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Forced vibration tests and simulation analyses of a nuclear reactor building - Part 2: Simulation analyses

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ABSTRACT : Forced vibration tests of a BWR-type reactor building, Hamaoka Unit 4, were performed. Valuable data on the dynamic characteristics of the soil-structure interaction system were obtained through the tests.

Simulation analyses of the fundamental dynamic characteristics of the soil-structure system were conducted, using a basic lumped mass soil-structure model (lattice model), and strong correlation with the measured data was obtained. Furthermore, detailed simulation models were employed to investigate the effects of simultaneously induced vertical response and response of the adjacent turbine building on the lateral response of the reactor building.

1 INTRODUCTION

Chubu Electric Power Company conducted the forced vibration tests of the reactor building (R/B) of the Hamaoka Unit 4 in April and May, 1992. The details of the tests and the results are given in a reference (Nakagawa 1995). In this paper, the simulation analyses of the excitation in the north-south (NS) direction are presented.

The Hamaoka Unit 4 is a BWR-MARK I type and the R/B is a reinforced concrete structure with the basemat size of 83.5m x 83.5 m (thickness: 6.5m). The height of the building is 66.6m of which the embedment depth is 21.5m. The cross section of the R/B and the plan of the operating floor with the locations of a pair of exciters indicated are shown in Fig. 1 and Fig. 2, respectively.

2 ANALYTICAL MODEL

For the simulation analyses, a lattice model as shown in Fig. 3 was adopted as a mathematical model of the soil-structure interaction system (model 1). A lattice model was also used in simulation analyses for forced vibration tests of the Hamaoka Unit 3 R/B (Iida 1989), and in seismic response analyses in the design phase of both Unit 3 and 4.

The structure system consists of lumped masses connected by bending-shear beam elements representing the main shear walls, i.e., outer box walls (OW), inner box walls (IW) and a shell wall (SW) (see Fig. 1). The masses of the structure are lumped at each floor level, and the stiffness of floors between main walls are represented by the floor springs connecting those masses, while the basemat slab is assumed to be rigid. In-plane deformation of a roof (RF) and out-of-plane deformation of walls, from the operation floor level (4F) to the roof level (RF), are also considered. The modulus of elasticity and damping ratio of the structure are shown in Table 1. The modulus of elasticity of concrete was determined based on the dynamic property tests of concrete of the R/B conducted at the time of the forced vibration tests.

The soil system is modeled as a lattice model having four lumped mass soil columns with viscous boundaries (see Fig. 3). The masses are connected by shear springs (vertical) and axial springs (horizontal). The physical properties of the soil were determined by P-S logging investigation as listed in Table 2. The damping ratio of the soil is assumed to be 5% to the critical. However, the stiffness and damping for the rocking motion of the soil are modeled as impedance functions: the impedance function at the basemat is evaluated by the theoretical solution by Tajimi's method (Tajimi 1958), and the rotational impedance at the embedded sides of the R/B is also considered on the basis of the Novak's method (Novak 1978).

The harmonic excitation applied to the operation floor level (4F) at the tests was used as an input force to the corresponding lumped mass in the model.

3 RESULTS

3.1 *Rotational dynamic stiffness of soil*

The rotational dynamic soil stiffness obtained from the measurements and the computation are compared in Fig. 4. The rotational spring obtained by the measurements was evaluated from the lateral response of the structure and the rotational response of the basemat. The simulated spring is the summation of the rotational springs at the basemat and those at the embedded sides of the R/B.

Both the real and the imaginary part of the simulated function agree well with those from the measurements.

3.2 *Fundamental vibration mode of the reactor building*

The fundamental vibration mode of the R/B in the NS direction, obtained from the simulation at the fundamental peak (4.1 Hz), is compared with the measurements in Fig. 5. The mode shape as well as the response amplitudes evaluated by the simulation show very good agreement with these measurements.

