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SIMULATION ANALYSIS ON FORCED VIBRATION TESTS OF TSURUGA UNIT NO.2 NUCLEAR POWER STATION

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SUMMARY

Tsuruga Unit No.2 Nuclear Power Station of The Japan Atomic Power Co. is the first PWR plant (1100MWe) in Japan where a Prestressed Concrete Containment Vessel (PCCV) was adopted. Simulation analyses on forced vibration tests of the reactor building of the plant were performed in order to improve design analysis model. The effects of flexibility of the base mat and some other important properties on the vibration characteristics of the structure were grasped through simulation analyses. Earthquake response analyses and a simulation analysis on the latest observed earthquake motion were also performed using these simulation models, and the simulation methods were confirmed to be valid for seimic design analysis.

INTRODUCTION

Forced vibration tests were performed on the reactor building of Tsuruga Unit No. 2 Nuclear Power Station from October 1985 to March 1986. (Ref. 1) The outline of the reactor building is shown in Fig. 1. As shown in Table 1, the eigenvalues in tests and design analyses had good correlations with regard to the PCCV, but there were some amounts of difference for the Inner Concrete (I/C). The causes of these differences for the I/C are considered to be the unreasonableness in having adopted the stiffness evaluation method according to the beam theory based on the law of plane conservation in modeling at the time of design analysis in spite of the structural configuration being very complex, with, moreover, many openings at parts.

Detailed simulation analyses were performed in order to analyze these causes and also to grasp the vibration properties of the entire building with good accuracy.

In carrying out modeling, weight calculations, and cross-sectional stiffness calculations, particularly, cross-sectional stiffness calculations by three-dimensional FEM for the complex structural configuration of the I/C, were made based on the as-built drawings, and these were replaced by an equivalent lumped mass-spring model.

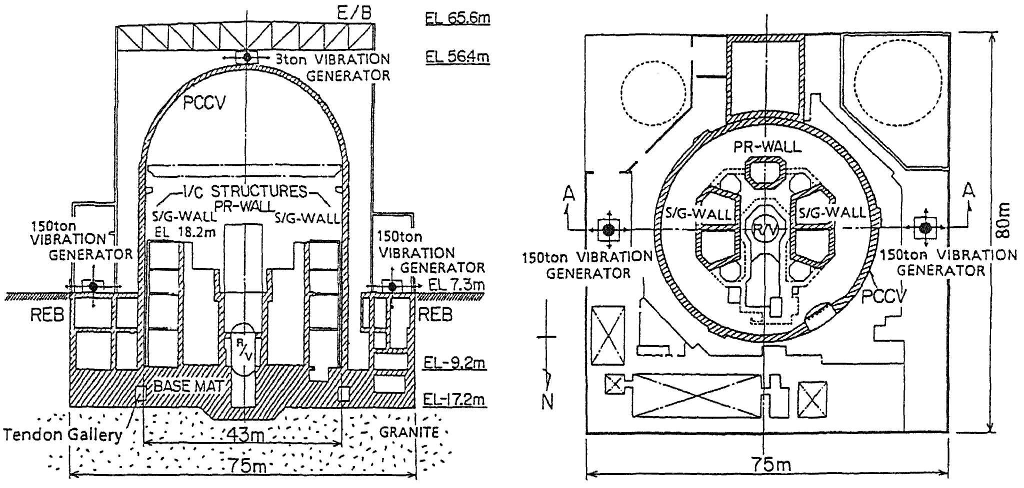
LUMPED MASS-SPRING MODEL WITH A RIGID BASE MAT

Outline of Simulation Model The lumped mass model used for simulation analyses was composed of two-dimensional I/C and PCCV and three-dimensional Reactor External Building (RE/B) standing on a rigid base mat. A diagram of the model in the NS direction is shown in Fig. 2. This was made a one-half model of one side with the NS axis as the axis of symmetry in consideration of the symmetry of the building.

