Study on Simulation Method for Non-Stationary Vertical Ground Motions

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Introduction

In asismic design of important structures such as nuclear power plant facilities, appropriate evaluation of input ground motions is important. Particularly for roof trusses or pipings and equipment systems, the influence of vertical ground motions is significant. Recently, three component records have been compiled together with the development of observation networks. In this paper, by making use of three component accelerograms observed at an observation array, a simulation method for vertical ground motions is proposed, which is based on non-stationary cross spectrum between horizontal and vertical components.

Earthquake Records

Used in this study are three-components of accelerograms of the Mexican earthquake (Ms=8.1) occurred on September 19, 1985 (Ref.1), which were observed at 5 stations (No.1-No.5) in the Guerrero Array. The location of the 5 stations is as shown in Fig.1. These stations are considered to be within the source region (Ref.2).

The accelerographs of each station are installed on the ground surface and the soil conditions of the ground are considered to be firm or rock (Ref.2). The maximum accelerations of observed ground motions are from 50 gal to 120 gal, and the ratios of the maximum vertical acceleration to the maximum horizontal component at the 5 stations are shown in Fig.2. Most of these are between 0.5 and 1.0.

The fault break of this earthquake is supposed to occur along the boundary at the oceanic plate (Ref.3) and a possibility of multiple fault breaks is pointed out. Therefore it seems difficult to determine the point of epicenter and to evaluate the definite epicentral distances from the fault break.

Stationary Analysis of Observed Ground Motions

In order to investigate the basic characteristics of correlation between horizontal and vertical ground motions, a coherence function, cross-correlation function and cross spectra are computed. With regard to the coherence and cross-correlation functions, it seems difficult to find out any specific tendency. Fig.3 shows the ratios of acceleration response spectra between horizontal and vertical components at the 5 stations. These figures indicate that the ratios are mostly below 1.0 throughout the frequency range, though in some specific frequencies, ratios exceed 1.0. These specific frequencies vary in each record.

Non-Stationary Analysis of Observed Ground Motions

To grasp the characteristics of correlation in more detail, non-stationary cross spectra based on physical spectrum are computed using Fast Fourier Transform (FFT) (Ref.4). The non-stationary physical spectrum is represented as Eq.1.

$$S_{xx}(\omega,t)=E\left[\left|\frac{1}{2\pi}\int_{-\infty}^{\infty} X(u)\,W(t-u)e^{-i\omega u}du\right|^2\right] \qquad (1)$$

Where $x(t)$ is the horizontal ground motion, S_{xx} the non-stationary physical spectrum of horizontal ground motions, and $W(u)$ is the weighted time window defined as Eq.2.

$$W(u)=\left(\frac{\sqrt{2}}{T}\right)^{\frac{1}{2}} exp\,(-\frac{\pi u^2}{T^2}) \qquad (2)$$

Where T is the window bandwidth.

Therefore non-stationary cross spectrum S_{xy} between horizontal and vertical ground motion x(t), y(t), can be expressed as Eq.3.

$$S_{xy}(\omega,t)=E\left[\left(\frac{1}{2\pi}\right)^2\int_{-\infty}^{\infty} X(u_1)\,W(t-u_1)\,e^{-i\omega u_1}du_1\cdot\int_{-\infty}^{\infty} Y(u_2)\,W(t-u_2)e^{i\omega u_2}du_2\right] \qquad (3)$$

Fig.4 shows examples of the non-stationary cross spectrum between NS and UD components at the 5 stations. Predominant peaks in No.3 change in accordance with time process, that suggests the significance of non-stationary frequency contents. The general shapes of non-stationary cross spectra at the 5 stations seem to be similar, but it seems difficult to define the specific trend only from the shapes of non-stationary cross spectra.

Simulation Method for Vertical Ground Motions

The general flowchart for the simulation method of vertical ground motions is as shown in Fig.5. At first, non-stationary cross spectrum is computed from observed horizontal and vertical ground motions and then its shape is represented simply by 3 parameters Ts, Tp and α as shown in Fig.6. The spectrum shape can be drawn by these parameters as Eq.4.

$$\sqrt{S(\omega,t)}=\begin{cases} 0 & t'<0 \\ \alpha t' \,exp(1-t) & t'>0 \end{cases} \qquad (4)$$

Where t'=(t-Ts)/Tp

Tp: occurrence time of peak value

Ts: starting time

Fig.7 shows values of the 3 parameters Ts, Tp and α obtained from 10 non-stationary cross spectra. Though there is a slight difference in each station, Ts generally decreases in accordance with the frequency, and α tends to peak between 2.0 Hz and 5.0 Hz.

