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PREDOMINANT DIRECTION OF STRONG MOTION S-WAVES AND ITS SPATIAL VARIATION AT CHIBA ARRAY SITE

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S-wave records for 17 earthquakes observed by a dense accelerograph array are analyzed to investigate the source, path and site effects on polarization of strong ground motion. The polarization characteristics averaged over the array do not agree with those expected from the focal mechanism. The direction of the average polarization varies with frequency, and the degree of the average polarization decreases with increasing in the earthquake magnitude and the hypocentral distance. Each of the observation points shows its own local site effect on polarization of strong ground motion. It is suggested that the local site effect is caused by some anisotropic property of the surface layers.

Key Words : *strong ground motion, predominant direction, spatial variation, Chiba array, directional site resonance*

1. INTRODUCTION

Seismic ground motions synthesized based on an earthquake source model in a homogeneous isotropic medium have polarization characteristics which reflect the radiation pattern of seismic waves at the earthquake source. Generally, they show strong polarization and the maximum eigenvalue obtained through the principal axis analysis[1),2)] of ground motions is much larger than the other two eigenvalues. Actual ground motions, however, rarely show such strong polarization. The weak polarization of actual ground motions would be caused by nonuniformity of the radiation pattern of seismic waves on an earthquake fault plane[3)], influence of reflected and scattered waves[4)], and effects of topography and spatial variation of seismic wave velocity in surface layers at observation sites[5),6)].

Recently, Bonamassa and Vidale[7)] examined dominant directions of ground motions due to several aftershocks of the Loma Prieta earthquake of October 18, 1989. They found that only the first pulse of direct S-waves in the frequency range from 0 to 2 Hz shows the dominant direction expected from the focal mechanism. In the frequency range from 1 to 18 Hz, both the direct and the scattered S-waves show one preferred direction of strong ground shaking at each observation site independently of the earthquake focal mechanism. Also, Vidale et al.[8)] analyzed records of the Whittier Narrows earthquake of October 1, 1987, and its aftershock of October 4. They found that the dominant directions of strong ground motions for the two events are similar to each other at 8 stations out of 13 stations in spite of the difference between their focal mechanisms. They concluded that surface layers at each site have one preferred direction of strong amplification of incident seismic waves and named this phenomenon 'directional site resonance'.

One of the most effective way to examine influences of local site conditions on earthquake ground motions is the analysis of array data. It is well known that coherence between ground motions at two observation sites decreases with increasing in the distance between the sites[9)~11)]. The decrease in coherence with distance is more rapid for higher frequency contents of the ground motions. Katayama et al.[10),11)] pointed out through an analysis of the Chiba array database that dominant directions of high frequency ground motions during an earthquake are very different among the observation points of the array while those of low frequency contents are similar to one another.

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Izutani and Terada[12] investigated dominant directions of 8~10 Hz ground motions at the Chiba array site and separated qualitatively the effects of source, path and local site conditions on the dominant directions. They found that the dominant directions of ground shaking due to relatively large earthquakes tend to coincide with one another at each observation point. On the other hand, the dominant directions for relatively small earthquakes are not so influenced by local site conditions because the polarization of incident waves is strong for small earthquakes.

In the present study, analyses similar to the previous paper[12] are made for ground motions of 0~2, 2~4, 4~6, and 6~8 Hz contents. Polarization characteristics of ground motions are examined in terms of the earthquake magnitude, the hypocentral distance and the frequency of ground shaking. Also, the effect of local site condition is discussed in relation to shaking characteristics of surface layers during earthquakes.

2. METHOD

Since the method of analysis used in the present study has been described in detail in the previous paper[12], we briefly summarize it.

Accelerograms for 17 events in the Chiba array database[10),11)] are analyzed, which were recorded by accelerometers installed at a depth of 1 m of 9 observation points (C0~C4, P1~P4). These 9 points are located in a circle with a radius of 15 m (see **Fig. 5**). The epicentral distances of these events are shorter than 70 km. Accelerograms are processed through each of 5 kinds of band-pass filters (0~2, 2~4, 4~6, 6~8, and 8~10 Hz). The principal axis analysis is carried out for S-wave records picked out by a data window whose width is 5 sec. A small change of the window width affects little the result of the principal axis analysis.

