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LARGE-SCALE MODEL TESTS ON SOIL-REACTOR BUILDING INTERACTION PART II : EARTHQUAKE OBSERVATION

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SUMMARY

This paper describes the results of earthquake observations and analytical studies of large-scale models of nuclear reactor buildings. The purpose of the earthquake observations is to study the dynamic behaviors of the soil-reactor building interaction during earthquakes and to compare them with the results of the forced vibration tests. The results of the simulation analyses of seismic response correspond well with those of observed ones. The analytical models used in the seismic response are the same as those of the vibration tests. This indicates that the effects of soil-structure interaction can be evaluated by the same method in both cases of the forced vibration tests and the earthquake observations.

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 out not only the forced vibration tests but the earthquake observations for the same model. 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. The results of the forced vibration tests and their analytical studies are shown in PART I (Ref. 1).

EARTHQUAKE OBSERVATION SYSTEM

The earthquake observation system consisted of sensors, amplifiers, a recorder, and a controller for those devices. To obtain accurate records, a servo-type accelerometer was used as a sensor. A delay device was installed not to miss the initial motion. In addition, a clock with an autocalibration device was installed to determine the arrival time of seismic waves. As a recorder, a 12 bits digital recorder with a wide dynamic range was used.

Sixty-three sensors were installed on the models A, B 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 model B simulates a PWR-type reactor building.

OBSERVATION RESULTS

Favorable thirty-six earthquake records were obtained for 2 years observation. As shown in Fig. 2, the hypocentral distance were in a range of 45 - 1000 Km and the magnitudes of the earthquakes were in a range of 3.5 - 6.8. The observed maximum accelerations on the ground surface were in a range of less than 70 Gals.

Transfer Function In order to extract the common characteristics of soil-structure interaction effect from the earthquake records, thirteen earthquake records were chosen with consideration of the direction of epicenters. Fig. 3(a) shows the averaged transfer functions relating the roof motion to the foundation motion of each model. It can be noticed from these results that the resonance frequencies of the superstructure coincide with those obtained by the forced vibration tests. Fig. 3(b) shows the averaged transfer functions relating the foundation motion to the surface ground motion. It should be noted that curves of these transfer functions drop 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 tests as described in PART I (Ref. 1). Thus, it is confirmed that the results obtained by the earthquake observations correspond well with those of the vibration tests.

COMPARISON OF OBSERVED AND ANALYTICAL RESULTS

The simulation analysis of the seismic response was carried out using three analytical models - 1) the sway-rocking model (S-R model) in which the soil was substituted by equivalent complex and frequency-dependent springs whose constants were determined by a continuum elasto-dynamic theory, 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. Tables 1 and 2 show the list of earthquakes used in the analyses and the soil profiles estimated by the vibration tests, respectively.

Results of Models A and C The seismic motions recorded on the ground surface were used as the input motion for response analyses, in which the vertical incidence of seismic waves were assumed, as shown in Fig. 4. 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 of the NS direction were considered as shown in Fig. 5. The comparison of the calculated distribution of the maximum accelerations and response spectra with the observed results are shown in Figs. 6 to 9.

Some remarks obtained from the comparison are as follows:

1) The results of the simulation analyses correspond well with those of observed ones except for No. 4 earthquake in which higher frequencies predominate.

2) In regard to the S-R model, a better correspondence between the observed and the analyzed results are obtained for the NS direction than for the EW direction. This may be caused by the fact that the dynamic stiffnesses of two foundations were estimated independently from the forced vibration tests and, as the results, the effect of cross interaction between two foundations were not taken into account in the analyses.

3) The pseudo-3D FEM is proved to be applicable for the seismic response analyses though it shows a tendency to overestimate the radiation damping into soil for the case of the forced vibration tests.

4) The results obtained by the lattice model are similar to those by the pseudo-3D FEM.

Results of Model B The model B resonated at comparatively higher frequencies such as about 10Hz at the 1st natural frequency of the Inner Concrete and 15Hz at the 2nd one of the Outer Shield Wall as shown in Fig. 3(a). As there was three-meter difference in level between the bottom of the model B and the free surface ground, the input motion impinging to the model B might probably different from the ground motion observed on the free surface especially in a range of high frequencies. Therefore the observed earthquake motions should be modified with consideration of the cavity of soil in the simulation analyses. The modification of input motions were performed by use of the axi-symmetric FEM. Fig. 10 shows a schematic explanation of the way to estimate the input motions and its meaning is expressed by the equation shown in the bottom of this figure. Thus calculated input motion tends to decrease with decrease of periods as shown in Fig. 13.