Fig.8 shows the average and one standard deviation of Ts, Tp and α. In order to obtain the general property, regression analysis was carried out. The obtained regression curves are shown in Fig.8. Applying these regression curves to Eq.4, non-stationary cross spectrum is idealized.

When horizontal ground motion is provided, the non-stationary power spectrum of vertical ground motion can be obtained from the idealized cross spectrum and coherence as defined by Eq.5.

$$S_{yy}(\omega,t)=\frac{|S_{xy}(\omega,t)|^2}{S_{xx}(\omega,t)\,coh^2(\omega,t)} \qquad (5)$$

Consequently, the acceleration time history of vertical ground motion is generated by a sum of cosine functions as Eq.6.

$$y(t) = \sum_j \sqrt{4S_{yy}(\omega_j,t)\Delta\omega}\, cos(\omega_j t + \Phi_j) \qquad (6)$$

Where the phase angle ϕj is a random number uniformly distributed between 0 and 2π. As for the coherence, since no specific features can be seen, its values are assumed to be constant.

According to above mentioned procedure, the acceleration time histories at the 5 stations are generated.

Fig.9 shows the comparison of observed and simulated acceleration time histories at No.1, No.3 and No.5 stations. The wave envelope forms of observed ground motions are similar to those of simulated ground motions.

Acceleration response spectra with 5% damping ratio are shown in Fig.10. The spectrum shape of simulated wave at each station is similar to that of the observed one, but several spectrum peaks do not seem to correspond to those of the simulated one.

Fig.11 shows the comparison of maximum accelerations between observed and simulated ground motions, and Fig.12 shows the ratios of spectral intensity(Ref.5). The accelerations of simulated waves are well matched with those of the observed ones, except for No.1 and No.3 station cases. One reason for unmatching is to obtain the value of α from the regression curve, and another is to generate the time history using a set of uniformly distributed random numbers for the phase angles.

Conclusions

The simulation method for vertical ground motions is developed based on the non-stationary cross spectrum. The results are summarized as follows.

1) Non-stationary cross spectra which are obtained from observed ground motions of the Mexican earthquake are represented by 3 parameters.

2) The shape of the idealized non-stationary cross spectrum is given by using the regression curves of these 3 parameters. This idealized spectrum seems to have the average properties of observed ground motions in the source region.

3) The vertical ground motion can be generated using the idealized non-stationary cross spectrum and the horizontal ground motion.

4) The time histories and response spectra of simulated waves are similar to these of the observed ones, but in some cases, a slight discrepancy can be seen between the observed and simulated ground motions.

Acknowledgments

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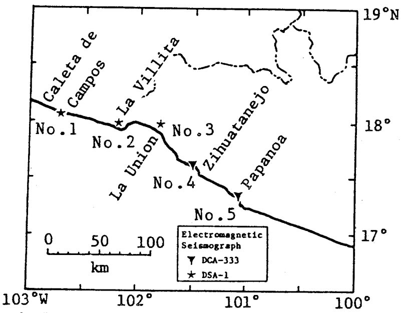


Fig.1 Location of observation stations

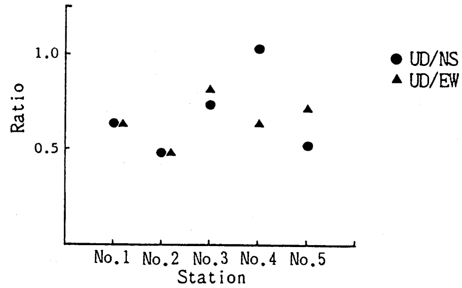


Fig.2 Ratios of max. acc.