The building structures including the I/C and the PCCV were modeled based upon stiffness analysis results due to rather two- or three- dimensional FEM than the linear beam theory. (Ref. 2)

The soil-structure interaction was evaluated by sway-rocking ground stiffness based on half-space elastic wave theory with shear wave velocity Vs = 1600 m/s obtained from elastic wave tests of the bearing ground.

Since it was found from analyses of test results and comparison studies during preparation of the



A-A Section

Plan at EL 7.3m

Fig. 1 Outline of the Reactor Building

simulation model that the Steam Generator (S/G), an equipment of large weight, greatly influences the interaction to the I/C, the S/G was condensed into a single separated bar and incorporated as a coupled model. As for the supports connecting the I/C and the S/G, values taking into consideration the conditions at the time of testing were adopted.

The Young's moduli of concrete used for analyses here were taken to be 270 t/cm^2 for the I/C and the RE/B (design value, 230 t/cm^2) and 400 t/cm^2 for the PCCV (design value, 304 t/cm^2) based on the investigations of compressive strengths of cylinder test specimens in-situ and elastic wave tests on the actual building structural parts.

Results of Analyses The results of eigenvalue analyses and test values are compared in Table 1. As this table shows, correspondence is good between the analyses and test results.

On obtaining damping of the superstructure under the assumption such that the modal damping of this lumped mass model coincides with the modal damping in the vibration test results, the values are 2 percent of critical damping for the PCCV and 4 percent for the I/C and the RE/B, and simulation analyses of RE/B excitation in the NS direction were performed using these values.

The resonance curves of the point-excitation response analysis results compared with test results are shown in Figs. 3 to 5. Figs. 3 and 4 show the results at the heights of top and the Operating Floor (OPF,EL 7.3m) for the S/G Wall and the Pressurizer (PR) Wall, respectively. Fig. 5 shows the results for the top of the PCCV and upper surface of the base mat.

Table 1 Natural Frequencies in the NS direction

		SIMULATION (Hz)	TEST (Hz)	DESIGN (Hz)
PCCV	1st	4.92	4.86	4.63
I/C	1st	7.66	7.57	9.64
I/C	2nd	10.57	10.61	11.5

