Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Vertical response characteristics of a nuclear reactor building during earthquakes

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ABSTRACT : The vertical response characteristics of a BWR-MARK II type reactor building are statistically studied based on a record of forty-six observed earthquakes. We examined the amplification characteristics of the reactor building and its neighboring soil. The coupled effects of the rocking response and vertical response are also discussed. These results are important when the determination of a dynamic analysis model for design purposes comes up for discussion.

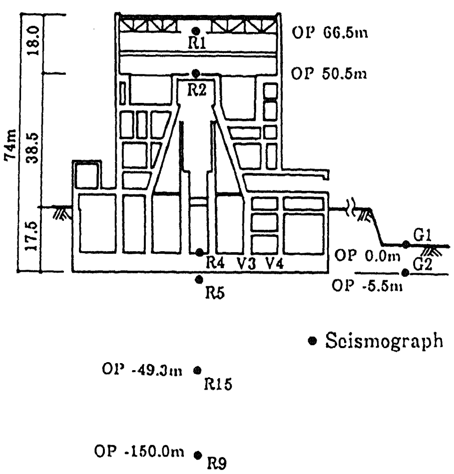
1 INTRODUCTION

Since 1981, the earthquake response of a BWR-MARK II type reactor building, which is located at Fukushima Prefecture in northeastern Japan, has been systematically measured. The record of these observations is useful for establishing a seismic design procedure for nuclear power plants, since the present procedure in Japan for the seismic design of nuclear reactor buildings subjected to vertical ground motion is primarily based on the static method.

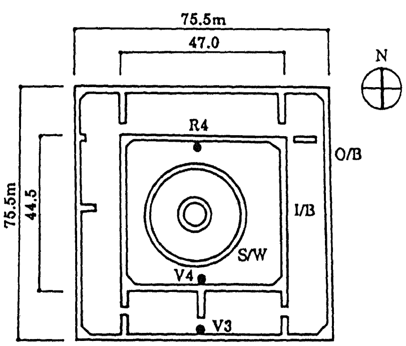
In this paper, the vertical response behavior of a nuclear reactor building and its neighboring soil during an earthquake is statistically studied on the basis of observed records. The coupled effects of the rocking response and the vertical response of the building, the characteristics of maximum acceleration amplification, and the dominant frequencies and the corresponding mode shapes of the building and the soil are investigated by using the vertical components of accelerograms.

2 SEISMIC OBSERVATION OUTLINE

Seismographs were installed in the nuclear reactor building and its neighboring soil, as shown in Fig. 1. Forty-six earthquakes whose epicenters were within 200 km of the observation site were recorded in the period from 1981 to 1987. Most of these



(a) Section



(b) Plan (OP 0.0m)

Figure 1. Location of seismographs.

