Vertical Response Characteristics of a Nuclear Reactor Building Based on Observed Earthquake Records

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ABSTRACT

Response characteristics of vertical motion of a BWR-MARK II type reactor building are investigated on the basis of a number of observed earthquake records. Simulation analysis by using two different types of mathematical models is carried out and a modeling procedure of the building for vertical response is studied by comparing analysis results with observed responses.

1 INTRODUCTION

Since 1981, measurement of earthquake response of a BWR-MARK II type reactor building, which is located at Fukushima Prefecture in northeastern Japan, has been systematically conducted. It seems that these observed records are useful for the establishment of 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 motions is mainly based on the static method.

In this paper, response characteristics of vertical motion of the nuclear reactor building during earthquakes are studied on the basis of observed records. Amplification characteristics of the resistance walls of the building, natural frequencies and the corresponding mode shapes of the building are statistically investigated by using vertical components of accelerograms. Successively, simulation analyses are carried out by employing the mass and spring system considering the soil-structure interaction and the analysis results are compared with the observations. Discussions on the modeling of the nuclear reactor building for vertical response are made.

2 OUTLINE OF SEISMIC OBSERVATION

Seismographs are installed in the nuclear reactor building and its neighboring soil, as shown in Fig. 1. Forty-six earthquake events whose epicenters are within 200 km from the observation site have been recorded in the period from 1981 to 1987. Most of these earthquakes were occurred in the east offshore of Fukushima Prefecture. Several histograms of all the events in terms of magnitudes(JMA), epicentral distances, forcal depths and maximum accelerations at the free field surface are illustrated in Fig. 2. The magnitudes of the events are in the range from 4 to 7. Both the epicentral distances and the forcal depths of most events are about 50 km. The maximum accelerations are mostly within the range of 5 to 50 gals and there are few earthquakes inducing acceleration values larger than 50 gals at the free field surface. It is regarded that the building would exhibit the elastic behavior.

3 VERTICAL RESPONSE CHARACTERISTICS

Basic characteristics of vertical response of the building are investigated by using all the accelerograms. Fig. 3 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 are illustrated in Fig. 3 (a). Those of the building and the soil are plotted in Fig. 3 (b). It is seen from these figures that the amplification factors are gradually larger as the observation level becomes high. The maximum acceleration at the highest observation point (R1) of the building is about three times as much as that at the deepest point (R9) of the soil. It is also noticed that the amplification of the surface layer between G1 and G2 points is remarkably large, and that the response of the foundation is much smaller than that of the free field surface when comparing the resulting ratio at R4 with that at G1.

Fig. 4 shows the average Fourier spectrum ratios obtained from the forty-six observations. The ratios of the Fourier amplitude at the different levels of the building to that at the foundation top surface (R4) and the free field surface (G1) are presented in Figs. 4 (a) and (b), respectively. From these figures, it is understood that dominant frequencies of the building are about 13Hz and 18Hz, and that these frequencies are in comparatively higher frequency range. It is also recognized from Fig. 4 (b) that the dominant frequency relating to the interaction effect between the soil and the building is found in the frequency range of 1Hz to 4Hz. It is concluded that the natural frequency of the structure system is far higher than that of the soil-structure system.

Fig. 5 shows the mode shapes of the building corresponding to the dominant frequencies which are indicated by the shaded areas depicted in the plot of Fourier spectra obtained from the accelerograms of the earthquake event($M_J=6.5$, $\Delta=59$km) 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 frequency contents of the shaded areas shown in the spectra, by the FFT method. From this figure, it is seen that the mode shapes of the dominant frequencies found in the 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 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 the axial motion with the same phase. On the other hand, the one indicated by ④ shows the second axial mode which has the opposite phase between the top and bottom parts of the wall.

4 SIMULATION ANALYSES

Simulation analyses by employing the mass and spring system are carried out and the analysis results are compared with the observations. Two different types of mathematical models are chosen for the analyses, as shown in Fig. 7. One is a simple stick model and the other is a relatively detailed model consisting of four sticks, which correspond to the main resistance walls, so-called outer box(O/B), inner box(I/B), shield wall(S/W) and RPV pedestal, respectively. The simple stick model is constituted by lumped masses connected with axial spring elements which represent O/B, I/B, S/W and most of partition walls. Young's modulus and Poisson's ratio of the reinforced concrete are assumed to be 300t/cm^2 and 1/6, respectively. The foundation mat is modeled as a rigid body and the total weight of RPV pedestal is included in that of the foundation. A frequency dependent soil spring is added to consider the soil-structure interaction effect in case that the foundation undergoes the rigid motion in the vertical direction. The soil spring is obtained from the fundamental solutions of the governing equation for a halfspace subjected to a harmonic point load. In the computation, shear wave velocity of the soil is assumed to be 500m/s and embedment effect is neglected to reduce the complexity of the problem, at this stage. The roof constructed with trusses is idealized by the mass and spring system considering the coupled shear and bending behavior to account for the flexural mode of the roof. The damping factor of the roof is assumed to be 2%.