Since only S-waves are treated, the major and the intermediate principal axes of strong ground motions are nearly horizontal. The dominant direction of ground shaking is represented by the direction of the major axis, ϕ_{jk}, measured counter clockwise from the east, where subscripts j and k stand for the event and the observation point, respectively. The degree of polarization is expressed by γ_{jk}, the ratio of the intermediate eigenvalue to the maximum eigenvalue.

Observed polarization, (ϕ_{jk}, γ_{jk}), must be affected by characteristics of the earthquake source, the wave propagation path and the local site condition. Fourier spectrum, $O(f)$, of observed ground motion is generally expressed as,

$$O(f) = S(f)P(f)G(f) \tag{1}$$

where $S(f)$ is the source spectrum, $P(f)$ and $G(f)$ are the effects of the path and the local site condition. Similarly to the spectrum, we assume that the observed polarization, (ϕ_{jk}, γ_{jk}), is the result of composition of the average polarization among the 9 observation points, (ϕ_j, γ_j), and the deviation at each observation point, (ϕ_k, γ_k). The average polarization, (ϕ_j, γ_j), includes the radiation pattern of S-waves at the earthquake source and the effect of the wave propagation path from the source to the Chiba array. It represents the average shaking characteristics of the Chiba array site during the j event. The deviation, (ϕ_k, γ_k), represents very local effect of surface layers at the k point. Although the site effect might depend on the incident direction of seismic waves, we assume that (ϕ_k, γ_k) are constants independently of the events. When γ_k is small, the k point tend to shake in the ϕ_k direction during any earthquakes.

The average polarization, (ϕ_j, γ_j), and the local site effect, (ϕ_k, γ_k), are expressed by ellipses as shown in **Fig. 1**. The direction of the longer axes of the ellipses shows ϕ_j or ϕ_k and the ratio between the lengths of the longer and the shorter axes shows γ_j or γ_k. The composition of (ϕ_j, γ_j) and (ϕ_k, γ_k) is assumed to be carried out by the multiplication between the radii of the ellipses in every direction. The result of the multiplication cannot be expressed with an ellipse. For simplicity, we assume the following relationship in order to express the multiplication result with an ellipse.

$$\phi_{jk} = \begin{cases} \phi_j \ ; & \phi_j = \phi_k \pm 90^\circ \text{ and } \gamma_j < \gamma_k \\ \phi_k \ ; & \phi_j = \phi_k \pm 90^\circ \text{ and } \gamma_j > \gamma_k \\ \frac{\{\gamma_k(1-\gamma_j)\}\phi_j + \{\gamma_j(1-\gamma_k)\}\phi_k}{\gamma_k(1-\gamma_j)+\gamma_j(1-\gamma_k)} ; & \text{otherwise} \end{cases} \tag{2}$$

$$\gamma_{jk} = \begin{cases} (\gamma_j/\gamma_k)\sin^2(\phi_j - \phi_k) + \gamma_j\gamma_k\cos^2(\phi_j - \phi_k) \\ \qquad ; \ \gamma_j < \gamma_k \\ (\gamma_k/\gamma_j)\sin^2(\phi_j - \phi_k) + \gamma_j\gamma_k\cos^2(\phi_j - \phi_k) \\ \qquad ; \ \gamma_j \geq \gamma_k \end{cases} \tag{3}$$

Examples of the composition of (ϕ_j, γ_j) and (ϕ_k, γ_k) by Eqs. (2) and (3) are shown in **Fig. 1**. **Fig. 1(a)** shows that the Chiba array site is shaking in an isotropic manner in average during the j event and the k point has the local site effect, (ϕ_k, γ_k). In this case, the resultant polari-

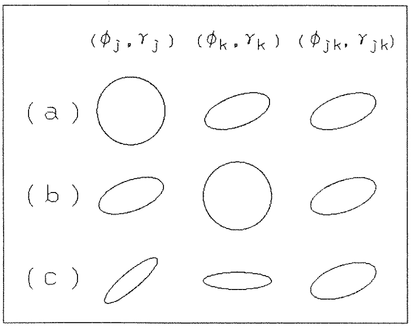

Fig. 1 Examples of the composition of (ϕ_j, γ_j) and (ϕ_k, γ_k) by Eqs. (2) and (3).

