Forced vibration tests on the reactor building of Tsuruga Unit No. 2 Nuclear Power Station

M.Kato & A.Kato
Construction Department, The Japan Atomic Power Co., Tokyo, Japan
T.Takeda, T.Tsunoda, Y.Yasui, K.Wakamatsu, M.Kaneko & M.Nakamura,
Technical Research Institute, Ohbayashi Corporation, Tokyo, Japan
T.Kuno & H.Murahashi
Nuclear Facilities Division, Ohbayashi Corporation, Tokyo, Japan

ABSTRACT

Tsuruga Unit No. 2 Nuclear Power Station of The Japan Atomic Power Co. is the first PWR plant (1100 MWe) in Japan where a Prestressed Concrete Containment Vessel (PCCV) was adopted. This report describes the results of forced vibration tests performed on the reactor building of the plant, the simulation analyses of the tests, and the assessment of the aseismic safety of the structures.

The forced vibration tests were carried out to ascertain the vibration characteristics of the reactor building such as natural frequency, modal shape, and modal damping, and to confirm the earthquake-resistant safety of the structure. The simulation analyses were performed for the two cases of a lumped mass model to evaluate the vibration characteristics of the entire building, and an FEM model to evaluate the three-dimensional vibration characteristics of the PCCV.

The aseismic safety and the appropriateness of the earthquake-resistant design technique for the reactor building were examined based on the lumped mass model used in these simulation analyses.

1 VIBRATION TESTS

1.1 Outline of Tests

The reactor building which was the object of the vibration tests is a structure composed of a PCCV, an Inner Concrete Structure (I/C) of a complex configuration, a Reactor External Building (REB), and an Enclosure Building (E/B) of structural steel construction rising on top of the REB, all built independently on the same base mat. An outline of this is shown in Figure 1.

The tests were performed from October 1985 to March 1986, a stage when construction of the plant had been more or less completed.

In the first case, two vibration generators were installed on the floor of the REB at a height of EL+7.3m. Each vibration generator had a maximum exciting force of 150 ton, and the two worked in synchronism. Exciting was done in the three directions of EW, NS, and vertical. The purpose of these tests was to obtain the vibration characteristics of the entire reactor building, the I/C in particular.

In the other case, the vibration characteristics of the PCCV were obtained using a vibration generator of maximum exciting force of 3 ton

set at the top of the PCCV. In this case, exciting was done twice, before and after prestressing, to investigate the influence of tensioning of prestress tendons on vibration characteristics.

The locations where the vibration generators were installed are shown in Figure 1.

Measurements were made mostly on the I/C and PCCV, with measuring points also provided at the REB and E/B. The measurement results were immediately put into a data processing system on the spot.

Exciting was done in a frequency range of 2 Hz to 20 Hz.

The natural frequency and damping for each mode were evaluated performing regression analysis by the theory of one-degree-of-freedom systems based on the measurement results, and modal shapes were determined.

1.2 Tests Results

Natural frequencies in which vibrations of PCCV, I/C, and E/B were predominant were obtained for each test case. Table 1 gives the results of NS excitation of the REB and excitation of the PCCV together with design values.

Examples of resonance curves of the test results for REB NS excitation are shown in Figures 3 through 5. The results of measurements at the top and the Operating Floor (O/F) (EL+7.3m) of the Steam Generator (SG) Wall and Pressurizer (PR) Wall, respectively, are shown in Figures 3 and 4, while the results of measurements at the top of the PCCV and on the base mat are shown in Figure 5. These are the test results indicated by marks o and Δ. For these resonance curves amplitudes are normalized per unit (ton) of exciting force. It can be seen from these figures that the fundamental mode of the PCCV and the fundamental and secondary modes of the I/C have been excited.

Examples of modal shapes of the I/C obtained in REB NS excitation are shown in Figure 6. These are the test results indicated by • marks in the figure. It can be seen that in the fundamental mode of the I/C, flexural deformation of the PR Wall is more prominent at the top than at the O/F.

With regard to three-dimensional vibration characteristics of the PCCV, beam, oval, torsional, and vertical (during vertical excitation) types were obtained from low- to high-order modes. The results are shown in Figure 7. The test results are indicated by the marks o, □, and Δ in the figure.

Comparisons of vibration characteristics of the PCCV before and after prestressing are given in Table 1 and Figure 7. Natural frequencies were slightly higher and dampings smaller in the high-frequency range after prestressing, but the indication was that there is practically no influence of tensioning of prestress tendons on the vibration characteristics of the PCCV.

