Model Test on Interaction of Reactor Building and Soil
Part 2: Excitation by Earthquakes

Michio Igushi, Kinji Akino, Masanori Niwa
Nuclear Power Engineering Test Center, Tokyo, Japan

INTRODUCTION

Theoretical studies of soil-structure interaction have progressed in recent years. At the same time, experimental studies to verify the theoretical results have been carried out energetically. These experimental studies, however, have been mostly conducted by means of vibration tests or earthquake observations individually. In order to investigate experimentally the effects of soil-structure interaction, it is desirable to carry both the forced vibration tests and the earthquake observations for the same models. To this end, the earthquake observations were conducted to obtain the dynamic behaviors of soil-reactor building system during earthquakes and to compare them with the results of the forced vibration tests. In a companion paper (Iguchi, 1989), the results of the forced vibration tests and their analytical studies are described.

EARTHQUAKE OBSERVATION SYSTEM

The earthquake observation system consists of sensors, amplifiers, a recorder and a controller for those devices. To obtain the accurate records, servo-type accelerometers were used as the sensors. A delay device was installed to record the initial motion. In addition, a clock with an autocalibration device was installed to determine the arrival time of seismic waves. As the recorder, 12 bits digital recorder providing a wide dynamic range was used.

Fifty-five sensors were installed on the models A and C, underneath each model and in the free ground as shown in Fig. 1. The models A and C simulate a BWR-type reactor building and its adjacent building respectively. The reduced scale ratio of these models are approximately one fifth.

OBSERVATION RESULTS

Favorable thirty-six earthquake records were obtained for 2 years observation. Figure 2 shows that the hypocentral distance were in a range of 45 - 1,000 km and the magnitudes of the earthquakes were in a range of 3.5 - 6.8. The recorded maximum accelerations on the ground surface were less than 70 Gals. In order to extract the common characteristics of cross interaction effect from the earthquake records, thirteen earthquake records were chosen with consideration of the direction of epicenters, and the averaged transfer functions relating the roof motion and foundation motion to the free ground surface motion were calculated. These results are compared later with the analytical results. Besides, as shown in Table 1, five earthquake records were chosen with consideration of the maximum accelerations which are comparatively larger among all earthquake records, and used in the simulation analyses.

METHOD OF SIMULATION ANALYSIS

Analytical Models

The simulation analyses of the seismic response were worked out using three analytical models - 1) the sway-rocking model (S-R model) in which the soil is substituted by equivalent complex and frequency-dependent springs whose constants are determined by a elasto-dynamic theory for continuum body, 2) pseudo-three-dimensional FEM model (pseudo-3D FEM model) and 3) the lattice model. These analytical models are the same as used in the simulation analyses of the forced vibration tests. In the simulation analyses using S-R model, six degrees of freedom were taken into account for each foundation. On the other hand, in the analyses using FEM and the lattice models the vibrations in the NS direction were considered as shown in Fig. 4. Table 2 shows the soil profile estimated by the vibration tests and used in the analyses of the seismic response.

Input Motion

The seismic motions recorded on the free ground surface were used as the input motion for response analyses by using S-R model. In the cases of FEM and lattice model, the input motions impinging to the bottom of the analytical models were calculated by a deconvolution technique, in which the vertical incidence of seismic waves are assumed. Figure 3 shows the schematic explanation of the input motion in these analyses.

ANALYTICAL RESULTS

Transfer Function

Figures 5 to 7 show the observed transfer functions and those calculated by using three different analytical models for comparison. The observed transfer functions were determined as an average of the before mentioned thirteen earthquake records. In Fig. 5, the three different calculated transfer functions of models A and C from NS component by S-R model are shown for the three different directions input motion. On the other hand, the observed NS transfer function is affected simultaneously by the three directions. Some remarks obtained from this study are as follows:

1) It was confirmed from the observed transfer functions that the resonance frequencies of the superstructure coinside with those obtained by the forced vibration tests. Futher, from the observed transfer functions relating the foundation motion to the surface ground motion, it should be noted that curves of these transfer functions observed on the foundation drop remarkably near the resonance frequencies of superstructures. Same phenomenon is also recognized in the case that the system was excited at the foundation in the forced vibration test.
2) In regard to the first resonance frequencies of Model A (about 5 Hz) and Model C (about 4 Hz), whose values were confirmed from the earthquake records, it is recognized from the analytical results calculated by the S-R model that the response of NS direction to the input motion of UD component is slightly induced. In the frequency range between 7 and 8 Hz, it is noticed that torsional vibration is also induced by the input motion of EW component.
3) The analytical results of EW direction calculated by the S-R model correspond well to the observed ones similarly as in the case of NS direction.
4) The analytical results of NS direction by the FEM and the lattice models do not agree well with the observed ones at the resonance frequency of the torsional vibrations (about 7 to 8 Hz) though they correspond well to the observed resonance frequencies in NS direction. This is due to the fact that the torsional component was not taken into account in both analytical models.

