

## Simulation analysis of vertical response of a nuclear reactor building

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**ABSTRACT :** In order to establish a seismic design procedure of nuclear power plants for vertical ground motion, simulation analyses were carried out for a BWR-MARK II type reactor building. Using a simple and detailed model, a modeling procedure of the building for vertical ground motion was studied from a design point of view. This study revealed that a detailed model could anticipate the precise and accurate behavior of the reactor building's response. Nevertheless, to evaluate the earthquake response of the main resistant walls, a simple model was sufficient.

### 1 INTRODUCTION

Earthquakes affecting the BWR-MARK II type reactor building (Fig. 1) located in Fukushima Prefecture in northeastern Japan have been observed since 1981. By 1987, records of 46 earthquakes had been accumulated. Since the seismic design procedure of nuclear power plants for the vertical ground motion is mainly based on the static method in Japan, these records will be useful for establishing a dynamic

seismic design procedure that subjected to vertical ground motions. Simulation analyses of the reactor building were carried out by employing the mass and spring system considering the soil-structure interaction. The results were compared with the records. Detailed studies on the response characteristics of the reactor building based on the recorded vertical motion were presented in the work of Morishita et al.(1991, 1992).

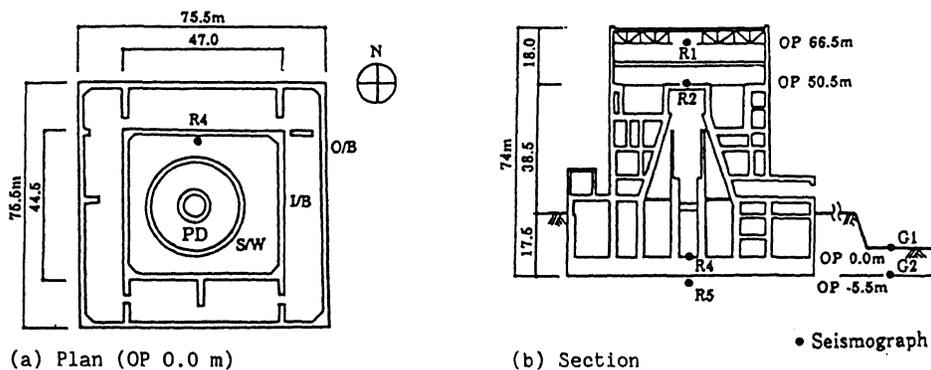


Figure 1. Reactor building and location of the seismograph.

## 2 SIMULATION MODELS

The reactor building is modeled by the mass and spring system. This paper considers two different models as shown in Fig. 2. The one-stick model is a simple model in which the main resistant walls (the outer box (O/B), the inner box (I/B) and the shield wall (S/W)) and the RPV pedestal (PD) are concentrated on one stick. The four-stick model is a relatively detailed model which represents the main resistant walls and PD as four separate sticks. Young's modulus, the shearing stiffness and Poisson's ratio of the reinforced concrete are assumed to be  $300t/cm^2$ ,  $129t/cm^2$  and  $1/6$ , respectively. The axial stiffness and shearing stiffness are evaluated using the full section of the walls.

### 2.1 One-Stick Model

This model is constituted by lumped masses connected with axial spring elements, which represent the stiffness of O/B, I/B, S/W and most of the partition walls. The foundation mat is assumed to be rigid and the total weight of the PD is included as part of the weight of the foundation. A frequency dependent soil spring is added to consider the soil-structure interaction effect. The solution for a half space subjected to the vertical load that assumes the base motion to be rigid is used for the soil spring (Yoshida, K. and Kawase, H. 1988). In the

computation, the shear wave velocity of the soil is assumed to be 500m/s and embedment effects are not considered because they are not large in this case. The roof, which is constructed with four main trusses, is idealized by one stick. This model represents the coupling of the shearing and bending behavior and accounts for the flexural mode of the roof. The damping factor of the roof is assumed to be 1%.