3.3 *Resonance curve*

The resonance curves measured and the corresponding simulated results per unit excitation force are compared in Fig. 6. The fundamental peak frequency and the amplitude levels calculated by the simulation analysis agree reasonably well with measured ones at 4.1 Hz, while there are some small fluctuations around the fundamental peak in the measured curves. The damping ratios of the soil-structure system at the fundamental frequency, computed by the half power method from the resonance curves, are 36% and 40% to the critical for the measurements and the simulation, respectively. Noticeable indentations in the measured resonance curves at approximately 9Hz are likely due to the vibration absorbing effects of the response of the roof; moreover, the simulated results obtained from the basic mathematical model reproduce the phenomenon.

3.4 *Study on small fluctuations around the fundamental peak of the resonance curves*

The simulation analyses were further extended to investigate the causes of the small fluctuations around the fundamental peak shown in the measured reasonance curves. The following were considered to be likely to be the causes of the small fluctuations in the resonance curves.

1) Effects of the vertical response of the structure induced by the rocking motion.
2) Effects of the adjacent turbine building (T/B).

Following these, three more cases of simulation analyses were conducted using three types of models, i.e., (a) model 2, to investigate the effects of induced vertical response of the R/B on the horizontal response, (b) model 3, to investigate the effects of the adjacent T/B and (c) model 4, to investigate the combined effects of (a) and (b). The results of these analyses are presented in the following sections.

(a) *Effects of the vertical response of the structure induced by the rocking motion*

It was found in the measurements that there are a few meters of eccentricity between the geometric center and the rotational center of the basemat. Therefore, the vertical response must have been generated by the rocking motion due to the horizontal excitation test (see Fig. 7(a)).

In order to simulate the above described effects, a vibration model was proposed as shown in Fig. 8 (model 2). The model 2 consists of the basic model (model 1) shown in Fig. 3 and an additional vertical degree of freedom (DOF) of R/B for evaluating the effects of the induced vertical motion. The additional vertical DOF is connected to the basemat of R/B by a rigid beam element which has the equivalent length of the eccentricity. The vertical soil spring of the added DOF of R/B is evaluated as an impedance function by the Tajimi's method.

The resonance curves evaluated by model 2 are compared with those obtained by the measurements and model 1 in Fig. 11. The results of model 2 show local indentations in the resonance curves at the frequency of 4.7Hz, which correspond well to those of the test results.

(b) *Effects of the adjacent turbine building*

The fundamental frequency of the soil-structure interaction system of the T/B and the frequency of the in-plane vibration mode of its roof are 3.8Hz and 5.4Hz, respectively. Since these frequencies are close to the fundamental frequency of the R/B, it was thought that some interaction effects might be found among them (see Fig. 7(b)). In order to study such interaction effects, a simplified R/B-T/B interaction sway-rocking model (model 3) as shown in Fig. 9 was proposed. The sway and rocking springs at the base of each structure were determined based on the measurements. The interaction soil springs between both buildings were evaluated by the Tajimi's method. The resonance characteristics obtained by model 3 are shown in Fig. 11. There are two small fluctuations caused by the interaction effects at 3.8Hz and 5.4Hz.

(c) *Combined effects of (a) and (b)*

In order to evaluate the combined effects of (a) and (b), a rather simple model combining model 2 and model 3 was adopted as shown in Fig. 10 (model 4). The resonance curves evaluated by model 4 and the other results are compared in Fig. 11. The small fluctuations around the fundamental peak observed in the measurements are well simulated by using model 4.

4 CONCLUSIONS

The main features of the simulation analyses for the forced vibration tests of the Hamaoka Unit 4 R/B are summarized as follows: (1) The basic lattice model can simulate the fundamental dynamic characteristics of the soil-structure system reasonably well; (2) Simulation analyses using detailed analytical models indicate that the interaction effects of the induced vertical response of the R/B and the induced vibration of the adjacent T/B on the lateral response of the R/B are highly likely to be the causes of small fluctuations around the fundamental peak of the measured resonance curves.