Simulation Analyses of Seismic Response

The results of simulation analyses correspond well to those of observed ones except for No. 4 earthquake in which higher frequencies predominate. Figures 8 to 10 show two kinds of analytical results as examples of the good (No. 1 earthquake) and poor (No. 4 earthquake) agreement. Figures (a) and (b) in each figure are the results for No. 1 earthquake while figures (c) and (d) are for No. 4 earthquake. In these figures the observed results are also plotted for comparison. Some remarkes obtained from this study are as follows:

1) The analytical results of No. 1 earthquake agree with the observed ones better than those of No. 4 earthquake.
2) The frequency components of No. 1 earthquake are distributed uniformly in a wide frequency range investigated in the analysis. On the other hand, the frequency components of No. 4 earthquake predominate only about 16 Hz (0.06sec).
3) It may not be appropriate to consider the frequencies over 16 Hz, since the soil properties used in the analysis were estimated from the vibration test results under 15 Hz.

CONCLUSIONS

Conclusions derived from this study can be summarized as follows:

1) The averaged transfer functions obtained from thirteen earthquake records agree well with the results of the forced vibration tests.
2) The results of the simulation analyses of seismic response show good agreement with those of observed ones except for earthquakes in which higher frequencies are predominant, where the analytical models used in the seismic response are the same as those of the vibration tests. This indicates that the effects of cross interaction can be evaluated by the same method in both cases of the forced vibration tests and the earthquake observations.
3) The S-R model with consideration of the cross interaction effects is proved to be applicable for the simulation analyses for both the forced vibration tests and the seismic response.
4) The pseudo-3D FEM is proved to be applicable for the cross interaction analysis during earthquakes though it shows a tendency to overestimate the radiation damping into soil for the case of the forced vibration tests.
5) The lattice model is shown to be applicable to the cross interaction analysis of earthquake response.

ACKNOWLEDGMENTS

This work was carried out as the entrusted project sponsored by the Ministry of International Trade and Industry in Japan. This work is supported by "Sub-Committee of Soil-Structure Interaction" under "Committee of Seismic Verification Tests" of NUPEC. The authors wish to express their gratitude for the cooperation and valuable suggestions given by the members of Committee.

REFERENCES

1. Iguchi, M., Akino, K. and Kiya, Y. (1989). MODEL TEST ON INTERACTION OF REACTOR BUILDING AND SOIL, Part 1: CROSS INTERACTION TESTS, 10th International Conference on Structural Mechanics in Reactor Technology.
2. Iguchi, M., Akino, K. and Noguchi, K. (1987). MODEL TEST ON INTERACTION OF REACTOR BUILDING AND SOIL, 9th International Conference on Structural Mechanics in Reactor Technology, Vol. K1, PP317.
3. Iguchi, M., Akino, K., et al. (1988). LARGE-SCALE MODEL TESTS ON SOIL-REACTOR BUILDING INTERACTION, Part 1 and 2, 9th World Conference on Earthquake Engineering.

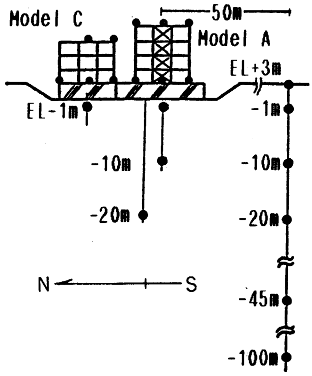
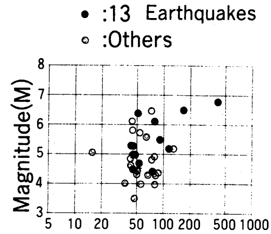
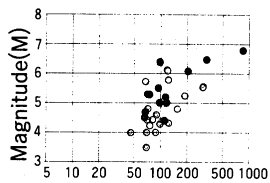