In the case of the four stick model, each of the sticks consists of lumped masses connected with axial spring elements in which the partition walls within the area governed by a stick are included. In addition, the sticks corresponding to O/B, I/B and S/W are connected with shear spring elements which represent the web-walls between the main walls. The foundation mat is divided into four blocks in accordance with the corresponding areas governed by the main walls, as illustrated in Fig. 6 (a). In order to explain the flexural motion of the foundation in the anti-plane direction, the flexibility of the blocked foundations is evaluated as a stiffness matrix of 4×4 components. The matrix is obtained by the condensation of a large matrix used in the finite element analysis of the bending plate composed of the isoparametric elements, as shown in Fig. 6 (b). As the boundary condition of the analysis, rotation of the nodes located at the bottom of the main walls, which are indicated by the solid lines depicted in Fig. 6 (b), is fixed and the rest of the nodes are given as rotation free. To consider the interaction effect between the blocked foundations and the soil, a frequency dependent impedance matrix is employed as the soil springs. In the computation, it is assumed that each of the blocked foundations undergoes the rigid motion in the vertical direction. The stiffness matrix of the soil is finally superimposed on to that of the foundation. Other assumptions and conditions for the four stick model are same as in the case of the simple stick model.

By using these models, simulation analyses are performed for two cases in which damping factors of 5% and 10% are assumed for the building. The resulting transfer functions obtained by the analyses, which denote the frequency response at the different floor levels of the building, are compared with the average Fourier spectrum ratios obtained from the forty-six observations, as shown in Fig. 8. From this figure, it is understood that the results from the four stick model are fairly well coincident with the observations. The model can accurately produce the two dominant peaks found in 13Hz and 18Hz, because the flexibility of the foundation mat and the coupling effect between the main walls are appropriately considered in the modeling. It is recognized from another studies that the first peak of 13Hz is induced by compression and elongation of I/B independently, and that the second one of 18Hz is developed by interaction between I/B and S/W through the partition walls. It is concluded that the four stick model can provide the precise behavior of vertical response of the building. On the other hand, the results from the simple stick model can not accurately trace the two dominant peaks because of the simplicity of the modeling. However, it is verified that the model is good enough to grasp the overall tendency of the vertical response characteristics seen in the observations.

5 CONCLUSIONS

As response characteristics of vertical motion of a nuclear reactor building, the natural frequencies of the building appear in the range far higher than 10Hz, and hence the building exhibits not only the axial behavior of a main resistance wall but also the coupled behavior between the main walls connected with the partition walls.

As a modeling procedure of the building for vertical response, a four stick model, which independently represents the main resistance walls of O/B, I/B, S/W and RPV pedestal, can provide the precise and accurate behavior of vertical response of the building. On the other hand, a simple stick model can simulate the reasonable tendency of vertical response of the building. It is possible to conclude that the model is valid for the practical seismic design purpose.

