that observed at site-B. This implys that horizontal motions in a range of frequency lower than 3 Hz are not affected by the topographic feature of the hill. **Fig. 6-b** shows horizontal particle motions in a frequency range of 4 to 6 Hz where crest-to-tunnel ratios for T-

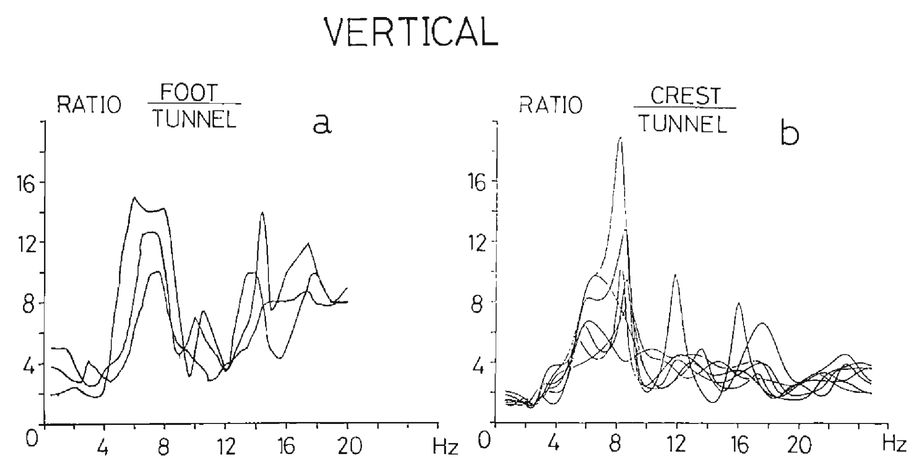

Fig. 5 Comparison of spectral ratio for vertical component, (a) foot-to-tunnel ratio and (b) crest-to-tunnel ratio