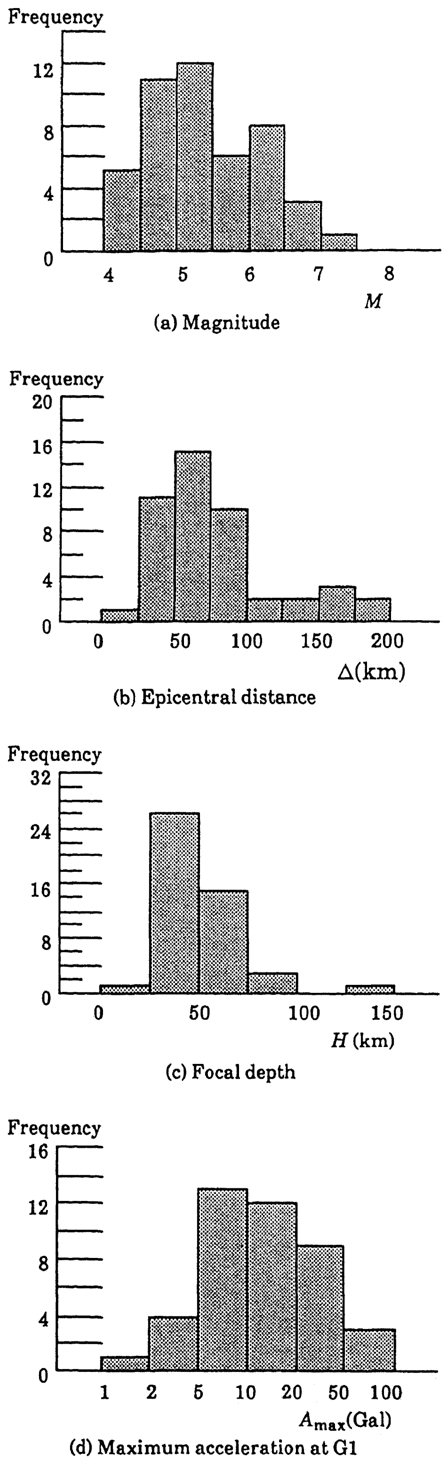


Figure 2. Histograms of forty-six Earthquake events.

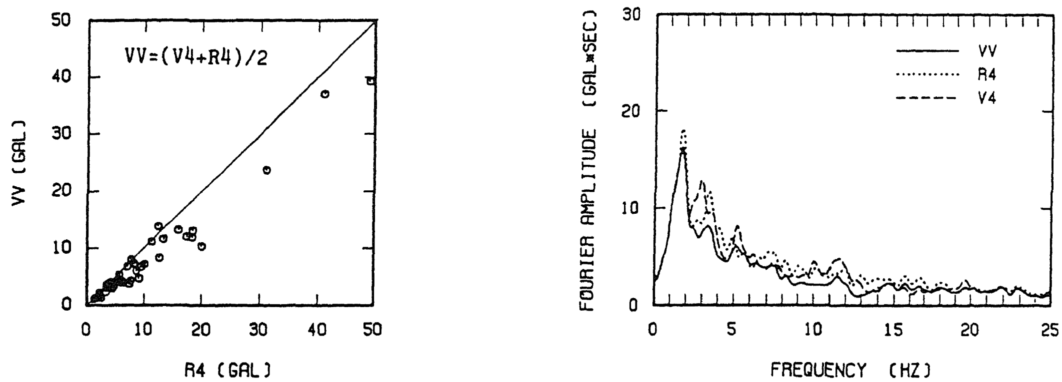
earthquakes occurred in the east offshore of Fukushima Prefecture. The various histograms of the events in terms of magnitudes(JMA), epicentral distances, focal depths and maximum accelerations at the free field surface are illustrated in Fig. 2. The magnitudes of the events are within a range of 4 to 7. Both the epicentral distances and the focal depths of most of the events are about 50 km. The maximum accelerations are mostly within a range of 5 to 50 Gals, and there are few earthquakes that induce acceleration values greater than 50 Gals at the free field surface. It is regarded that the building exhibits an elastic behavior.

3 VERTICAL MOTION INDUCED BY ROCKING MOTION

None of the accelerographs in the reactor building are located at the center of the plan, and the building was subjected to both vertical and horizontal ground motion simultaneously. Hence, the observed vertical motion includes that induced by the rocking of the building.