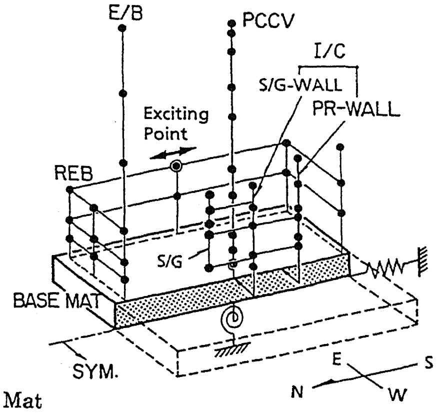


Fig. 2 Simulation Model with Rigid Base Mat

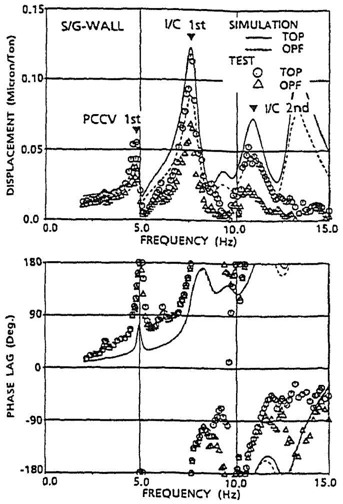


Fig. 3 Simulation Results of the S/G Wall with Rigid Base Mat

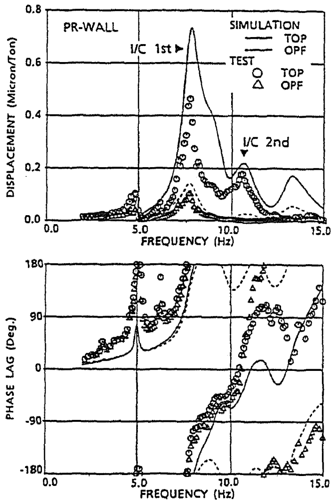


Fig. 4 Simulation Results of the PR Wall with Rigid Base Mat

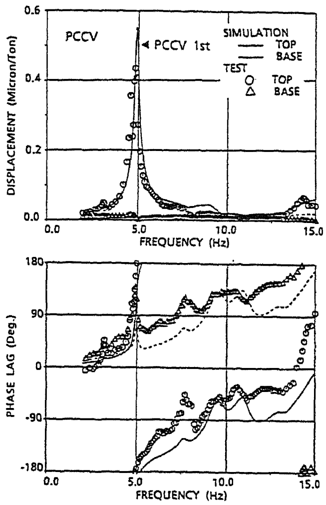


Fig. 5 Simulation Results of the PCCV with Rigid Base Mat

In the figures above, the simulated resonance curves of the I/C and PCCV coincide almost with test results with respect to both amplitude and phase.

It was shown through the abovementioned simulation results that the vibration properties of an actual structure can be expressed well with the lumped mass models used in simulation analyses.

LUMPED MASS-SPRING MODEL WITH A ELASTIC BASE MAT

Here, a base mat according to an FEM model giving consideration to elasticity was connected to the superstructure of the simulation analysis model made up in the preceding section, and it was attempted to find what kind of influences differences in assessments of base mat stiffness would have on vibration characteristics.

The base mat was modeled with FEM shell elements, while discretized soil springs according to vibration admittance theory were connected to the nodal points of the base mat. The model diagram in the NS direction is shown in the Fig. 6.

Regarding the I/C and the PCCV, the superstructure and the base mat were connected by means of a rigid beam. Regarding the RE/B,, the stress transmission mechanism between the superstructure and the base mat was modeled setting the stiffness of the upper structure on the base mat as a beam member in order to consider the restraining effect on the base mat contributed by the superstructure.

The results of simulation analyses by this model are shown in Figs. 7 through 9. Figs. 7 and 8 are respectively the results of S/G Wall and PR Wall at the tops and OPF height, while Fig. 9 shows the results at the top of the PCCV and the upper surface of the base mat. The following may be comprehended from these figures:

With regard to amplitudes, at fundamental frequency of the I/C, they were fairly large for both S/G Wall and PR Wall compared with test results, but at fundamental frequency of the PCCV, they were conversely on the small side compared with test results. With regard to phase characteristics, there was good agreement with test results for both the I/C and the PCCV.

It is considered that phase characteristics were improved because phase lag in excitation force transmission accompanying elastic deformation of the base mat had been evaluated. On the other hand, that for amplitude characteristics the differences with test results were slightly larger compared with a rigid base model was considered to be due to roughness of modeling of the base mat or to local deformation not having been considered because the base mat had been modeled with shell elements.