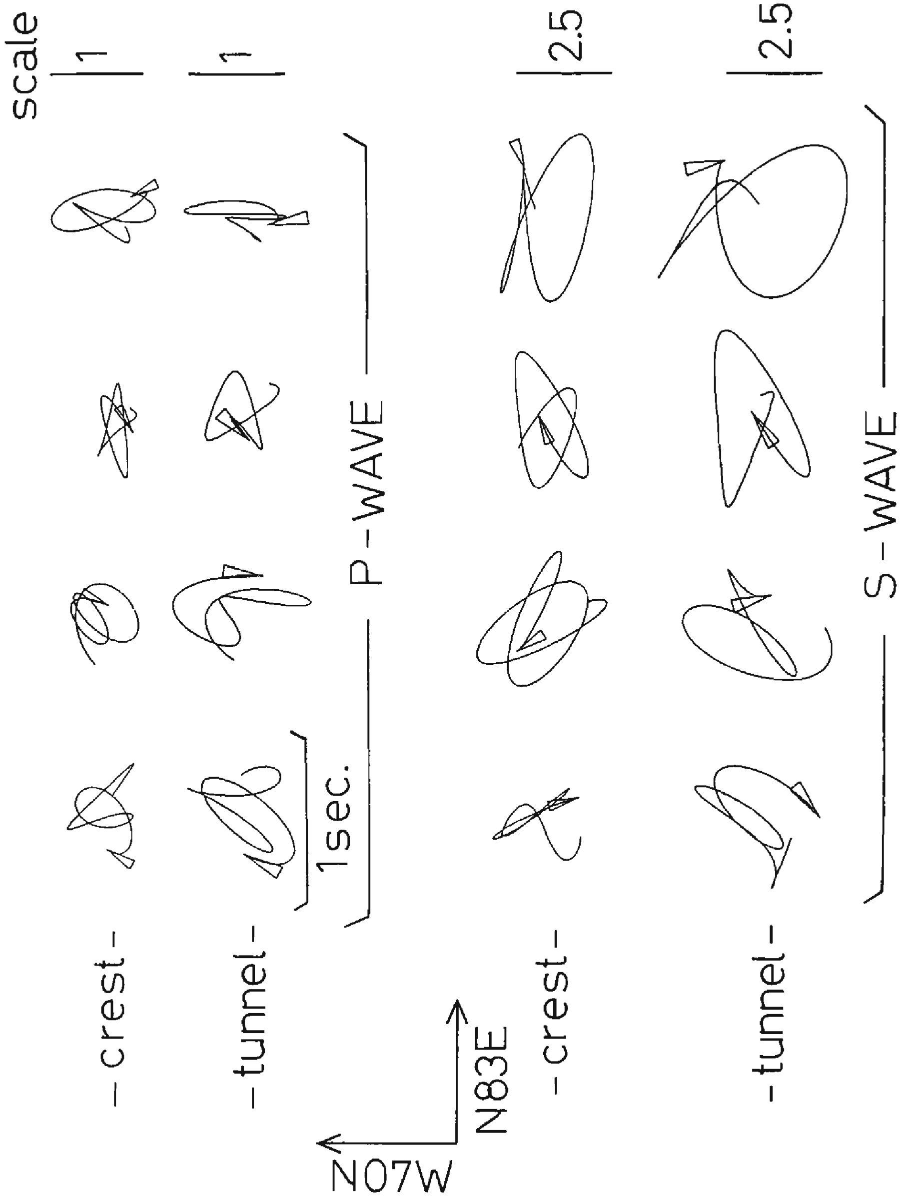

Fig. 6a Comparison of horizontal particle motions in the frequency range lower than 3 Hz

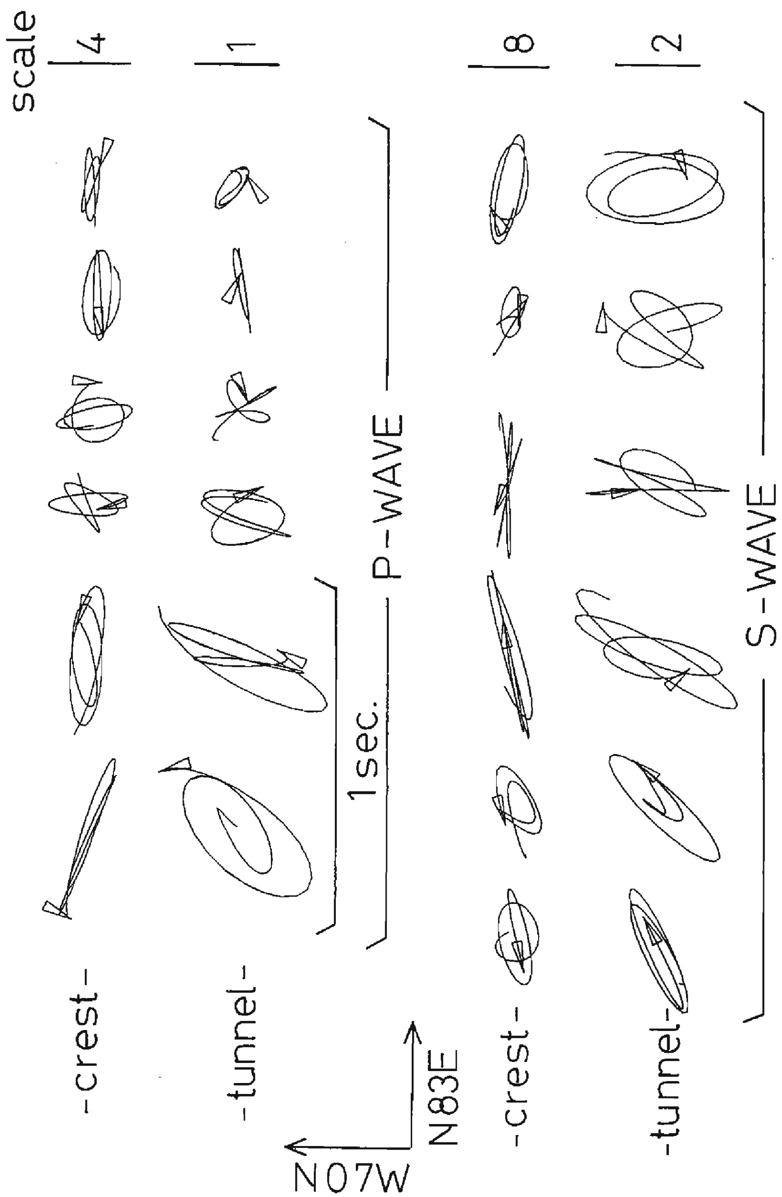

Fig. 6b Comparison of horizontal particle motions in the frequency range from 4 to 6 Hz

component have a projecting value, as shown in **Fig. 3**. In this case, there is a remarkable difference between horizontal motions at site-A and those at site-B. Horizontal motions at site-A are strongly polarized in the direction perpendicular to ridge strike, especially in the later part of P- and S-wave, though in the early part both motions somewhat resemble each other. Accordingly, it can be suggested that in a frequency range of 4 to 6 Hz horizontal motion at site-A is polarized in the direction of T-component, the linearity of particle motion increasing gradually with time. In a frequency range higher than 7 Hz, however, horizontal motion at site-A is not strongly polarized and there is no gradual increament of linearlity of particle motions.