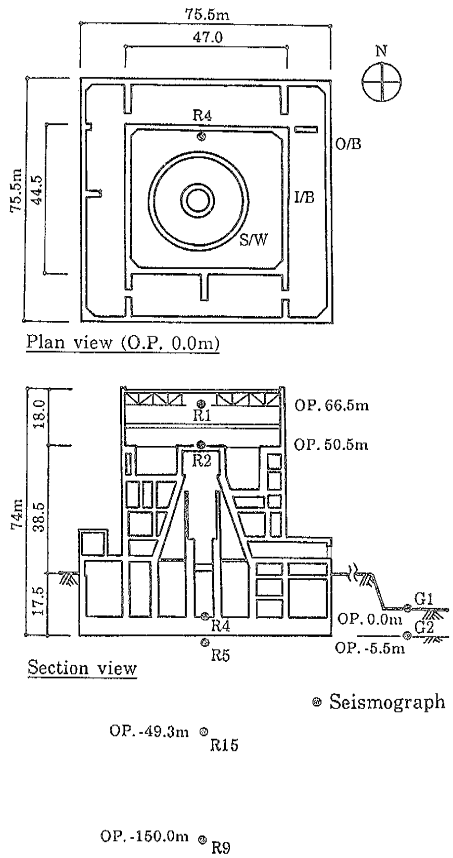


Fig. 1 Location of Seismographs

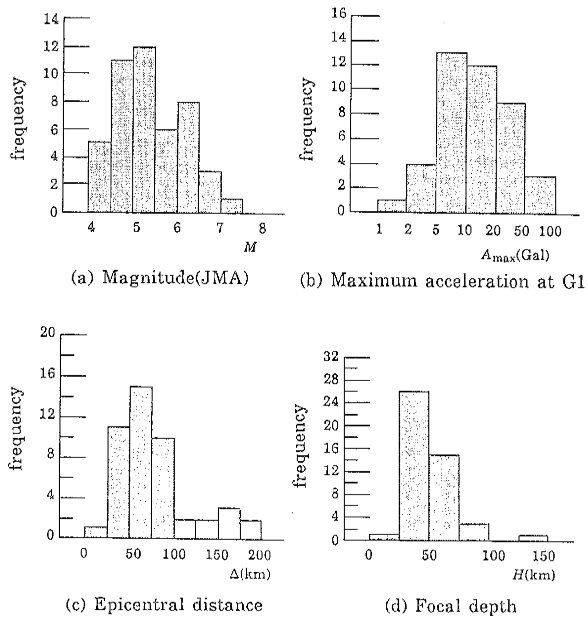


Fig. 2 Histograms of forty-six earthquake events

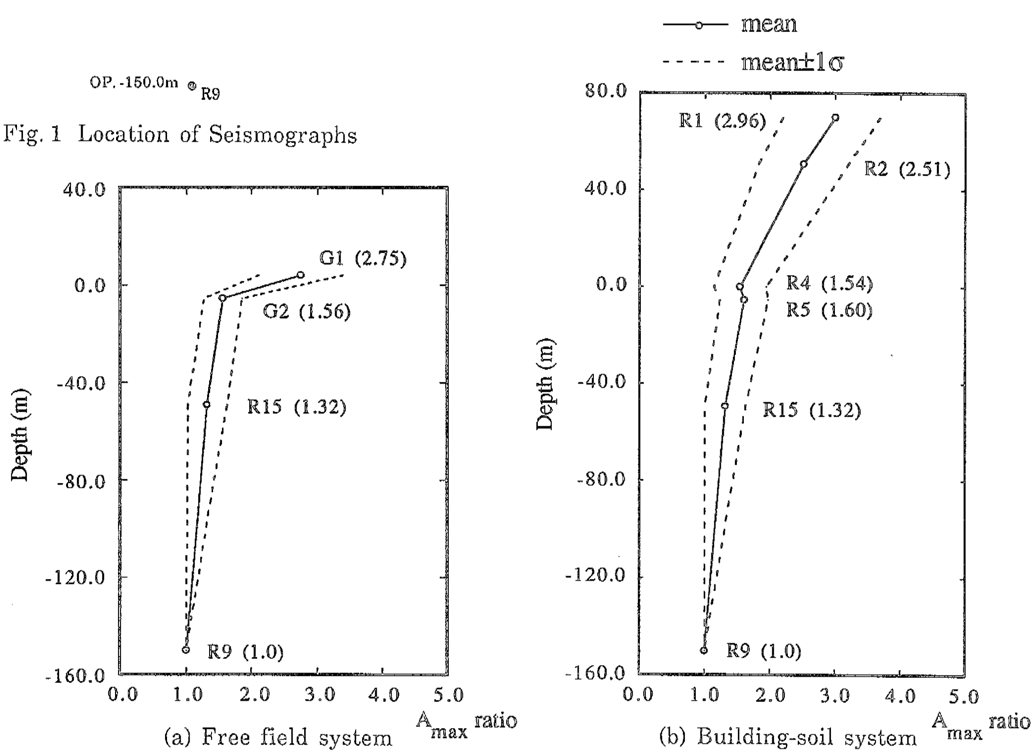
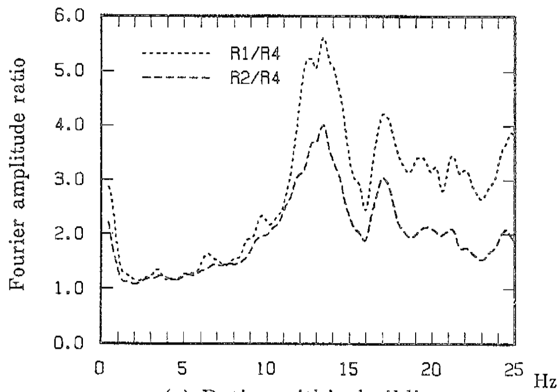
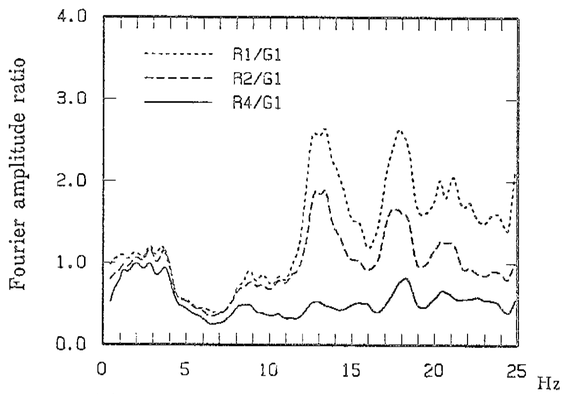