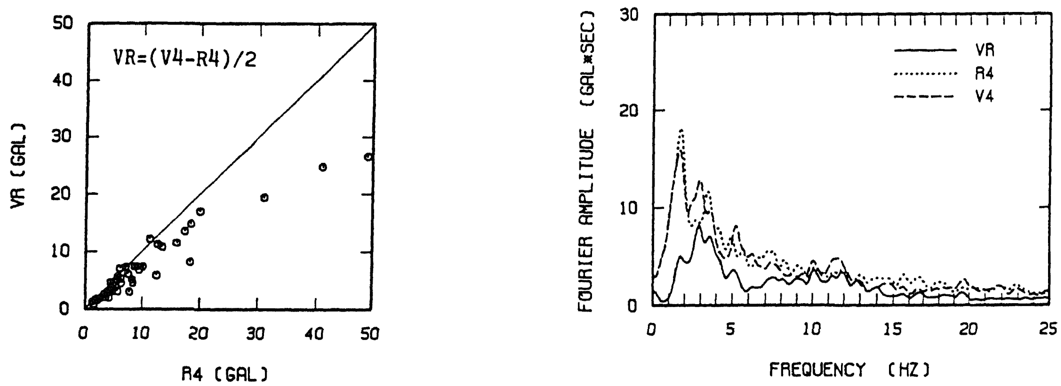
Figures 3 and 4 indicate the maximum values and the Fourier spectra of the acceleration responses of the foundation mat which are caused by the horizontal and vertical ground motion. The Fourier spectra are obtained from the accelerograms of an earthquake(M=6.5, Δ=59km) in 1987. V4 and R4 represent the records by the accelerographs located symmetrically with respect to the center of the plan. VV=(V4+R4)/2 and VR=(V4-R4)/2 correspond to the vertical motion caused by the vertical and rocking motion, respectively.

Figure 3 shows that the maximum values of VV are as large as those of R4. And there's no clear difference between the characteristics of the Fourier spectra of R4, V4 or VV. Therefore, the vertical response of the building can be discussed by using the records directly without considering the rocking motion. From Fig. 4, on the other hand, the maximum values of VR are not so large as those of R4. The characteristics of the Fourier spectra of VR are quite different from those of R4 and V4 especially at low frequencies. The predominant frequency around 3 Hz corresponds to the rocking motion and completely separate from that for the vertical vibration modes of the main walls, as discussed in Section 6(see Fig. 8). It is considered that these diminish the effect of the rocking on the vertical response of the building.



(a) Maximum acceleration values (b) Fourier spectra (M=6.5, Δ=59km)

Figure 3. Vertical responses induced by the vertical motion of the building.



(a) Maximum acceleration values (b) Fourier spectra (M=6.5, Δ=59km)

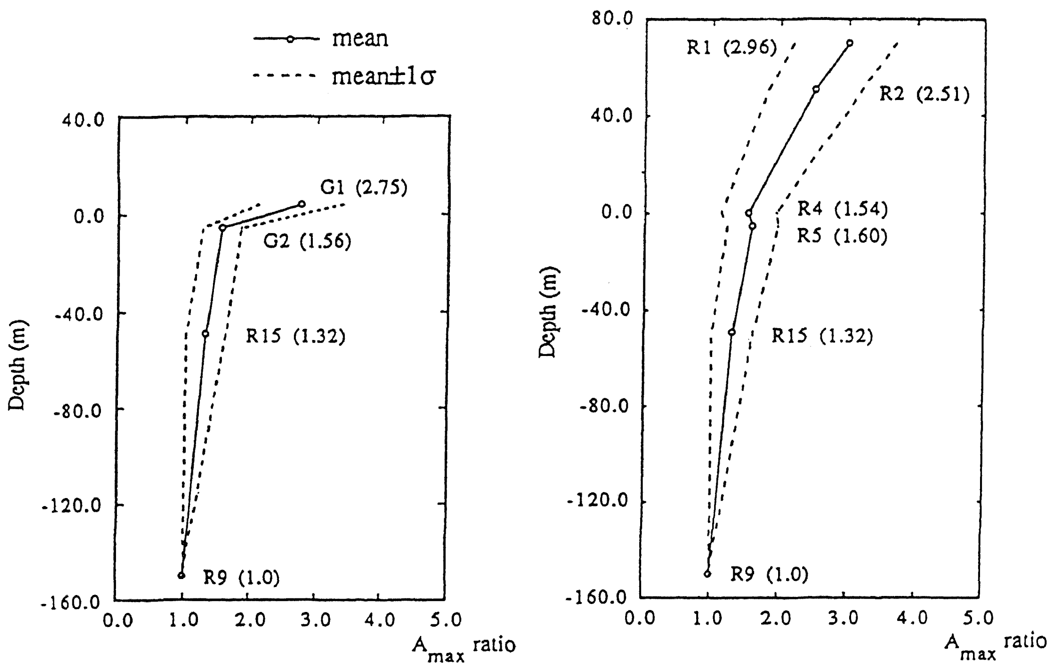
Figure 4. Vertical responses induced by the rocking motion of the building.