Thus, the most likely reason for the projection of amplitude spectrum ratio round 5 Hz found for T-component is polarization of horizontal motions at the ridge crest in the direction perpendicular to the ridge strike.

In the next place, filtered seismograms in a frequency range of 4 to 6 Hz are analyzed in order to examine the time-dependent amplification of horizontal motions at the ridge crest. Taking into account that the polarization of motions, as mentioned above, is most prevailing in the S-wave portion of the seismograms, we confine our attention to a temporal variation of S-wave amplitude ratios estimated by using band-pass filtered seismograms. **Fig. 7** illustrates the method of estimation of

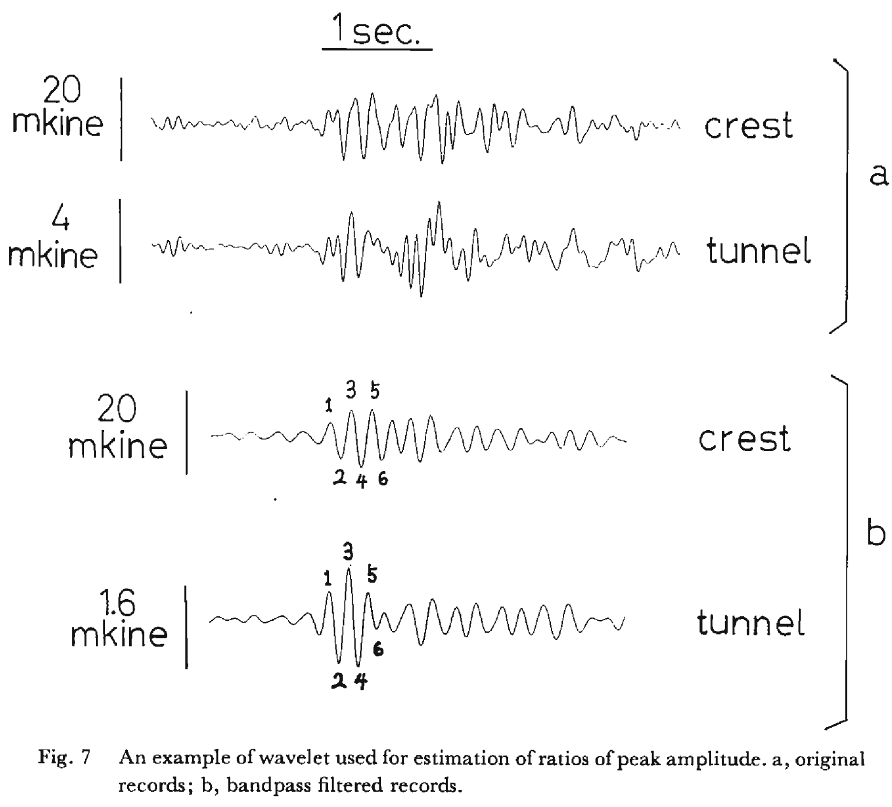

Fig. 7 An example of wavelet used for estimation of ratios of peak amplitude. a, original records; b, bandpass filtered records.

succesive amplitude ratios. As shown in the figure, peaks and troughs of wave trains are numbered in order, so that the corresponding phase at site-A and at site-B may be identified by the same number. The n-th peak-to-trough amplitude, that is, the amplitude between the n-th peak (or trough) and corresponding following trough (or peak), is denoted by "A_n" for motions at site-A and "B_n" for motions at site-B, and then ratios of A_n to B_n are plotted in accordance with the number "n". In **Fig. 8** open and solid circles indicate A_n/B_n for T-component and open and solid triangles A_n/B_n for L-component. Open symbols (circle and triangle) denote most accurate values of the ratio obtained from S-waves with simple waveform and solid symbols denoting the values of ratio obtained from the first 4 or 5 cyles of S-waves with composite waveform. It is evident from **Fig. 8** that the variation of A_n/B_n for T-component is different from that of A_n/B_n for L-component. For T-component, the amplification factor is about 5 in the early part of S-wave train and, increasing gradually with time, the amplification factor eventually amounts to more than 15 in the later part of the wave train. On the other hand, such a gradual increment of amplification factor is never found for L-component and ratios of A_n to B_n remain constant from beginning to end.