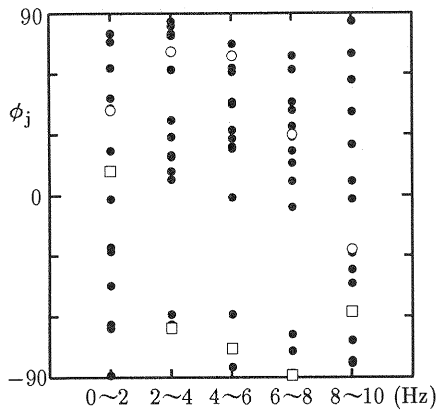

Fig. 2 Average polarization direction ϕ_j.

zation, (ϕ_{jk}, γ_{jk}), agrees with (ϕ_k, γ_k). **Fig. 1(b)** shows that average polarization at the Chiba array site is (ϕ_j, γ_j) during the j event and the k point has no local site effect. In this case, the resultant polarization, (ϕ_{jk}, γ_{jk}), agrees with (ϕ_j, γ_j). **Fig. 1(c)** shows a general case.

(ϕ_j, γ_j) for 17 events and (ϕ_k, γ_k) for 9 points are estimated for 5 frequency contents of ground motions by minimizing squares of residuals between observed (ϕ_{jk}, γ_{jk}) and those calculated by Eqs. (2) and (3). It should be noted here that Eqs. (2) and (3) have no exact physical meaning. However, they are considered to be appropriate for qualitatively expressing the relationship among (ϕ_j, γ_j), (ϕ_k, γ_k) and (ϕ_{jk}, γ_{jk}) as shown in **Fig. 1**.

3. RESULT

(1) Average polarization characteristics

The average polarization direction, ϕ_j, of the 17 events are shown in **Fig. 2** for 5 frequency contents. A vacant area of plots can be seen in the figure between $-10°$ and $-60°$ for the frequency contents of 2∼4, 4∼6 and 6∼8 Hz. For 0∼2 and 8∼10 Hz contents, however, plots exist between $-10°$ and $-60°$. Since the radiation pattern of seismic waves at an earthquake source does not depend on the frequency[13], the vacant area is not caused by the source characteristics. Also, the vacant area would not be due to the path effect, because the wave propagation paths to the Chiba array are not the same for the 17 events. Therefore, it is attributed to the average site effect at the Chiba array. It is suggested that the surface layers at the Chiba array site have characteristics of not to be easily shaken in the direction between $-10°$ (E10°S) and $-60°$ (E60°S) in the frequency range of 2∼8 Hz.

Focal mechanism solutions of the Chiba-Toho-Oki earthquake of 1987 and its largest aftershock have been estimated[14]. Dominant directions of ground shaking due to S-waves can be calculated based on the focal mechanisms. They are about $-40°$ (E40°S) for the main shock and $-10°$ (E10°S) for the aftershock. The open squares and the open circles in **Fig. 2** indicate the polarization direction for the main shock and the aftershock. The theoretical polarization directions nearly coincide with ϕ_j's for the events in the frequency range of 8∼10 Hz but do not in the other frequency ranges. No characteristic tendency can be found in the frequency variation of the polarization directions for the two events.

Observed polarization directions of ground motions vary with the frequency, and they do not directly reflect the radiation pattern of seismic waves at the earthquake sources. Therefore, as pointed by Irikura[15], it would be impossible to correct the radiation pattern when we synthesize ground motions of large events from records of small events by the empirical Green's function method.

Figs. 3 and **4** show γ_j plotted against the earthquake magnitude, M, or the hypocentral distance, R (open squares: 0∼2 Hz, open triangles: 2∼4 Hz, crosses: 4∼6 Hz, solid triangles: 6∼8 Hz, solid squares: 8∼10 Hz). It can be seen that γ_j has positive correlations with M and R. Also, γ_j increases with the frequency. Type I quantification analysis is employed for a regression analysis of γ_j in terms of M, R and the frequency, and

$$\gamma_j = 0.4735 + \begin{Bmatrix} -0.0136; M < 5 \\ 0.0153; M \geq 5 \end{Bmatrix}$$

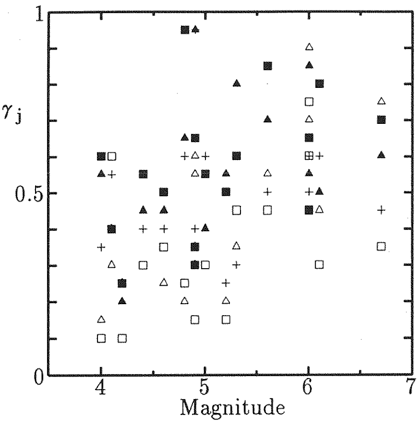

Fig. 3 Relationship between γ_j and magnitude.