4 AVERAGE MAXIMUM ACCELERATION AMPLIFICATION

Figure 5 shows the average maximum acceleration ratios together with the range of standard deviation (mean$\pm 1\sigma$ ratios). The amplification factors of vertical response at the different observation levels of the free field against the deepest observation point (R9) are illustrated in Fig. 5 (a). The amplification factors of the building and the soil are plotted in Fig. 5 (b). These figures indicate that the amplification factors become gradually larger as the observation level increases high. The maximum acceleration at the highest observation point (R1) of the building is about three times greater than that at the deepest point (R9) of the soil. Moreover, the amplification of the surface layer between the G1 and G2 points is remarkably large, and the response of the foundation is much less than that of the free field surface, if the resulting ratio at R4 is compared with that at G1.

5 AVERAGE FREQUENCY RESPONSE CHARACTERISTICS

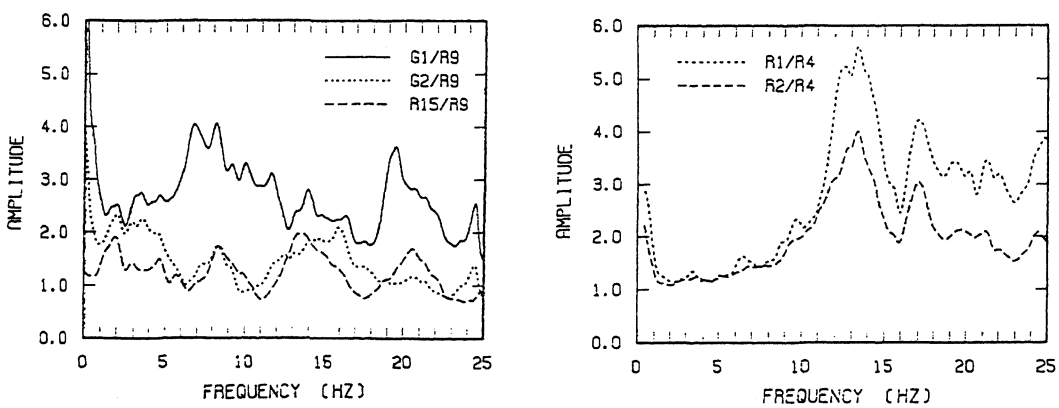
Figure 6 shows the average Fourier spectrum ratios obtained from the forty-six observations. The ratios of the Fourier amplitude at the different ground depths to the amplitude at R9 are presented in Fig. 6(a). Figure 6(b) indicates the ratios of the Fourier amplitude at the different levels of the building to the amplitude at the foundation top surface (R4). At the surface layer of the soil, remarkably large amplifications are recognized from 5 to 12 Hz and around 20 Hz. However, the amplification of the vertical ground motions seem to be little between the R9 and G2.



(a) Free field system

(b) Building-soil system

Figure 5. Average maximum acceleration ratios.