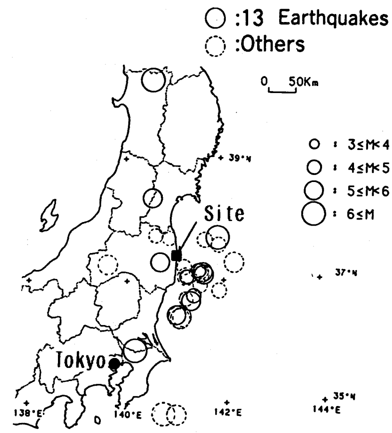
Fig. 1 Location of Seismographs



(a) Focal Depth (Km)



(b) Hypocentral Distance (Km)



(c) Epicenters

Fig. 2 Outline of Observed Earthquakes

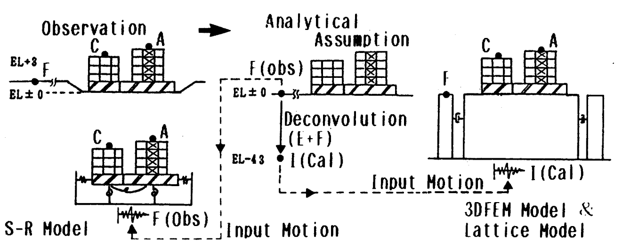
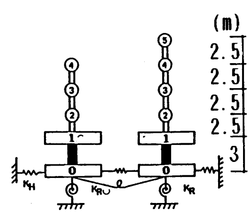
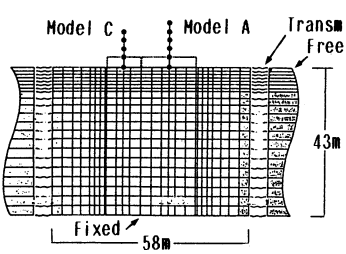


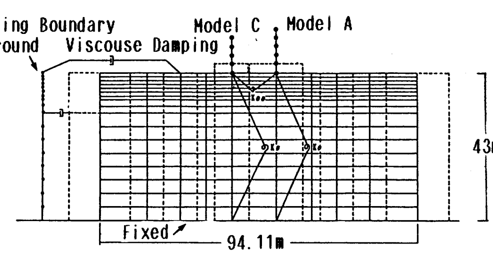
Fig. 3 Schematic Explanation of the Input Motion



(a) S-R Model



(b) Pseudo 3D-FEM Model



(c) Lattice Model

Fig. 4 Analytical Models

Table 1 Earthquakes used in Analyses

No.	Date	Origin Time (JST)	M	D (km)	X (km)	△ (km)	Amax (gal)
1	Mar. 29, 1985	1:07	6.5	164	327	322	12.2
2	Aug. 12, 1985	12:49	6.4	52	97	82	49.6
3	Oct. 4, 1985	21:25	6.1	78	203	189	7.5
4	Dec. 25, 1985	10:04	4.4	54	79	57	12.3
5	Feb. 12, 1986	11:59	6.1	44	119	111	14.6

M:Magnitude, D:Depth
X:Hypocentral Distance, △:Epicentral Distance
Amax:Maximum Acceleration of Free Surface Ground Motion

Table 2 Soil Profile used in Analyses

EL(m)	Model A,C			
	Vs (m/s)	ρ (t/m³)	ν	h (%)
±0 ~ -3	230	1.83	0	5
-3 ~ -7	290	1.91	0.412	3
-7 ~ -11	320	1.79	0.462	1
-11 ~ -45	480	1.78	0.455	1

Vs:Shear Wave Velocity ρ:Density
ν:Poisson's Ratio h:Damping Factor

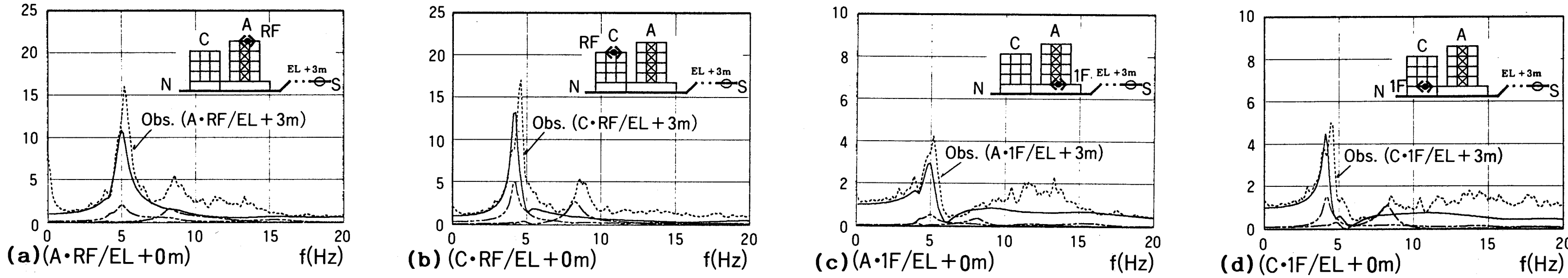


Fig. 5 Transfer Functions (S-R Model, NS-direction)