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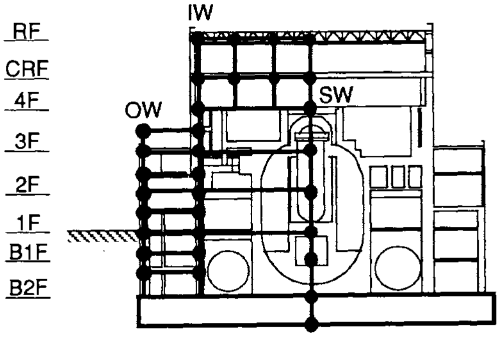


Fig. 1 Cross Section of R/B (A–A Section)

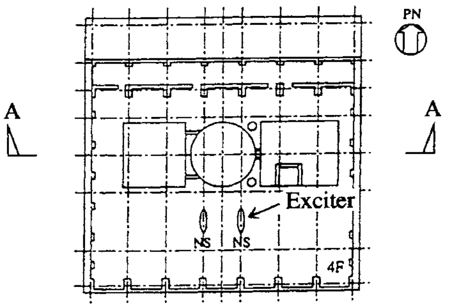


Fig. 2 Exciters on Operating Floor (4F)

Table 1 Modulus of Elasticity and Damping Ratio of R/B

	Modulus of Elasticity	Damping ratio
Reinforced concrete	E = 440 tf/cm^2	h = 5 %
Structural steel (roof trusses)	E =2100 tf/cm^2	h = 2 %

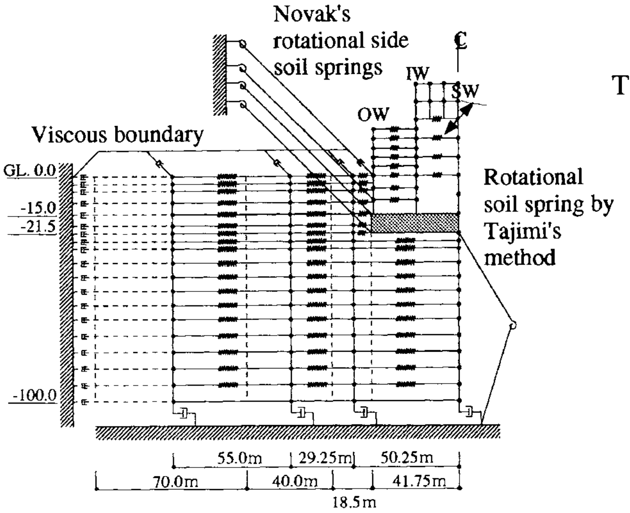


Fig. 3 Vibration Model (model 1)

Table 2 Physical Properties of Soil

(m) GL 0.0	Vs (m/s)	G (tf/cm^2)	h (%)
-5.0	165	0.50	5.0
-10.0	600	7.71	5.0
-20.0	670	9.62	5.0
-30.0	720	11.11	5.0
-60.0	770	12.71	5.0
-100.0	820	14.41	5.0