### 2.2 Four-Stick Model

Each stick consists of lumped masses connected by axial spring elements. The stiffness of the partition walls is distributed evenly on the adjoining main walls. The shear spring elements, which represent the partition walls, the walls around the main steam pipe and the pool walls between the main walls, connect sticks corresponding to O/B, I/B and S/W. To explain the anti-plane deformation of the foundation mat, it is divided into four blocks as shown in Fig. 3(a). The stiffness of the foundation mat is evaluated as a  $4 \times 4$  shearing stiffness matrix. The matrix is obtained via the condensation of a large matrix used in the finite element analysis of the bending plate consisting of isoparametric elements (Fig. 3(b)). As a boundary condition of the analysis, the rotation of the nodes located at the bottom of the main walls and PD indicated by the solid lines in Fig. 3(b) is fixed, while the

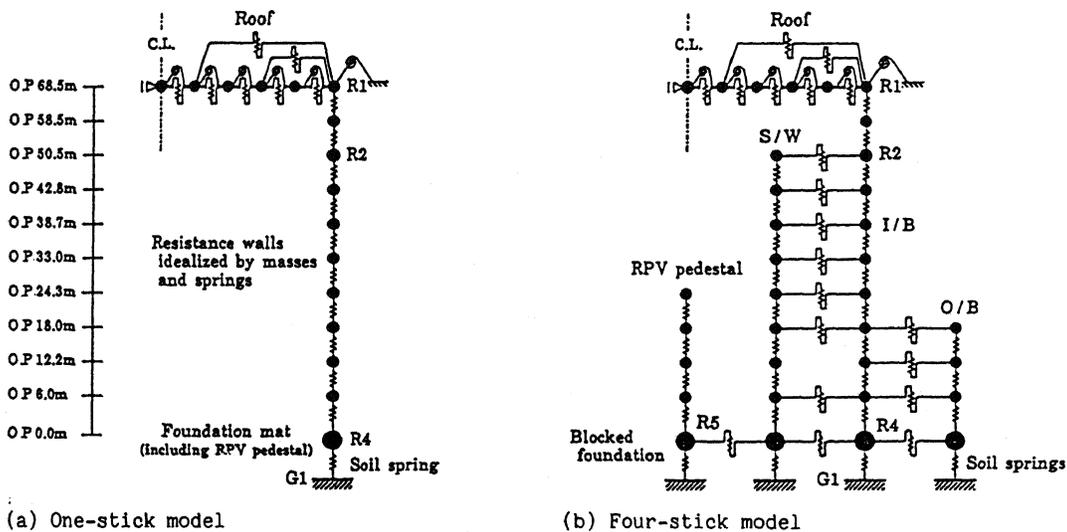


Figure 2. Two different models of simulation analyses.

rest are allowed to rotate freely. To consider the interaction effect between the blocked foundations and the soil, a frequency dependent impedance matrix is employed as soil springs. In the computation, it is assumed that each of the blocked foundations undergoes rigid vertical motion. The stiffness matrix of the soil is finally superimposed on that of the foundation. Other assumptions and conditions are the same as in the one-stick model.

### 3 SIMULATION ANALYSES

#### 3.1 Basic Characteristics of the Models

The sensitivities of the vertical response of the two models are studied on the basis of their spectral characteristics. Since it has been found that the vertical response of the main walls and that of the roof are independent under 20Hz, the results of response analyses of the roof have been excluded in this paper.

Figure 4 shows the transfer functions at R1, R4 and R5 of the models. As for one-stick model, the transfer function at R5 corresponds to that at R4. The thick broken line and dot-dash-line indicate cases of 5% and 10% damping ratios for the structure, respectively. In the figures, the Fourier spectral ratios obtained from the observed

records are also depicted by thin lines. These lines indicate the averages and their standard deviations ( $\text{mean} \pm \sigma$ ), which were obtained from the records of 46 earthquakes within an epicentral distance of 200km from the site. It is understood that the four-stick model provides a good explanation of the observation such as two dominant peaks of 13 and 18 Hz, and the different response behavior of the foundation mat (R4 and R5). On the other hand, the one-stick model does not accurately trace the two peaks of the observation, although it is good enough to assess the vertical response characteristics of the building.