↔ :Evaluated Point (NS), ——:Response(NS)/Input(NS)
– – –:Response(NS)/Input(EW), –·–:Response(NS)/Input(UD)

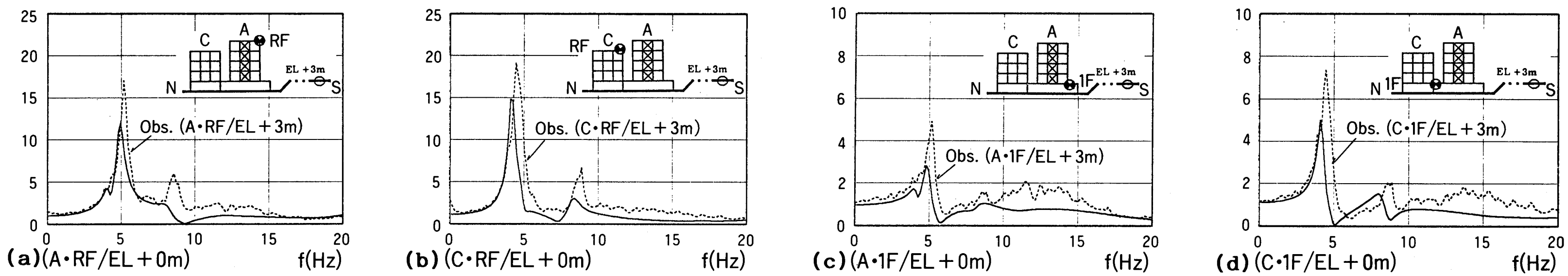


Fig. 6 Transfer Functions (S-R Model, EW-direction)

⊕ :Evaluated point (EW), ——:Response(EW)/Input(EW)

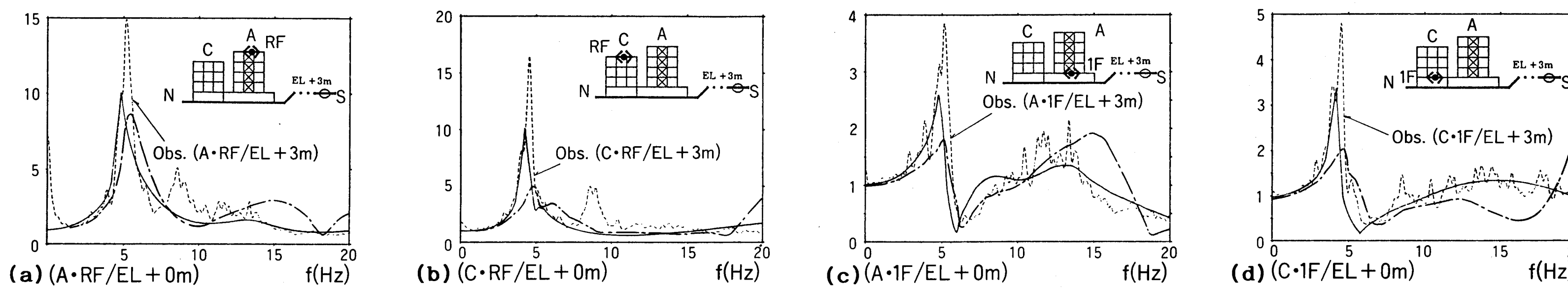


Fig. 7 Transfer Functions (Pseudo 3D-FEM & Lattice Model, NS-direction)