Fig. 11 shows the analytical model of the model B. Figs. 12 and 14 show the distribution of the maximum accelerations and the acceleration response spectra, respectively, compared with these calculated using the observed surface ground motions as the input motions (Case 1) and the modified motions as the input motions (Case 2).

Remarks obtained from this study are as follows:

1) The results of simulation analysis using the input motions evaluated with consideration of the cavity of soil correspond well with those of observed ones except for No.4 earthquake.

2) In the case of using the surface motions as the input motions, the analytical results tend to be larger than the observed results.

CONCLUSIONS

Conclusions derived from this study can be summarized as follows:

1) It is confirmed that the dynamic characteristics of models obtained by the earthquake observations correspond well with those of the forced vibration tests.

2) The results of the simulation analyses of seismic response correspond well with those of observed ones. The analytical models used in the seismic response are the same as those of the vibration tests. This indicates that the effect of soil-structure 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 is proved to be applicable for the simulation analyses of both the forced vibration tests and the seismic response.

4) The pseudo-3D FEM is proved to be applicable for the seismic response analyses though it shows a tendency to overestimate the radiation damping into soil for the case of the forced vibration tests.

5) The results obtained by the lattice model are similar to those by the pseudo-3D FEM.

ACKNOWLEDGMENTS

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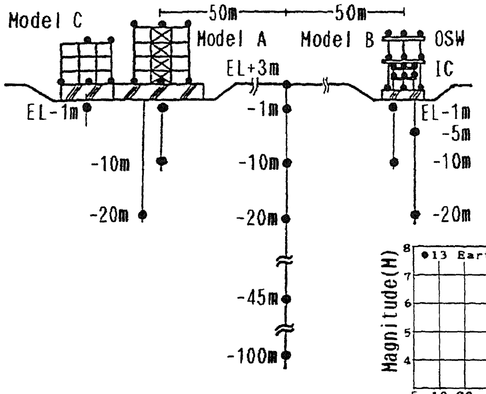
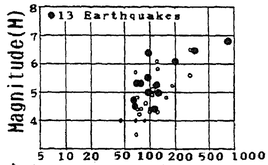
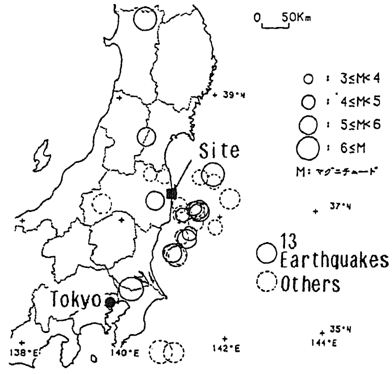