2 SIMULATION ANALYSIS BY LUMPED MASS MODEL

The design analysis model [Figure 2 (b)] was prepared with the main objective to maintain aseismic safety and can not be an adequate model for reproducing the results of forced vibration tests at such special locations as in the REB excitation of these tests. Therefore, in order to simulate vibration tests in more detail and examine aseismic safety based on test results, simulation analyses were performed preparing a new model.

This report describes the results of simulation analyses in the NS direction. Examinations were made based on a similar technique with regard to the EW direction also.

2.1 Outline of Lumped Mass Model

The lumped mass model used for simulation analyses was composed of two-dimensional I/C and PCCV and a three-dimensional REB standing on a rigid base mat. A diagram of the model is shown in Figure 2(a). It was made a one-half model giving consideration to symmetry of the building.

The PCCV was modeled directly computing shearing and flexural rigidities from horizontal cross sections. A rotating spring was provided at the base of the PCCV giving consideration to the elastic depression of the base mat.

In modeling of the I/C, since it had been predicted from FEM analysis that the PR Wall part would show flexural deformation locally, separation was made into the two straight bars of PR Wall portion and I/C structure portion other than the PR Wall, and the two were connected by tie beams representing rigidities of floors.

In making an evaluation of rigidity of the I/C, a three-dimensional FEM model was prepared and deformation patterns were obtained from static lateral unit load patterns. Next, the deformation was separated into shearing and flexural deformations from which shearing and flexural rigidities were computed respectively.

The REB was made into a three-dimensional frame model in order to reproduce the local vibration characteristics in the vicinities of the excitation locations. In carrying out the modeling, shearing and flexural rigidities were computed directly from member cross sections.

In Japan, the Young's modulus of concrete at a microscopic strain level is customarily considered to be 1.1 to 1.3 times the design value, and therefore, the Young's moduli of concrete used for analyses here were taken to be 400 ton/cm^2 for the PCCV, and 270 ton/cm^2 for the I/C and the REB.

2.2 Results of Analyses by Lumped Mass Model

Eigenvalue analysis was done with a sway-rocking model consisting of this lumped mass model to which static soil stiffness was added. The value of dynamic stiffness at fundamental natural frequency of the I/C was used for the soil stiffness. The dynamic stiffness was determined theoretically by the elastic half-space theory with shear wave velocity as 1600 m/s. Comparisons of the eigenvalue analysis results and test values are given in Table 2. These results show that the fundamental natural frequencies of the PCCV and the I/C agree well with the test results.

On estimating damping of the superstructure in the sway-rocking model such that the total damping including the damping due to the dynamic soil stiffness would coincide with the modal damping in the vibration test results, it was 2.0% for the PCCV and 4.0% for the I/C, where averaged modal dampings throughout all of the test results were 2.4% for the PCCV and 4.4% for the I/C.

Next, simulation analysis of the REB excitation test was performed for this lumped mass model, using the dynamic soil stiffness.

The resonance curves of the analytical results, shown in Figures 3 through 5, are compared with the test results. The solid and the broken lines in the figures indicate the analytical results. It is shown in these figures that the resonance curves of the PCCV and the I/C agree well with test results in both amplitudes and phases.

Comparisons of the modal shapes of the I/C are shown in Figure 6.

Based on these analytical results, it was shown that the vibration properties of the actual structure could be correctly ascertained with this model.

3 EIGENVALUE ANALYSIS OF PCCV BY THREE-DIMENSIONAL FEM MODEL

As the other model, an FEM model was prepared to evaluate the three-dimensional vibration mode of the PCCV, composed of shell elements and fixed at the base. Buttresses, an equipment hatch opening, and the weight of a polar crane were taken into account in modeling.

Eigenvalue analyses were made for this model and the results are shown in Figure 7. The solid lines in the figure are the analytical results using 304 ton/cm^2 as the design value for the Young's modulus of concrete, while the dot-dash lines are the results when the Young's modulus of concrete was made 1.3 times the design value, that is, the value in microscopic strain level.

In comparing the test results, it is seen that with oval vibrations the natural frequencies when the Young's modulus of concrete in microscopic strain level was used coincided well with test results up to a high order. In the modes of beam, torsional, and vertical vibration, the test results showed slightly lower natural frequencies than the analytical results, and this is thought to have been due to the depression of the base mat and the influence of the interaction with the soil stiffness.

4 EVALUATION OF ASEISMIC SAFETY

Earthquake response analyses were performed using the lumped mass model described in 2.1. The input seismic wave was the artificial seismic wave used in design and maximum acceleration was 365 gal. According to the results of analyses, both the maximum response shear forces and bending moments were below the allowable design values. Base shear coefficients are given in Table 3.

Thus, it was succeeded in confirming the aseismic safety of the structure at this plant and the appropriateness of the earthquake-resistant design analysis method through the simulation analyses described here.