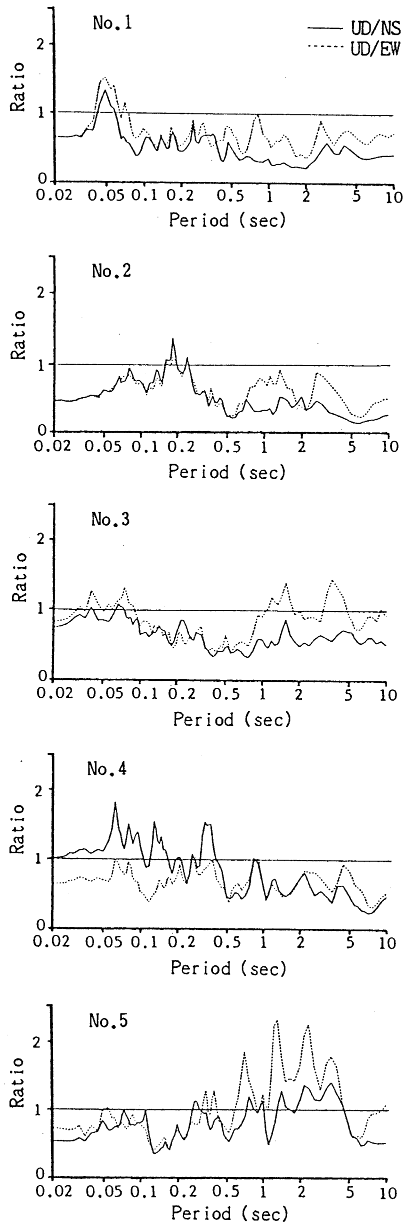


Fig.3 Ratios of acceleration response spectra (h=5%)