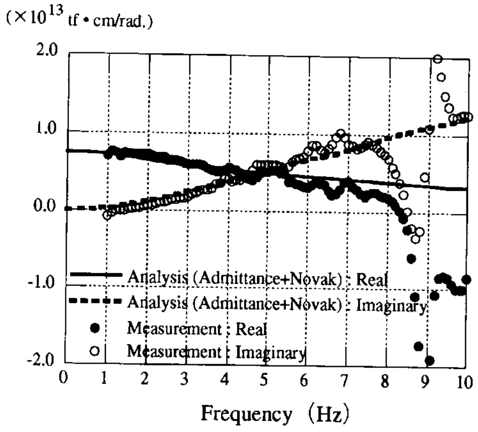


Fig. 4 Rotational Dynamic Stiffness of Soil

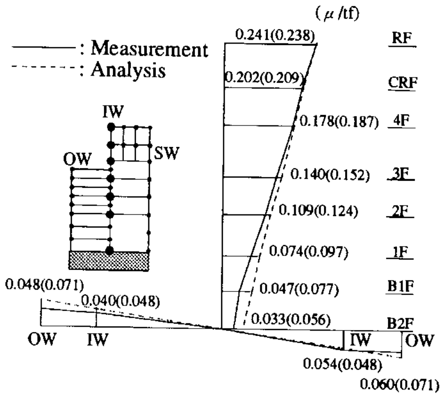
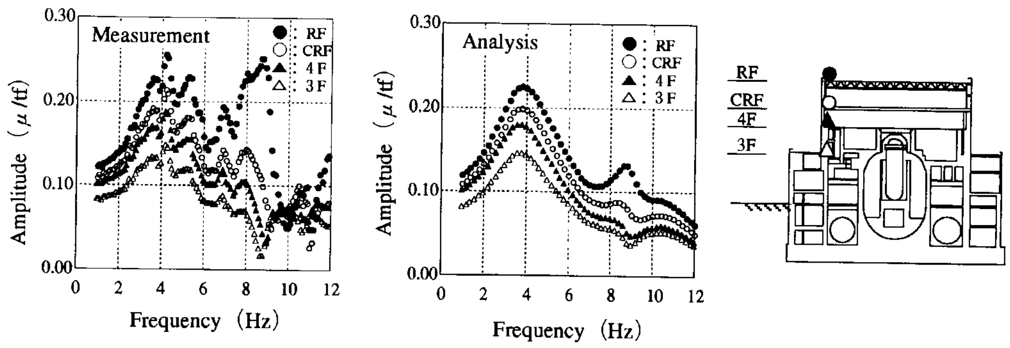
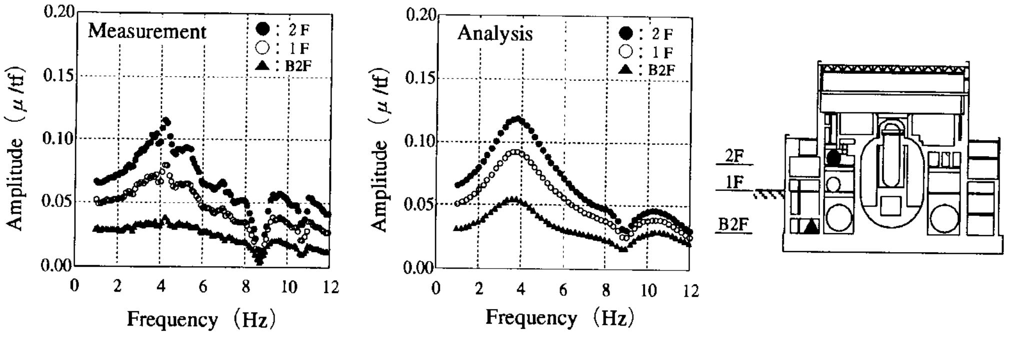