CONCLUSIONS

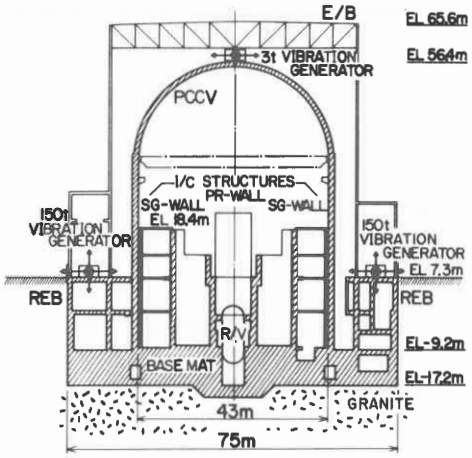
1) The vibration characteristics of the I/C and the PCCV were obtained through various tests. In order to make simulations of the vibration tests, a lumped mass model focusing on the local vibration characteristics in the surroundings of excitation points and the local flexural vibrations of the I/C was prepared to perform eigenvalue analyses. The result was that calculated natural frequencies agreed well with test results.

Furthermore, as a result of simulation analyses using dynamic stiffness of the soil, the resonance curves coincided well with the test results.

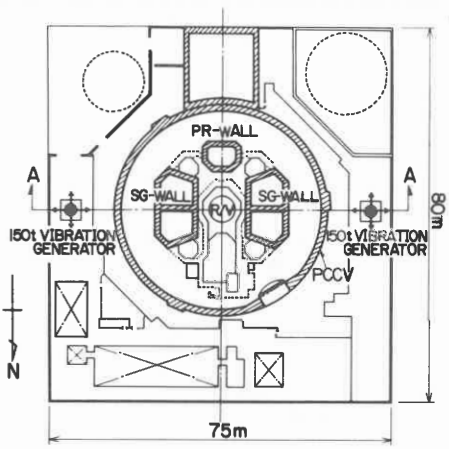
These results show that it is possible to correctly ascertain the vibration properties of the actual structure by a lumped mass model made in this manner.

2) Beam, oval, torsional, and vertical vibration modes of the PCCV were obtained in vibration tests. The results of eigenvalue analyses by three-dimensional FEM coincided approximately with these natural frequencies. Vibration properties of the PCCV before and after prestressing did not differ prominently; and it is considered that tensioning of tendons has hardly any effect on vibration properties of the PCCV.

3) Earthquake response analyses were performed using the design basis earthquake on the lumped mass model employed in simulation analyses. As a result, it was succeeded in confirming the aseismic safety of the structure in this plant and the appropriateness of the earthquake-resistant design technique used.



A-A Section



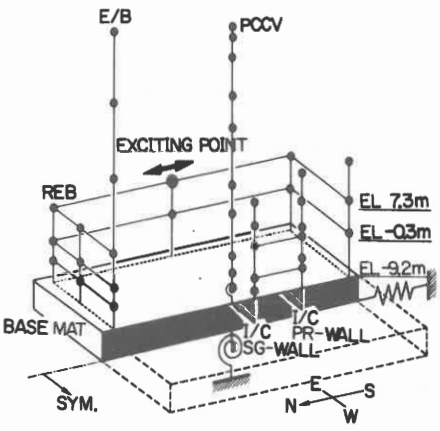
Plan at EL+7.3m

Figure 1. Outline of the Reactor Building

Table 1. Natural Frequencies and Modal Dampings Obtained in the Tests

REB NS Excitation					
		Test		Design	
		Freq.	Damp.	Freq.	Damp.
PCCV	1st	4.86 Hz	2.2 %	4.63 Hz	3.3 %
PCCV	2nd	14.36 Hz	2.7 %	14.8 Hz	3.2 %
I/C	1st	7.57 Hz	3.4 %	9.64 Hz	6.3 %
I/C	2nd	10.61 Hz	4.0 %	11.5 Hz	5.4 %
E/B	1st	3.15 Hz	2.2 %	2.79 Hz	2.1 %
E/B	2nd	6.31 Hz	1.8 %	7.26 Hz	2.4 %

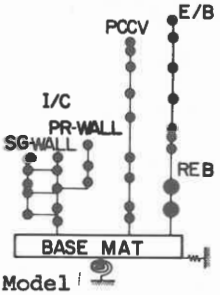
PCCV EW Excitation							
		Test				Design	
		Freq.	(after PS)	Damp.	(after PS)	Freq.	Damp.
PCCV	1st	4.71 Hz	(4.72 Hz)	2.4 %	(2.5 %)	4.62 Hz	3.3 %
PCCV	2nd	14.44 Hz	(14.70 Hz)	2.1 %	(1.6 %)	14.8 Hz	3.2 %