Fig. 3 Average maximum acceleration ratios obtained from forty-six observations



(a) Ratios within building



(b) Ratios between building and ground

Fig. 4 Average Fourier spectrum ratios obtained from forty-six observations

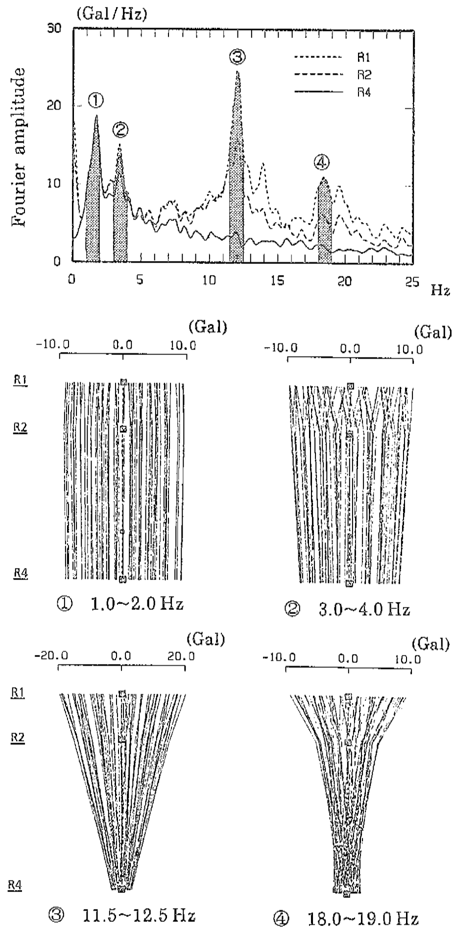
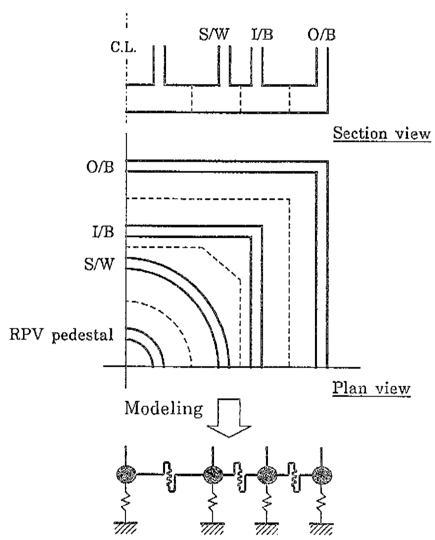
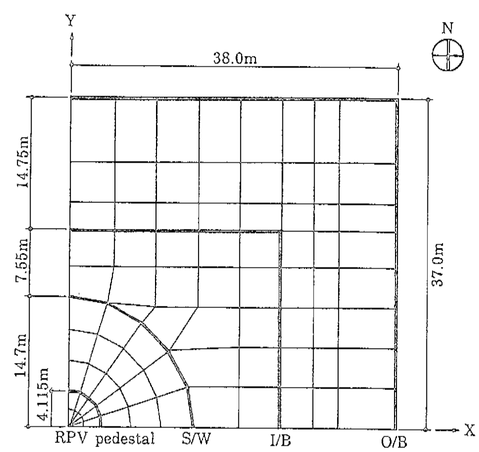


Fig. 5 Mode shapes of building corresponding to dominant frequencies in Fourier spectra of accelerograms ($M_J=6.5$, $\Delta=59$km)



(a) Modeling of blocked foundation



(b) Finite element model of foundation mat

Fig. 6 Schematic illustration of blocked foundation modeling for four stick model