Using reduction factors A and B, Fig. 5 shows how much the reduction of stiffness caused by the openings of the partition walls affects the response characteristics. The reduction factor A reduces the axial stiffness of the partition walls, while B reduces the shearing stiffness of the partition walls, although not the pool walls. The cases in which A and B take on values of 1.0, 0.7 and 0.5 are compared in the figures. The decrease in axial stiffness causes an increase in the amplitude of the peak at 13Hz, but its effect is small. The increase in shearing stiffness shifts the second peak of the walls to higher frequency. To simulate the records, it seems that the openings of partition walls need not be considered.

Figure 5 also indicates that the

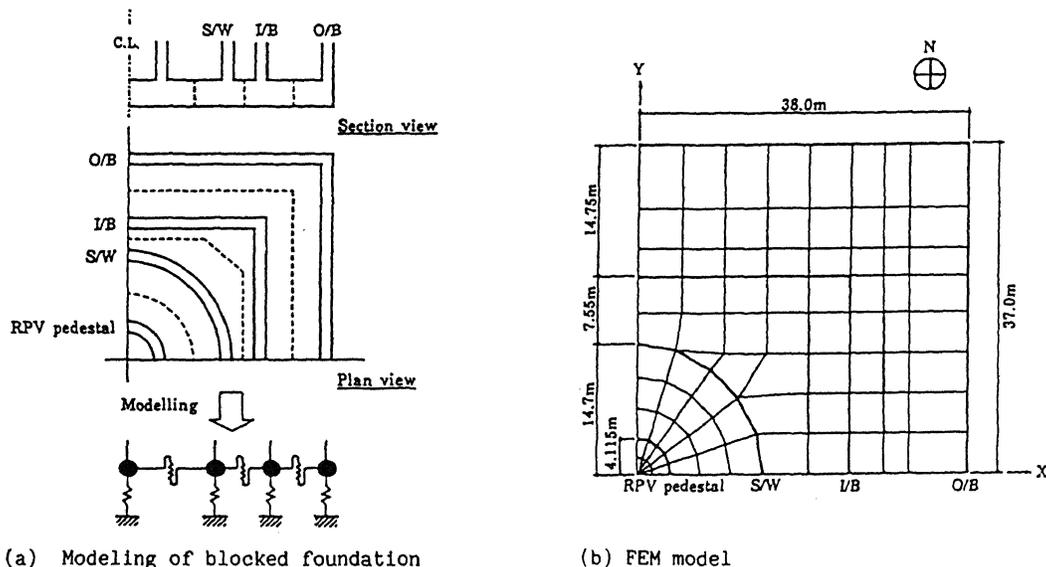


Figure 3. Schematic illustration of blocked foundation modeling for the four-stick model and a finite element model of the foundation mat.