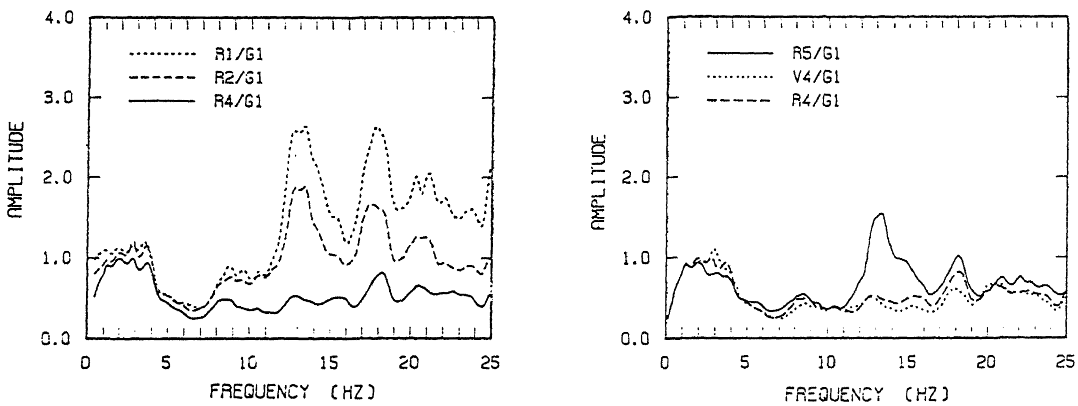
(a) Free field system

(b) Building system

Figure 6. Average Fourier spectrum ratios.

The dominant frequencies of the building are about 13 Hz and 17 Hz, and these frequencies are in a comparatively higher frequency range.

The ratios of the Fourier amplitude at the observation points in the building against that at the free field surface (G1) are shown in Fig. 7. Figure 7(a) shows that the dominant frequency relating to the interaction effect between the soil and the building is found within a frequency range of 1Hz to 4Hz. The dominant frequency of



(a) Soil-structure interaction system (b) Responses of the foundation mat

Figure 7. Average Fourier spectrum ratios between the building and the ground.

the soil-structure interaction system in the vertical direction is far lower than the frequency of the structure system and is almost identical to the frequency of the rocking motion of the building.

Figure 7(b) also indicates that the acceleration records of the observation points R5, located at the center of the foundation mat, include the dominant components around 13 Hz, which do not exist in the records of the other observation points on the foundation mat, R4 and V4.

6 MODE SHAPE

Figure 8 shows the mode shapes of the building corresponding to the dominant frequencies which are indicated by the shaded areas depicted in the plot of the Fourier spectra obtained from the accelerograms of an earthquake event (M= 6.5, Δ=59km) in 1987. The mode shapes are given by plotting the acceleration values of time histories at the different observation levels of the building. The acceleration time histories are obtained as filtered waves with the frequency contents of the shaded areas shown in the spectra, by the FFT method. This figure shows that the mode shapes of the dominant frequencies found in a range lower than 4Hz represent the behavior relating to the soil-structure interaction, and hence the building undergoes the rigid motion. Furthermore, the mode shapes of the dominant frequencies which are higher than 10Hz exhibit the axial elasticity of the resistance wall of the building. Looking into the mode shapes in detail, the vibration mode denoted by ③ is apparently the first mode of the building which shows an axial motion with the same phase. On the other hand, the one indicated by ④ shows the second axial mode which has an opposite phase between the top and bottom parts of the wall. The results of the simulation analysis (Morishita, H. et al. 1991 and Watanabe, T. et al. 1992) show that the building exhibits not only the axial behavior of a main resistance wall but also the coupled behavior of the main walls connected with the partition walls around 12 Hz.

Figure 9 shows the mode shapes of the foundation mat corresponding to the dominant frequencies which are indicated by the shaded areas depicted in the plot of the Fourier spectra. At around 3.5 Hz, rocking motions are clearly observed, and the outplane deformation of the foundation mat is very small. However, the outplane deformation is clearly observed at the center of the base mat (R5) at around 12 Hz. At around this frequency, the vertical motions at the shear wall and the outplane deformation of the foundation mat seem to be coupled with each other.