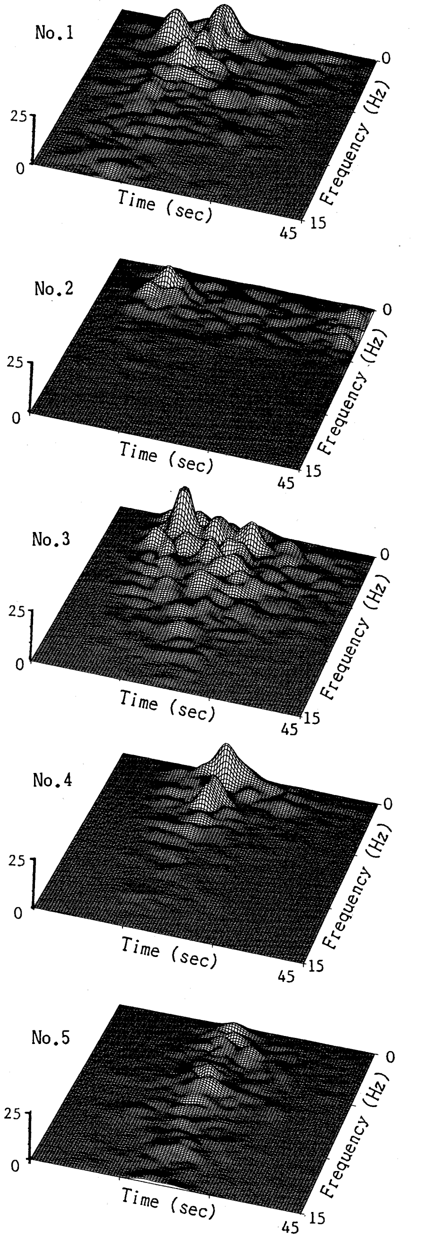


Fig.4 Examples of non-stationary cross spectrum

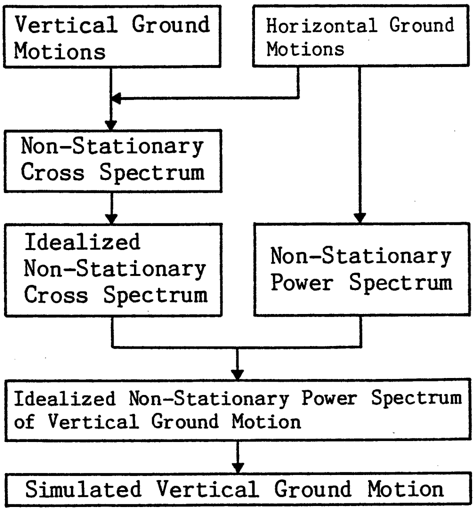


Fig.5 Flowchart of simulation method

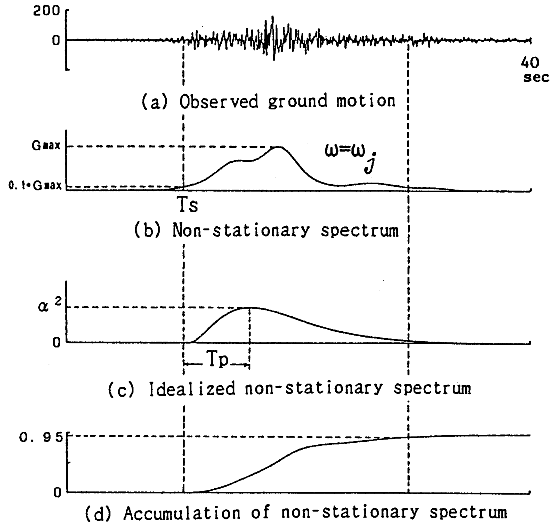


Fig.6 Idealization of non-stationary spectrum

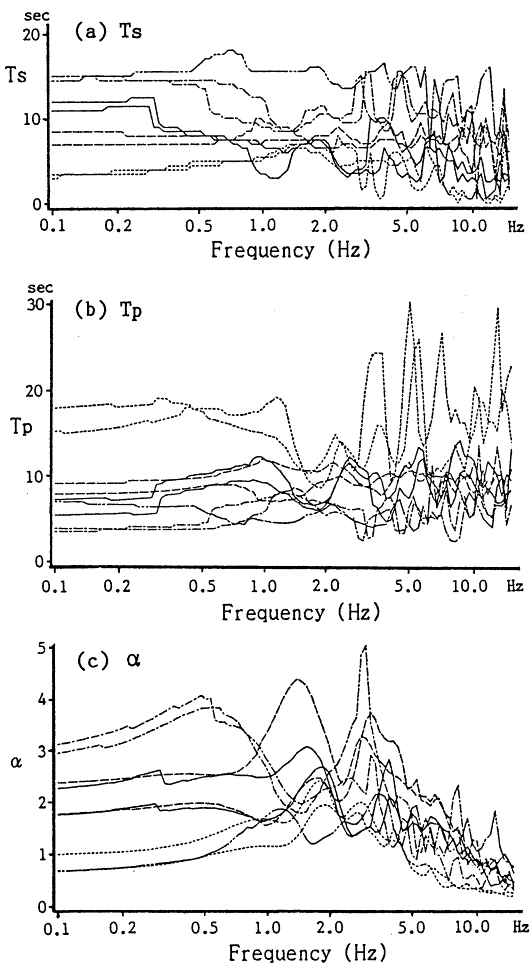


Fig.7 Values of parameters (5 stations)

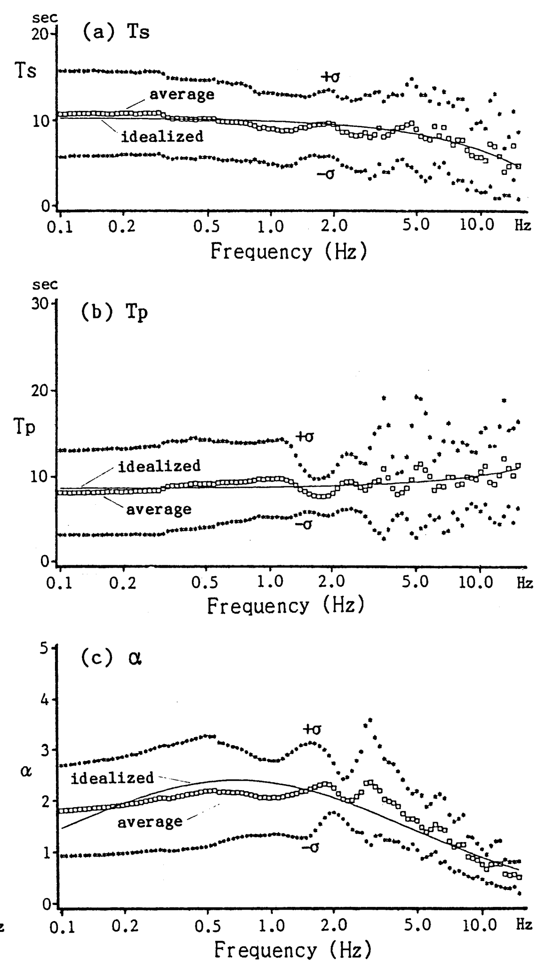
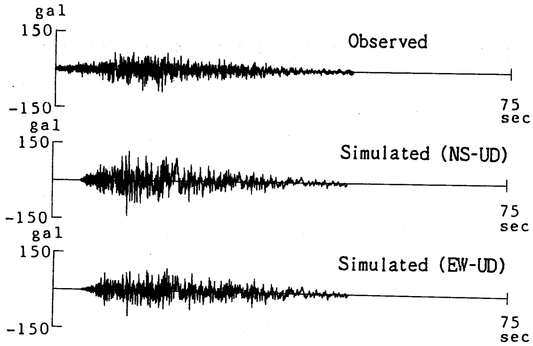
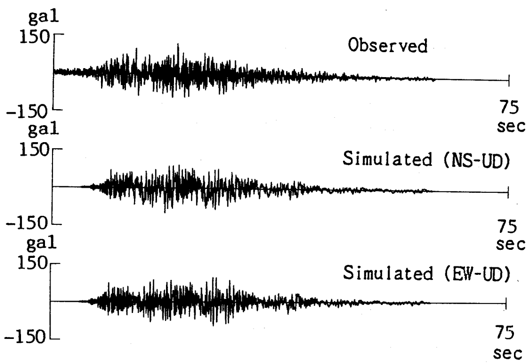