Fig. 1 Location of Seismometers

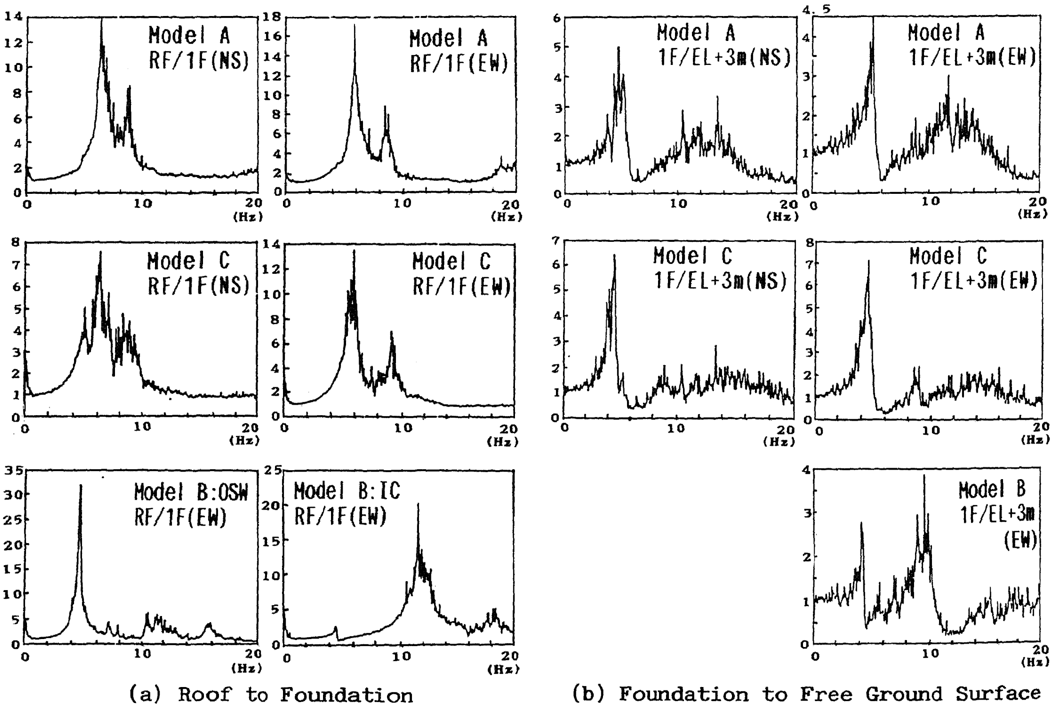


(a) Hypocentral Distance(km)



(b) Epicenter

Fig. 2 Outline of Observed Earthquakes



(a) Roof to Foundation (b) Foundation to Free Ground Surface

Fig. 3 Averaged Transfer Function of 13 Earthquakes

Table 1 Earthquakes used in Analyses

No.	Date	Origin Time (JST)	M	D (km)	X (km)	Δ (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 Δ:Epicentral Distance

Amax:Maximum Acceleration of Free Surface Ground Motion

Table 2 Soil Profiles used in Analyses

Model A,C

EL(m)	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

Model B

EL(m)	Vs (m/s)	ρ (t/m³)	ν	h (%)
±0 ~ -0.5	230	1.85	0.163	2
-0.5 ~ -2.3	360	1.85	0.319	2
-2.3 ~ -6.3	275	1.85	0.387	2
-6.3 ~ -9.3	375	1.75	0.379	2
-9.3 ~ -45	470	1.85	0.453	2