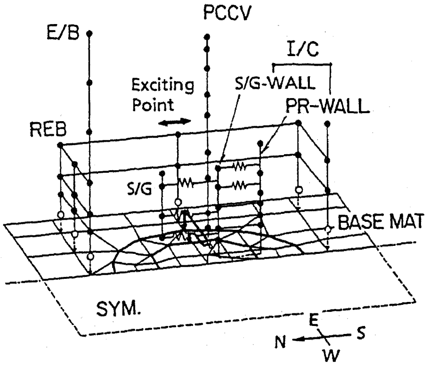


Fig. 6 Simulation Model with Elastic Base Mat

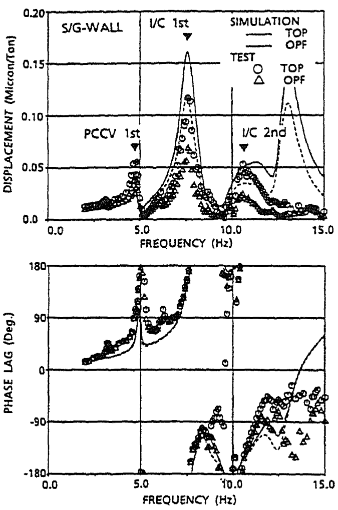


Fig. 7 Simulation Results of the S/G Wall with Elastic Base Mat

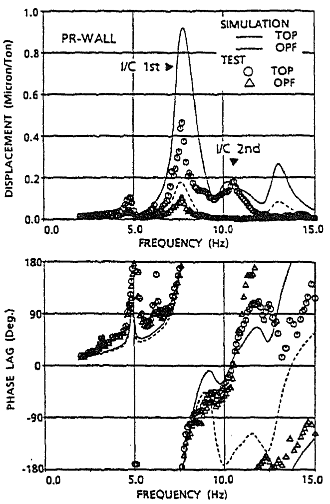


Fig. 8 Simulation Results of the PR Wall with Elastic Base Mat

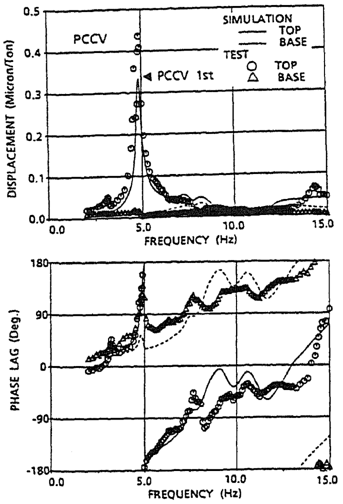


Fig. 9 Simulation Results of the PCCV with Elastic Base Mat

It was learned that prominent improvements are made concerning phase characteristics especially through consideration of the flexibility of the base mat in this way. However, as an overall trend, there was little difference from the simulation results with a rigid base, and with base-mat thickness of 8 m there was ample rigidity, and from a general view it may be said there was behavior as a rigid body.

FACTOR ANALYSES OF VIBRATION CHARACTERISTICS

In this section individual examination are made of the various factors considered in the process of preparing the simulation analysis model, and the influences of those factors on the vibration characteristics of the structure are evaluated.

Simulation analyses were made parametrically varying a number of parameters for the rigid base model made in the preceding section, and the influences of the factors on vibration characteristics were evaluated. The items of study taken up in this case and the findings made are as described below.

The stiffness of the support holding up the S/G will differ in condition when testing and when operating, and so a study was made of the influences of such stiffnesses. As a result, in the NS direction, influences on resonance frequency and amplitude were seen in a range above 10Hz. As for the EW direction, influences appeared even in the fundamental frequency of the I/C, and it was found vibration characteristics were greatly affected.

The weights of equipment units of large weight (for example, S/G) installed in the I/C differ slightly when testing and when operating, and on evaluating the influence of this, effects were seen in resonance frequencies and amplitudes in a range above 10 Hz.

Upon examination of the influence of stiffness of the structural steel slab constructed on the OPF, there was influence seen in a range of 7 to 11 Hz in the NS direction, but hardly any influence was noticeable in the EW direction.

Regarding the influence of the ground shear wave velocity, there was little influence on the peak frequency, and it was learned that there is a trend for amplitude to increase slightly when shear wave velocity becomes lower.

In order to examine the influence of ground damping, evaluations were made using a model with damping of soil springs doubled, and it was learned that amplitude is decreased as a whole when damping is increased.

EVALUATION OF ASEISMIC SAFETY

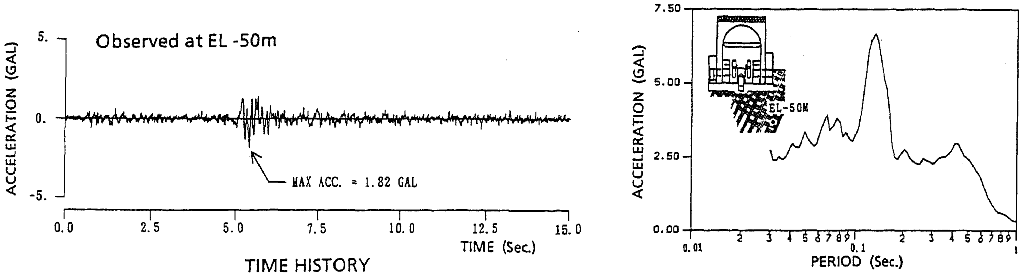
Earthquake response analyses were made employing a rigid base model using simulation analyses for a review of design analyses by the design model and to ascertain the aseismic safety of the actual facility.