(a) Simulation Model

Table 2. Natural Frequencies
- NS Direction -

		Simulation	Test
PCCV	1st	4.92 Hz	4.86 Hz
I/C	1st	7.59 Hz	7.57 Hz
I/C	2nd	11.81 Hz	10.61 Hz



(b) Design Model

Figure 2. Simulation and Design Models

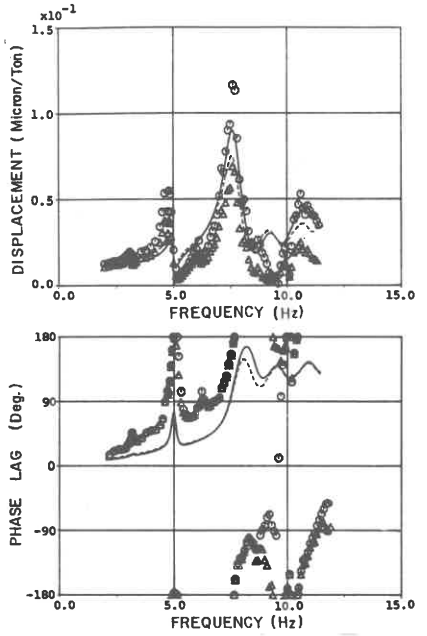


Figure 3. Resonance Curves of SG-Wall

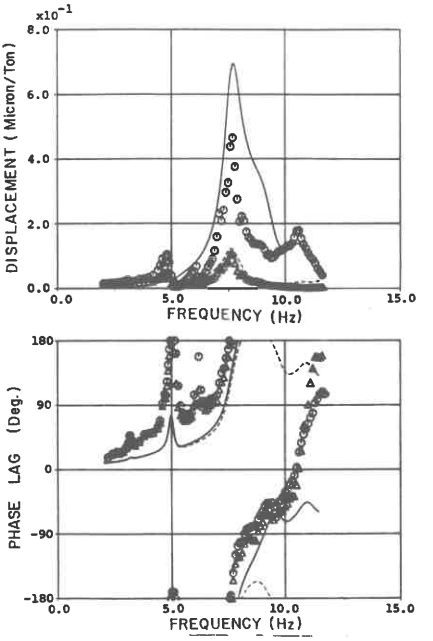


Figure 4. Resonance Curves of PR-Wall

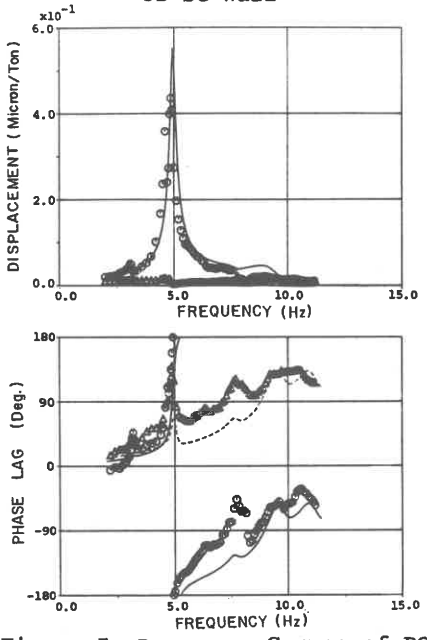
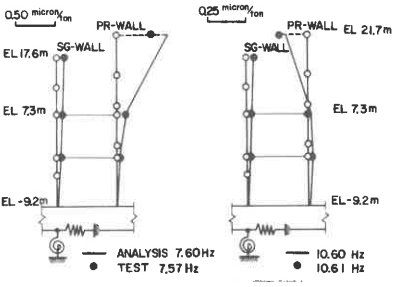


Figure 5. Resonance Curves of PCCV



(a) Fundamental (b) Secondary

Figure 6. Modal Shapes of I/C

Table 3. Base Shear Coefficients

	Simulation	Design
PCCV	0.981	1.871
I/C	0.634	0.806
REB	0.550	0.926
BASE	0.367	0.687

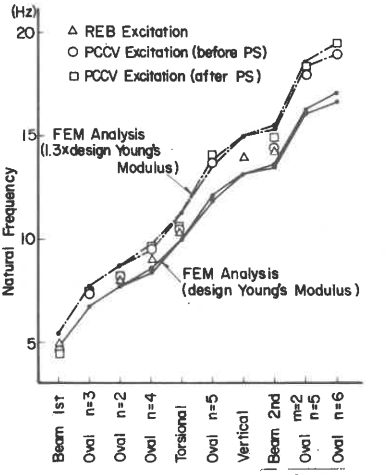


Figure 7. Natural Frequencies of PCCV