Vs : Shear Wave Velocity ρ : Density

ν : Poisson's Ratio h : Damping Factor

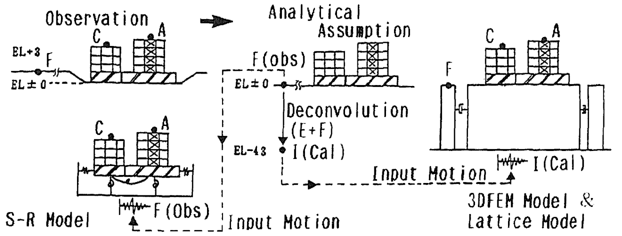


Fig. 4 Conception of Input Motion

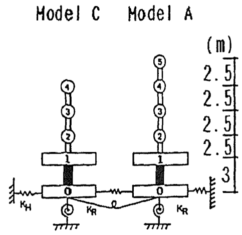


Fig. 5(a) S-R Model

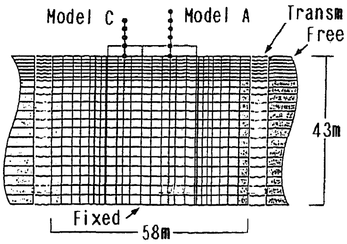


Fig. 5(b) Pseudo-3D FEM Model

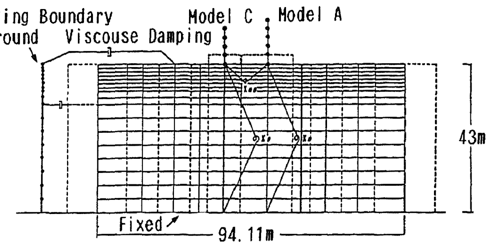


Fig. 5(c) Lattice Model

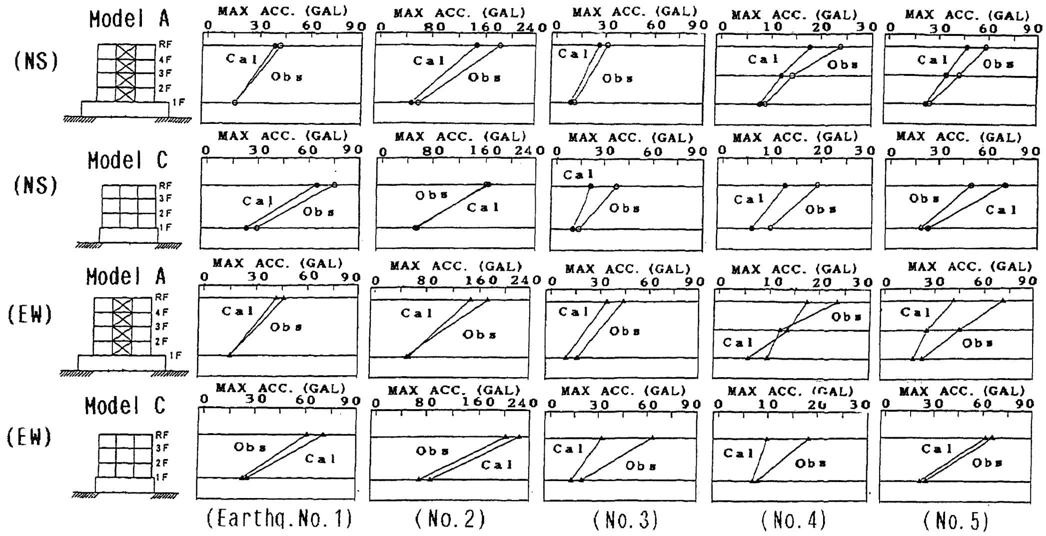


Fig. 6 Distribution of Maximum Accelerations (S-R Model)

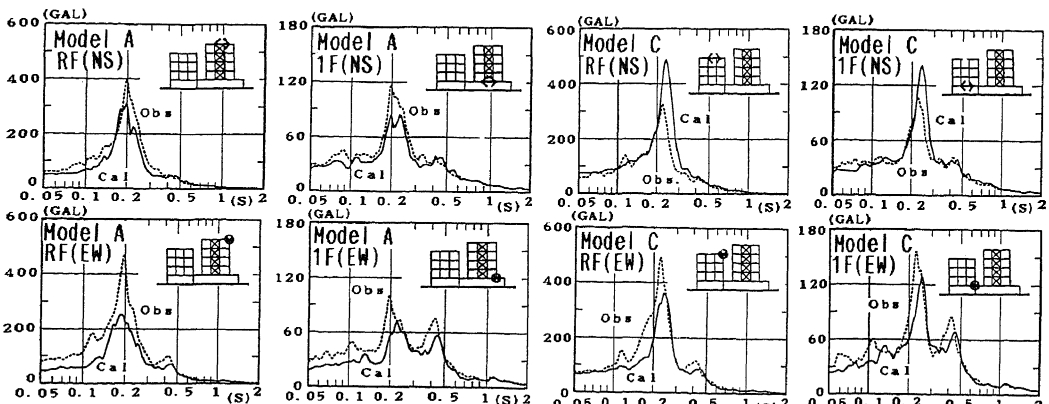


Fig. 7 Response Spectra (S-R Model, Earthq.No.5, h=0.05)