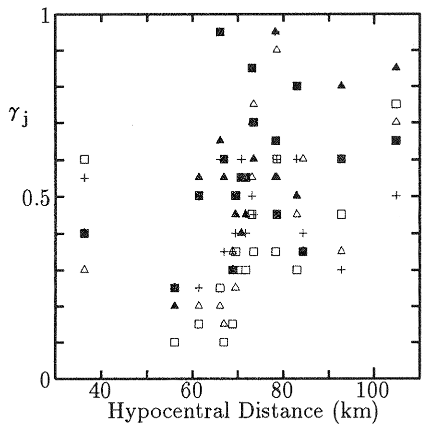

Fig. 4 Relationship between γ_j and hypocentral distance.

$$+\left\{\begin{array}{r} -0.0997; R<70 \\ 0.0698; R\geq 70 \end{array}\right\} + \left\{\begin{array}{r} -0.1265; 0\sim 2Hz \\ -0.0382; 2\sim 4Hz \\ 0.0000; 4\sim 6Hz \\ 0.0706; 6\sim 8Hz \\ 0.0941; 8\sim 10Hz \end{array}\right\} \quad (4)$$

is obtained. The multiple correlation coefficient is 0.5993. γ_j shows a positive correlation with M, R and the frequency.

Contributions of M and R to γ_j are more clearly shown by an analysis of the data for the Chiba-Toho-Oki earthquake and its 5 aftershocks only, because the wave propagation paths from the sources to the array site are nearly common for the events. The result is

$$\gamma_j = 0.3800 + \left\{\begin{array}{r} -0.0213; M<5 \\ 0.0427; M\geq 5 \end{array}\right\}$$

$$+\left\{\begin{array}{r} -0.0547; R<70 \\ 0.1093; R\geq 70 \end{array}\right\} + \left\{\begin{array}{r} -0.1550; 0\sim 2Hz \\ -0.0383; 2\sim 4Hz \\ -0.0300; 4\sim 6Hz \\ 0.0867; 6\sim 8Hz \\ 0.1367; 8\sim 10Hz \end{array}\right\} \quad (5)$$

and the multiple correlation coefficient is rather high as 0.7898. The contribution of M to γ_j is larger than that of Eq. (4).

The polarization of ground motions from small events is stronger than that from large events. Therefore, if we attempt to synthesize ground motions for large events from records of small events, the synthetic ground motions would show too strong polarization. This should be noted when we use the empirical Green's function method of strong motion synthesis.

(2) Local site effect

Fig. 5 shows the local site effect, (ϕ_k, γ_k), at each observation point. The directions of the longer axes of the ellipses show that ground motions tend to be dominant in the directions. A slender ellipse indicates that the observation point has its own preferred direction of strong shaking. The ellipses for 0~2 Hz indicate that the 9 points have very small local site effect in this frequency range. Orientation error of instruments has been corrected based on an assumption that low-frequency ground motions are the same in a small area[16]. As a consequence, ground motions of 0~2 Hz at the 9 points are almost the same, and the local site effect is small as in **Fig. 5**.

Meanwhile, the results for high frequency contents show that each observation point has its own characteristic and the ellipses in the figure become slender with the increase in frequency. Especially, P3 point shows the strongest site effect. It is natural to think that the cause of the local site effect exists in the condition of shallow surface layers because the predominant direction of ground shaking differs between two points whose distance is only 10 m.

At P3 point, accelerometers are installed at depths of 1 m and 10 m. **Fig. 6** shows the spectral ratio (1 m/10 m) at P3 point for S-waves due to the main shock of the 1987 Chiba-Toho-Oki earthquake. The open circles indicate the spectral ratio of the E10°N component, and the solid circles indicate that of the orthogonal component (E80°S). The spectral ratios of these two components are different with each other more than those for other two orthogonal component pairs. The peak frequency of the spectral ratio is about 5.5 Hz for E10°N component and 4.5