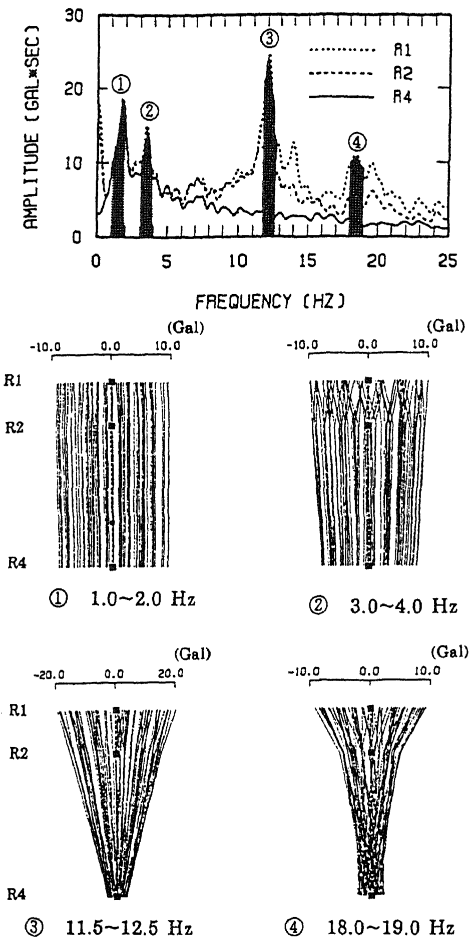


Figure 8. Mode shape of the building (Shear wall)

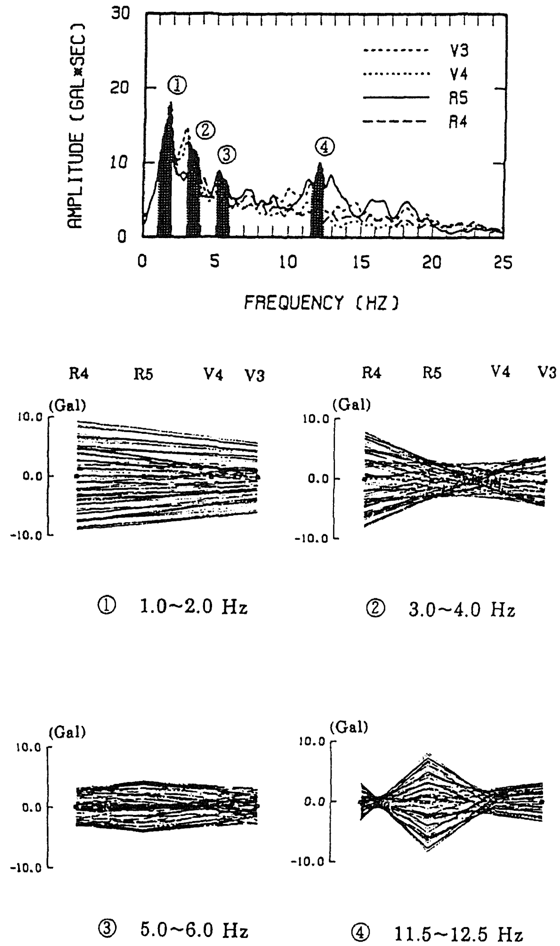


Figure 9. Mode shape of the building (Foundation mat)

7 CONCLUSIONS

We examined the vertical response characteristics of a reactor building and its neighboring soil based on the records of forty-six observed earthquakes. As a result, we have drawn the following fundamental characteristics.

1. The vertical response characteristics of the building do not change even excluding the contribution of rocking response. Therefore, the effect of the rocking on the vertical response of the building is considered to be negligible.

2. The natural frequencies of the building appear in a range higher than 10Hz, and are completely separate from that of the soil-structure interaction system(1 to 4 Hz) and that of the rocking motion of the building(about 3.5Hz). At the building's first mode (about 12 Hz), the outplane deformation of the foundation mat seems to be related to the vertical motion of the main shear wall.

3. The amplification of the soil is concentrated in the surface layer upper than the bottom level of the foundation mat.

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Watanabe, T. et al. 1992, "Simulation Analysis of Vertical Response of a Nuclear Reactor Building", 10th WCEE.