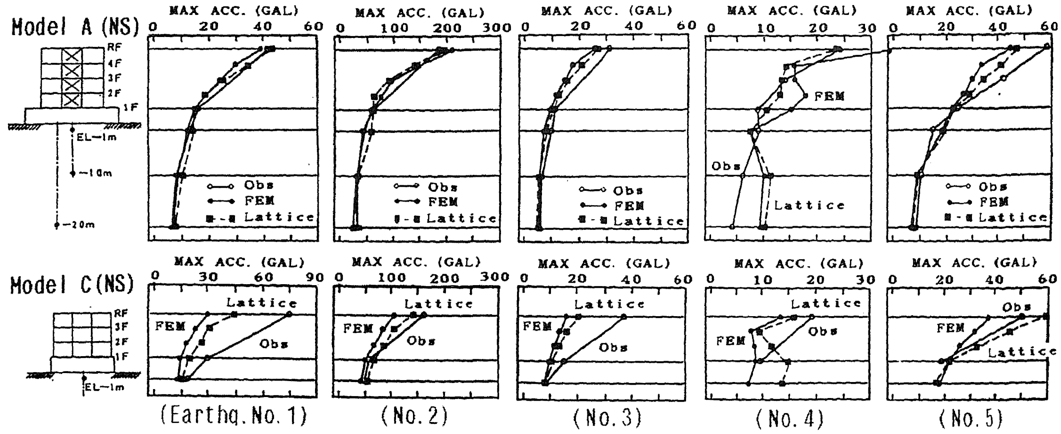


Fig. 8 Distribution of Maximum Accelerations (FEM, Lattice Model)

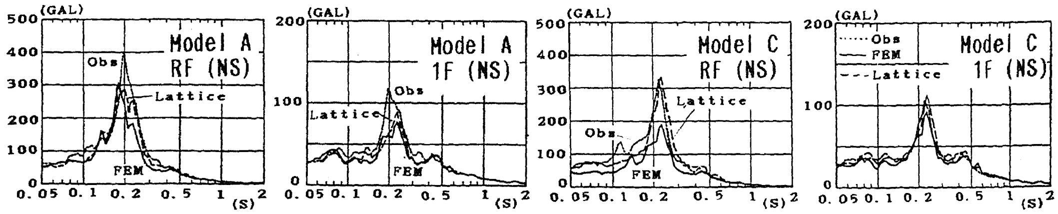


Fig. 9 Response Spectra (FEM, Lattice Model, Earthq.No.5, h=0.05)

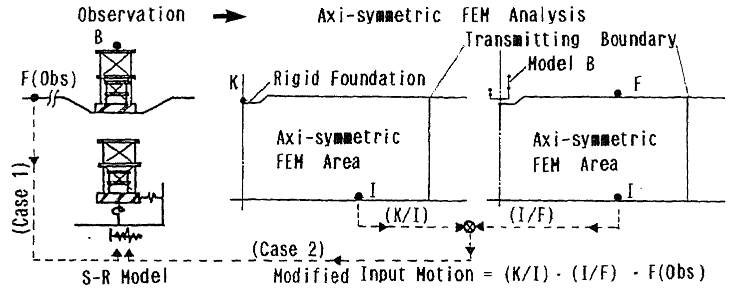


Fig. 10 Conception of Input Motion

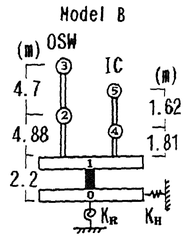


Fig. 11 S-R Model

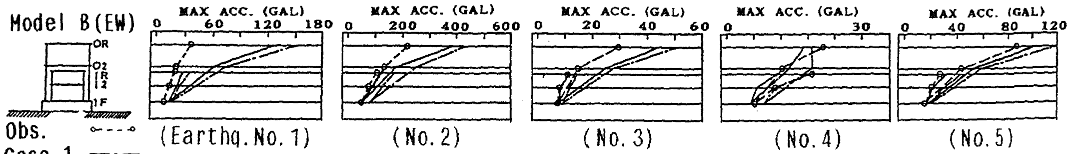
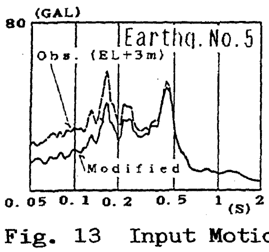


Fig. 12 Distribution of Maximum Accelerations (S-R Model)



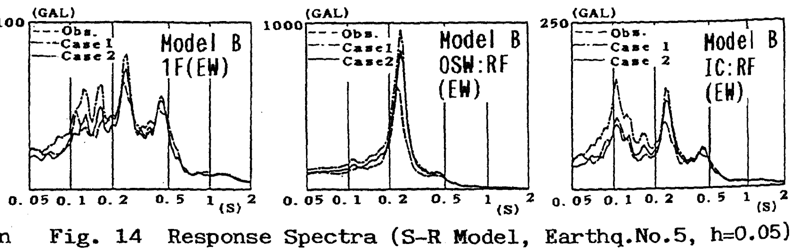


Fig. 13 Input Motion Fig. 14 Response Spectra (S-R Model, Earthq.No.5, h=0.05)