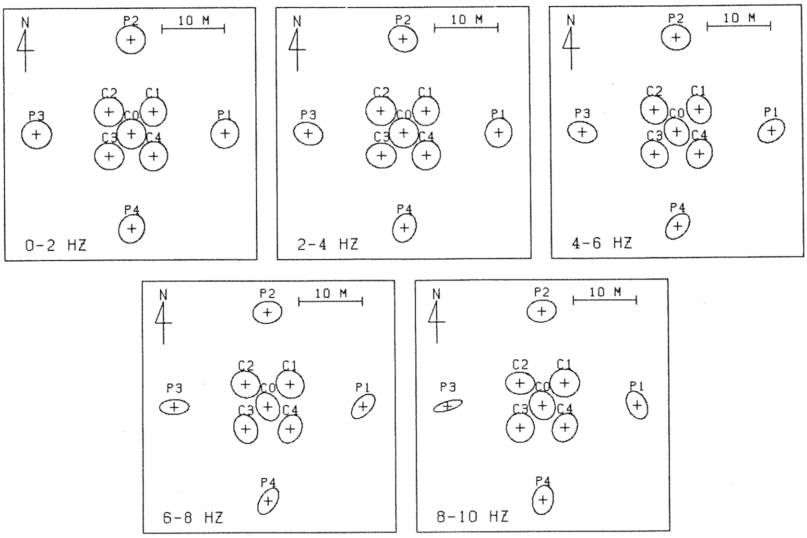

Fig. 5 Local site effect (ϕ_k, γ_k).

Hz for E80°S component. The peaks of the spectral ratios are splitting. The difference in transfer function of the surface layers for two orthogonal components was also found by Lu et al.[17] at the Chiba array site. Although they aimed at presenting a method to obtain an average transfer function, here we make a discussion on the cause of the difference of the spectral ratios.

The difference of spectral ratios at the other 8 observation points are not so severe as that at P3[18]. Therefore, the cause of the difference exists near P3. Inclined surface layers or surface layers of anisotropic media would cause the directional difference of transfer functions. There is an observational fact[19] that velocities of S-waves propagating vertically in surface layers are different to an amount of 20 % depending on the shaking directions. Anisotropy in S-wave velocity can cause the directional difference of the spectral ratios.

A ground survey has been carried out at C0 point[10]. Theoretical spectral ratio is calculated based on an assumption of the vertical incidence of plane SH-waves to the layer model[10] at C0 and is shown in **Fig. 6** with a solid curve. It can be seen that the observed spectral ratio for E10°N component is well approximated by the theoretical one, but not for E80°S component. The peak frequency of the theoretical spectral ratio agrees with the frequency of wave which makes a 'node' at a depth of 10 m. Therefore, in order to explain the spectral ratio of E80°S component by the vertically propagating S-wave model, it is necessary to assume that the S-wave velocity for

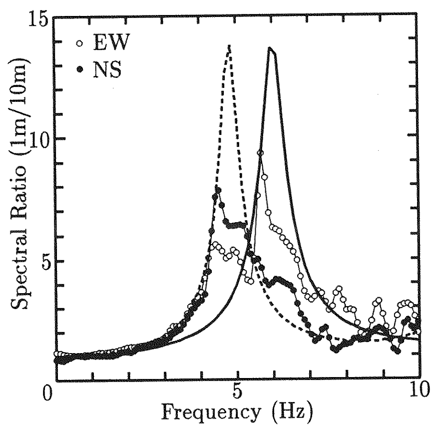

Fig. 6 Spectral ratio (1m/10m) at P3 point.

E80°S component is smaller than that for E10°N component. For example, the dashed curve in **Fig. 6** is a theoretical spectral ratio calculated for a layer model whose S-wave velocity between depths of 0 and 5 m is 25 % smaller than that of the original layer model. The dashed curve can explain the spectral ratio of E80°S component.

Through the above discussion, it is suggested that surface layers do not have one preferred direction of strong amplification of incident waves independently of the frequency. The directional difference of the transfer function of surface layers may cause the complex local site effect in **Fig. 5**.

4. CONCLUSION

Accelerograms of 17 earthquakes recorded by a dense array system (Chiba array) have been analyzed to investigate polarization characteristics of ground motions. The followings are concluded.

1. Chiba array site has a tendency of not to be easily shaken in the direction between E10°S and E60°S for 2∼8 Hz component of earthquake ground motion.
2. Average polarization characteristics of the array site vary with the frequency of ground shaking and do not directly reflect the radiation pattern of seismic waves at the earthquake source.
3. Polarization of ground motion becomes weak with the increase in earthquake magnitude, hypocentral distance and frequency.
4. The local site effects at the 9 observation points are very different from one another and the difference is severe for high frequency contents.
5. The local site effect on polarization characteristics may be caused by the directional difference in seismic response of surface layers.
6. The above items 2 and 3 should be noted in synthesizing ground motions due to large earthquakes from records of small earthquakes by the empirical Green's function method.

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