Fig. 5 Vibration Mode at Fundamental Peak

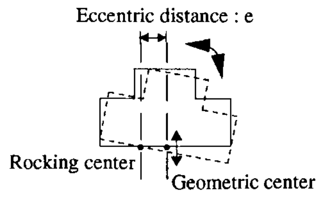


(a) IW 3F～RF

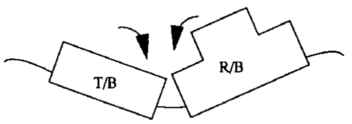


(b) IW B2F～2F

Fig. 6 Resonance Curves



(a) Vertical response induced by rocking motion



(b) R/B-T/B interaction

Fig. 7 Modeling Concept

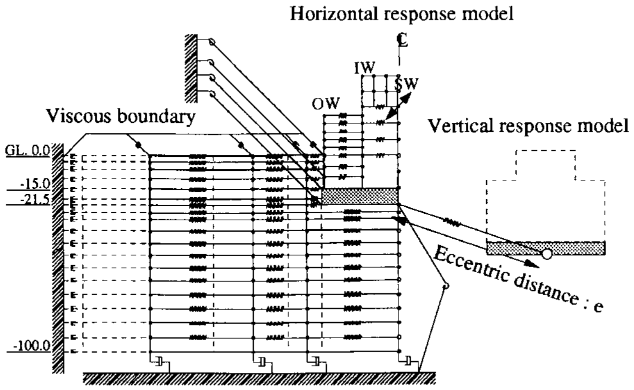


Fig. 8 Vibration Model (model 2)

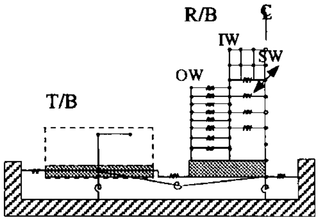


Fig. 9 Vibration Model (model 3)

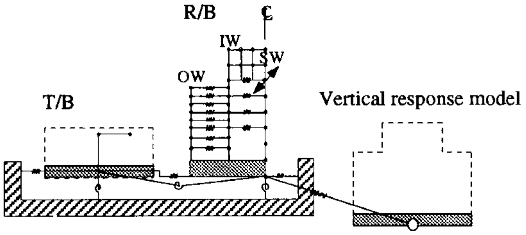
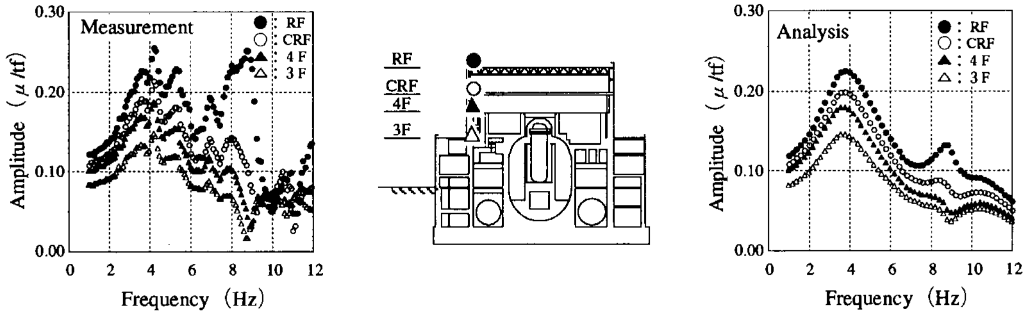
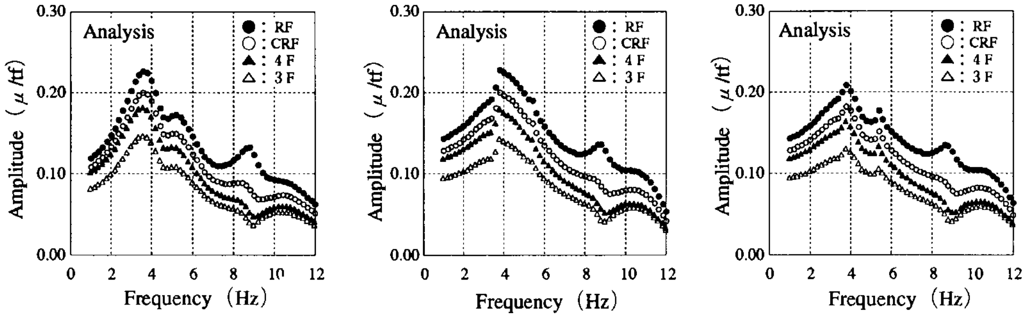


Fig. 10 Vibration Model (model 4)



(a) Measurement

(b) Model 1



(c) Model 2

(d) Model 3

(e) Model 4

Fig. 11 Resonance Curves