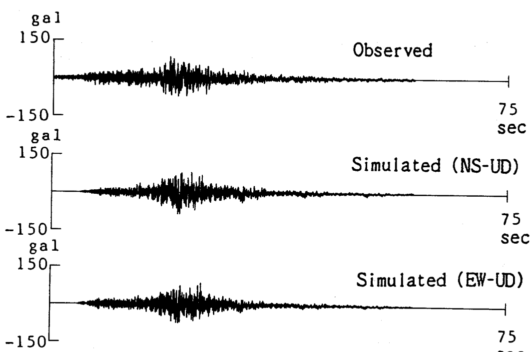
Fig.8 Idealization of parameters



(a) Caleta de Campos (No.1)

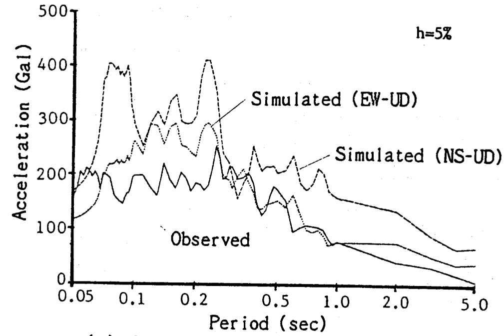


(b) La Union (No.3)

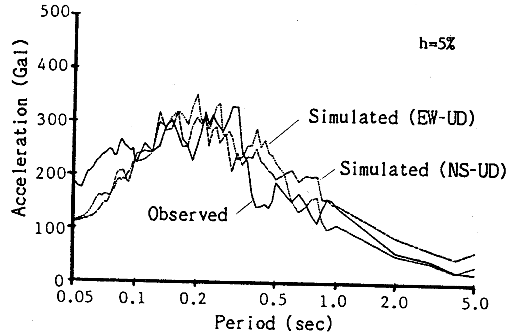


(c) Papanoa (No.5)

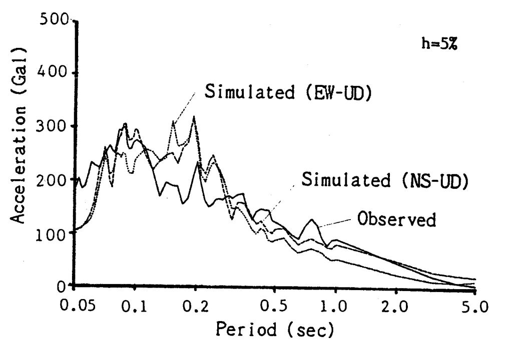
Fig.9 Comparison of time histories



(a) Caleta de Campos (No.1)



(b) La Union (No.3)



(c) Papanoa (No.5)

Fig.10 Comparison of response spectra

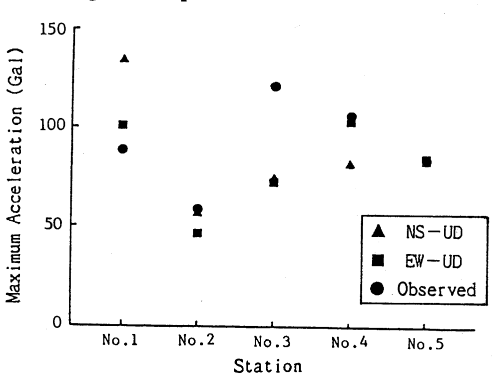


Fig.11 Comparison of max. acc.

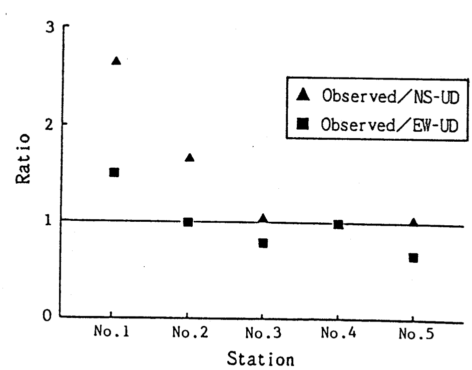


Fig.12 Ratios of spectral intensity