↔ :Evaluated point (NS)
——:Lattice, – – –:3D-FEM

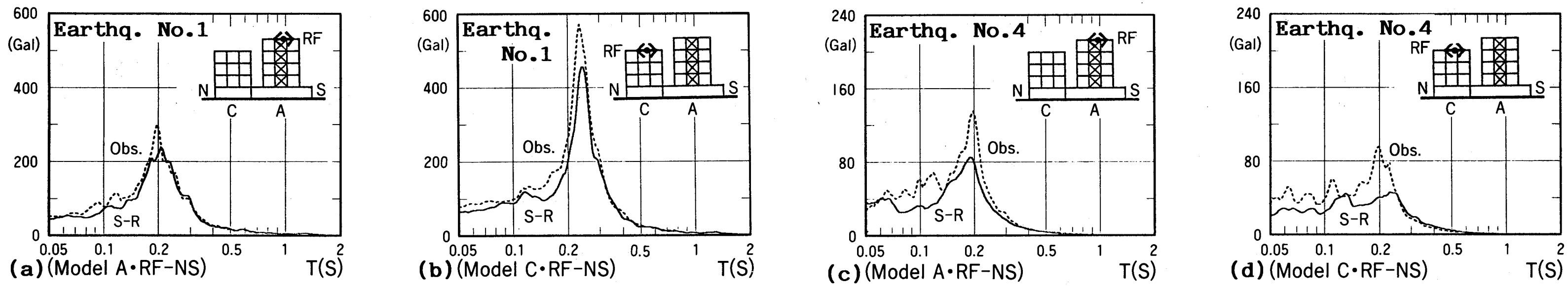


Fig. 8 Acceleration Spectra (S-R Model, NS-direction) ↔ :Evaluated point (NS)

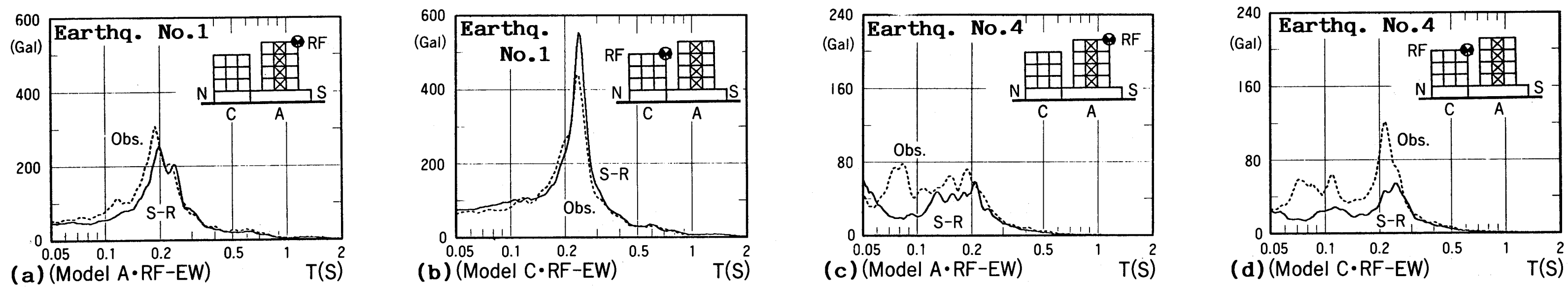


Fig. 9 Acceleration Spectra (S-R Model, EW-direction) ⊗ :Evaluated Point (EW)

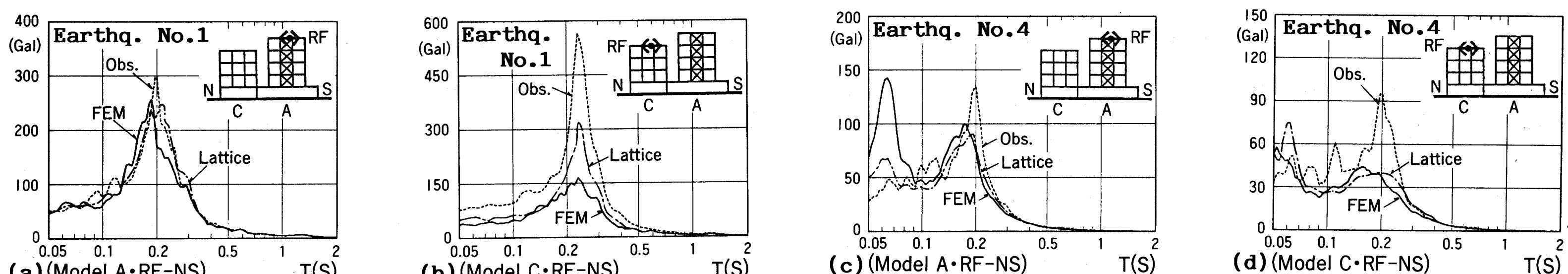


Fig. 10 Acceleration Spectra (Pseudo 3D-FEM & Lattice Model, NS-direction)

↔ :Evaluated Point (NS)
---:Lattice, — - —:3D-FEM