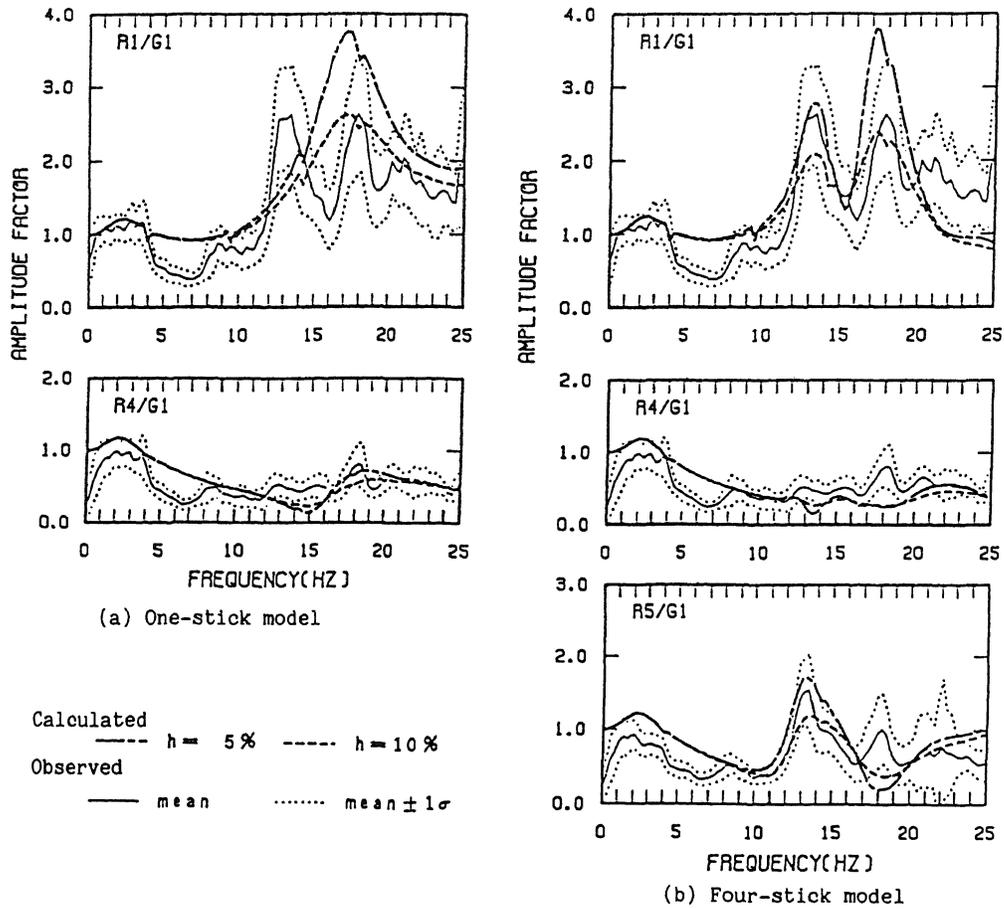


Figure 4. Comparison of the transfer functions obtained from analyses and those obtained from observations.

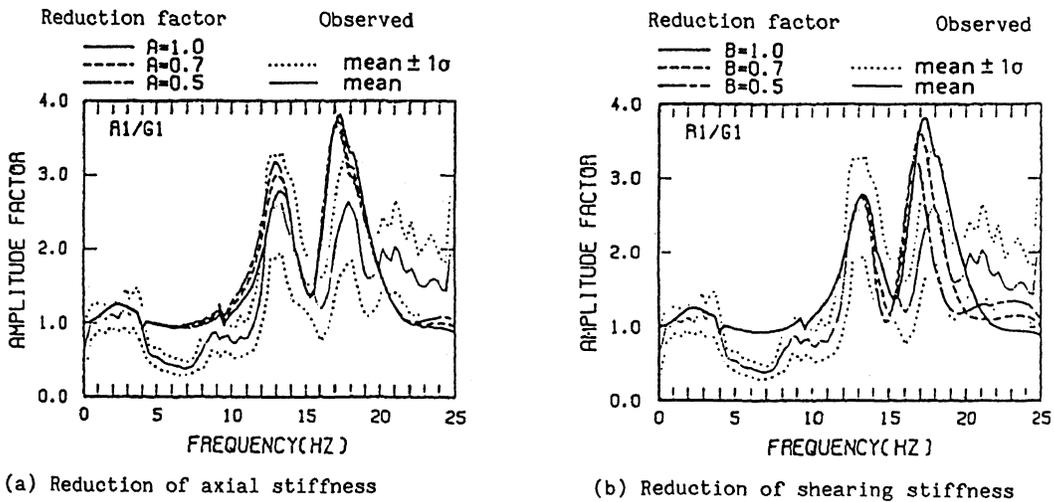


Figure 5. Variation in the transfer functions of the four-stick model caused by the reduction of axial and shearing stiffness of the partition walls.

predominant peak around 13Hz corresponds to the axial deformation of I/B and S/W, while the predominant peak at 18 Hz corresponds to the shearing deformation of the connecting walls between I/B and S/W. The predominant frequency of the main walls is completely separate from that of the soil-structure interaction system at about 3.5Hz.