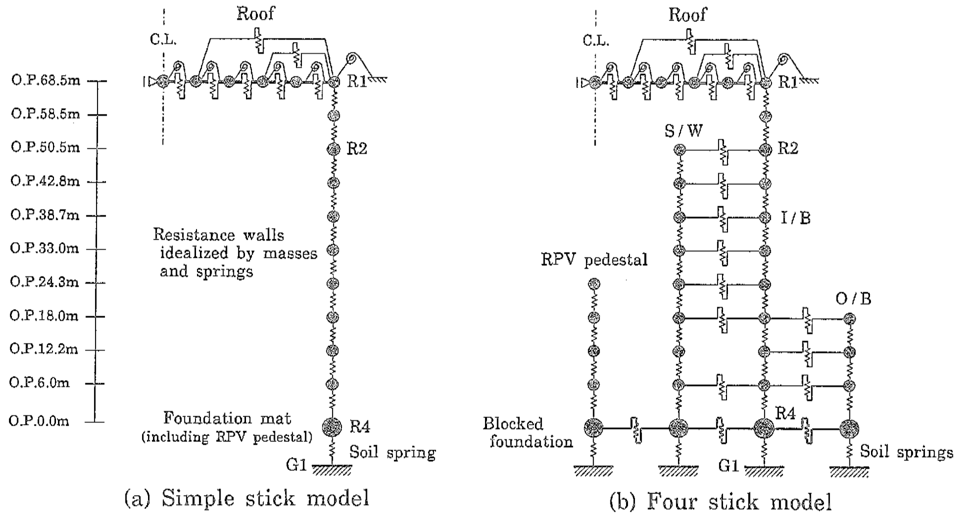


Fig. 7 Two different types of mathematical models for simulation analyses

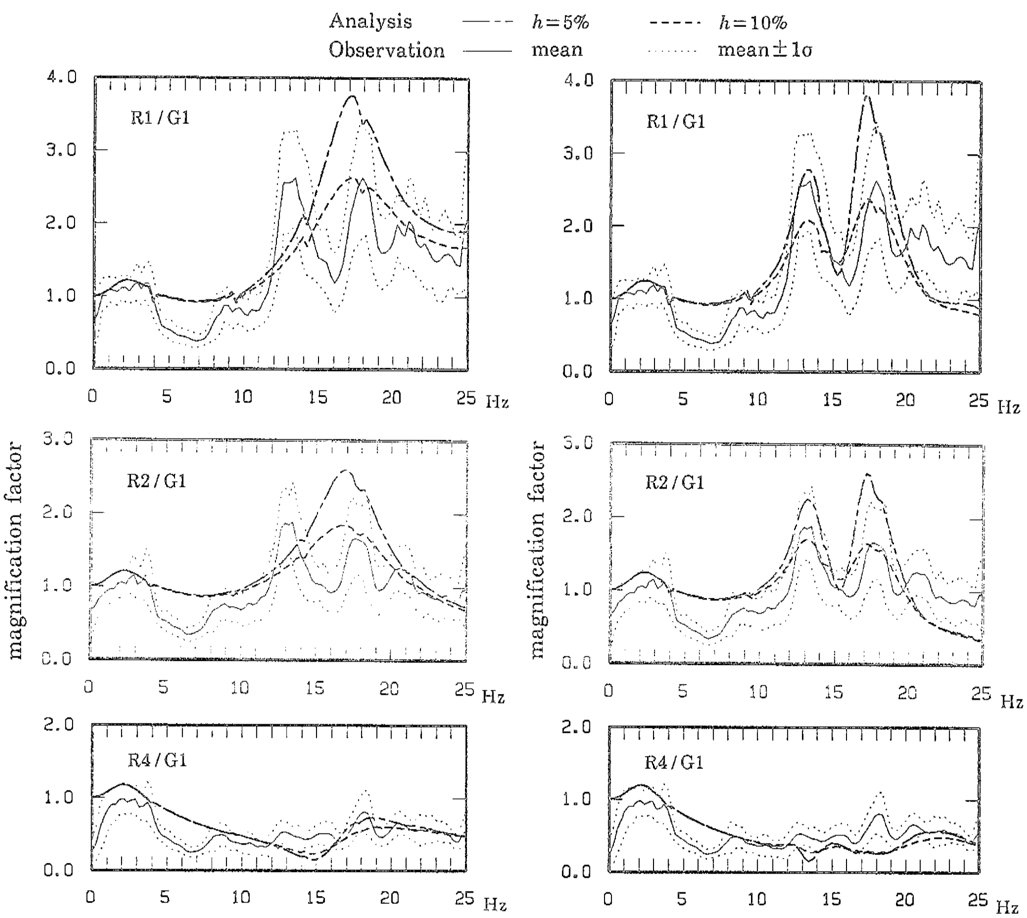


Fig. 8 Comparison of transfer functions obtained from analyses and observations