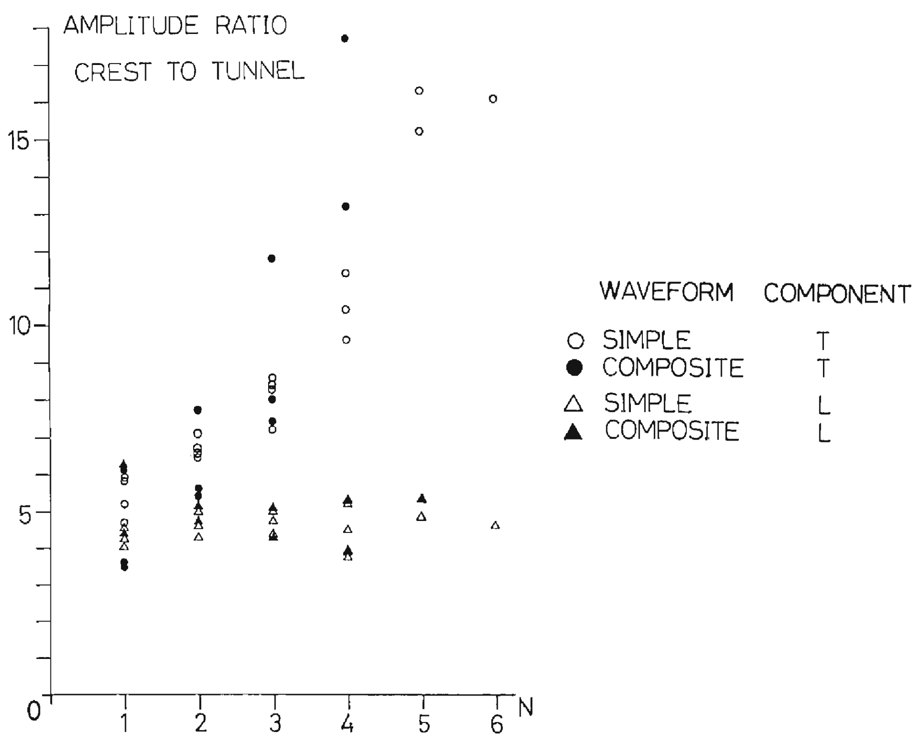

Fig. 8 Temporal variation of ratios of peak amplitude (crest-to-tunnel) in the frequency range from 4 to 6 Hz. T, transversal component perpendicular to ridge; L, longitudinal component parallel to the ridge.

After all, judging from the manner in which the motions are amplified, it seems possible to infer that the hill is excited at the resonant period in the direction perpendicular to ridge strike by the incident seismic wave motion. This inference yields a reasonable interpretation of the fact that, as shown in **Fig. 3**, amplitude spectrum ratio curves are similar in shape for P- and S-wave in spite of the difference of the wavelengths.

Comparison was made between theory and observation. Agreement between theory and observation is good as far as the fact that horizontal motion perpendicular to ridge strike is most strongly affected by topography. But, in quantitative estimation, there is a difference between theory and observation. For example, the amount of amplification estimated in this paper is factor of about 2 greater than Bouchon's result[4]. At present, it is difficult to explain the difference and we have to be contented with suggesting that the resonance of topographic features might bring about some modification in the results attained by theoretical calculation.

4. Conclusion

In this paper topographic effects on seismic ground motions were investigated, using some good quality records of local earthquakes observed simultaneously on the crest and in the tunnel. Noticeable feature were found out as follows:

1) For T-component, crest-to-tunnel spectral ratio curves peak over a narrow range of frequency round 5 Hz regardless of the wave type (P-wave or S-wave) and amount of amplification is the same or more than 15. On the other hand, for L-component, there are no clear peaks.

2) In a frequency range lower than 3 Hz, there is scarcely any difference between horizontal particle motions on the crest and those in the tunnel. In a frequency range of 4 to 6 Hz, horizontal motions on the crest are polarized in the direction perpendicular to ridge strike and the linearlity of particle motions increase gradually with time.

3) For T-component, the manner in which the motions are amplified exhibits a peculiar feature. Concerning with S-wave portion of seismogram, amplification factor increases gradually with time. On the other hand, for L-component, amplification factor remains almost constant. As a result, signal duration of T-component on the crest is much longer than that of the other component.

After all, we conclude that all the phenomena investigated in this paper can be attributed to resonance of the hill excited by incident seismic wave motions.

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The data processing was run on a FACOM M-382 at the Data Processing Center of Kyoto University.

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