### 3.2 Earthquake Response Analyses

Three earthquakes whose peak accelerations are comparatively large among the records are selected for analysis: EQ1(M 5.8,

epicentral distance  $\Delta=48\text{km}$ ), EQ2(M6.6,  $\Delta=77\text{km}$ ), EQ3 (M6.5,  $\Delta=59\text{km}$ ). Figure 6 shows the locations of epicenters and the observation site. The UD component of the accelerograms at the G1 point are depicted in Fig. 7. The input earthquake motion for each model is defined as a free-field surface ground motion at the bottom level of the foundation mat. This motion is calculated on the basis of the records obtained at the G1 station according to the one-dimensional wave propagation theory. According to the records, a ground model in which the system frequency is 6.5Hz for a vertically propagating P wave in the

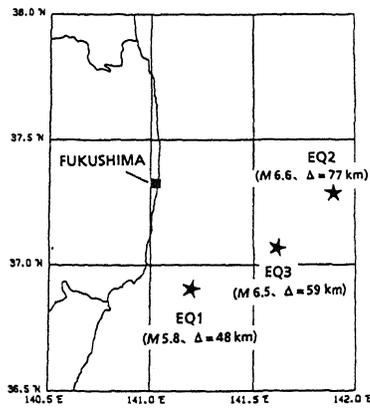


Figure 6. Location of the epicenters and the site.

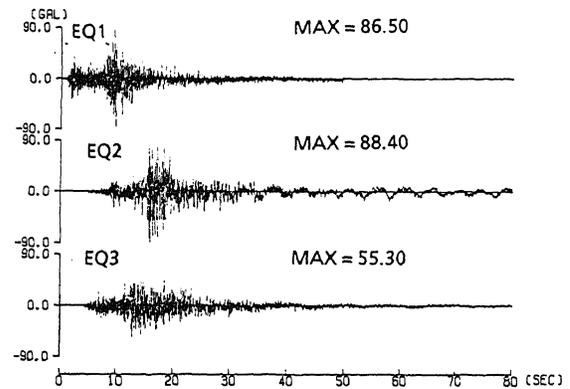


Figure 7. Accelerograms (UD) observed at the G1 point.

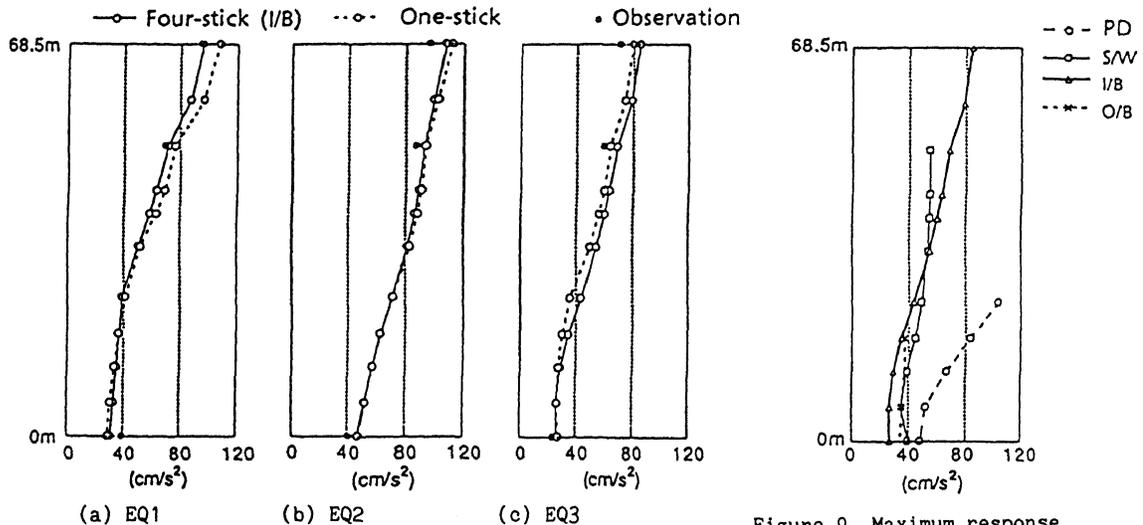


Figure 8. Comparison of the maximum response accelerations of the one- and four-stick models (I/B).

Figure 9. Maximum response accelerations of each stick of the four-stick model (EQ3).

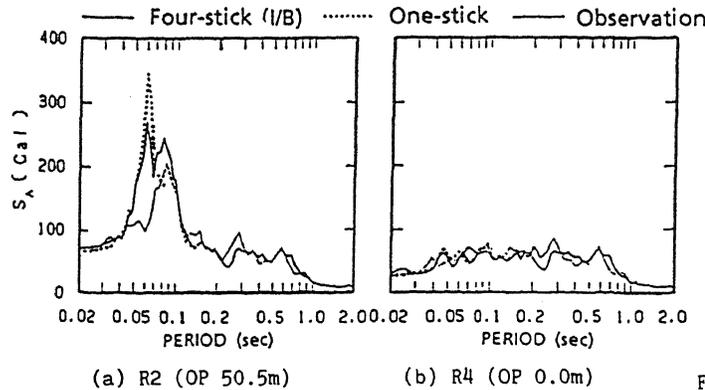


Figure 10. Comparison of the acceleration response spectra of one- and four-stick models (EQ3).

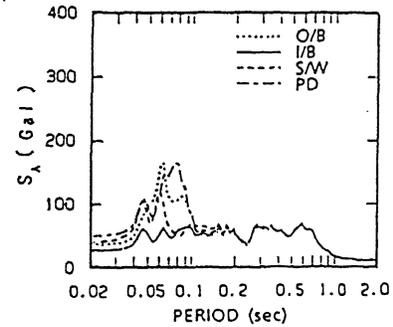


Figure 11. Acceleration response spectra of the divided foundations of the four-stick model (EQ3).

uppermost surface layer is used in the calculation.

The resulting maximum response accelerations are shown in Figs. 8 and 9. Figure 8 compares the responses of the one- and the four-stick (I/B) model with the record for each earthquake. The responses of both models are almost the same, and also accurately simulate the observations for all three earthquakes. Figure 9 compares the responses of the O/B, I/B, S/W and PD of the four-stick model. The responses of the main resistant walls are almost the same, and can be represented by values of the one-stick model as shown in Fig. 8. On the contrary, the response of the PD is clearly different from the response of the main walls. The reason for this is that the pedestal is not connected to the main walls and its weight causes the pedestal to behave differently from the main walls, and to be more affected by the flexure of the foundation mat.

Figure 10 shows acceleration response spectra of the one- and the four-stick (I/B) models at levels of OP 50.5m and OP 0.0m with observed spectra. The simulation results coincide with the records except the 0.06s component of the OP 50.5m spectra. The responses of foundation masses of the four-stick model are compared in Fig. 11. This figure indicates that the four-stick model can represent the different behavior of each part of the foundation mat within a period of 0.05-0.1s.

#### 4 CONCLUSIONS

Earthquake responses are analyzed by using two different reactor building models. Both models closely simulate the records. The obtained results are as follows.

1. The one-stick model is sufficient to study the vertical response of the resistant walls. As the vertical response of the main walls can be represented by the response at the same floor level of the one-stick model, it is not necessary to model the resistant walls separately.

2. On the other hand, when the anti-plane deformation of the foundation mat, the coupling effects between the main walls or the response of the pedestal are studied, it is necessary to model the pedestal and the main walls separately with a divided foundation.

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