The seismic waves used in this case were of the same earthquake as used in designing. Since modeling in simulation analyses had considered vibration testing, weight, S/G support stiffness, modulus of elasticity of concrete, damping coefficient, etc. were changed to correspond to the conditions during operation and to straints at the earthquake response level.

According to the results of response analyses, the response bending moment at EL+7.3m of the PR Wall was close to the short-term allowable limit locally, but the response shear forces and bending moments of the various other parts were all within the short-term allowable limits. As for base shear coefficient, this was also far below that for the design model, and it is judged to be of no problem in evaluation of safety.

EARTHQUAKE OBSERVATIONS

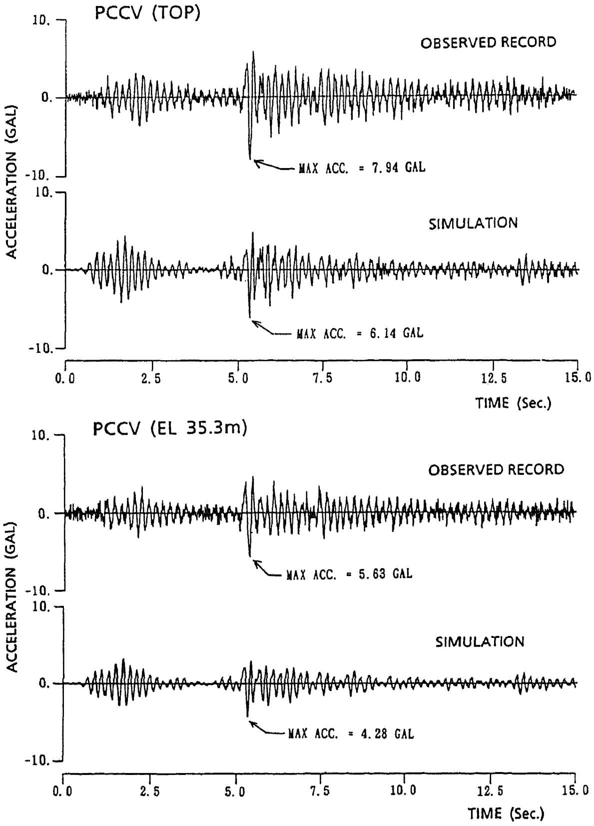
The first earthquake motions recorded at this plant were from an earthquake of magnitude 4.5 occurring at the central part of Fukui Prefecture on April 28, 1988. A study was carried out on the



TIME HISTORY

ACCELERATION RESPONSE SPECTRUM

Fig. 10 Input Earthquake Motion



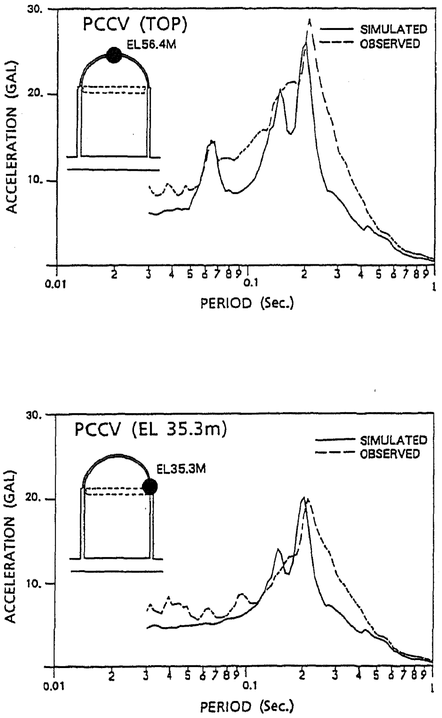


Fig. 11 Comparisons of Time History

Fig. 12 Comparisons of Response Spectrum reasonableness of the model made performing simulation analyses by the rigid base model used in the simulation analyses of vibration tests, and comparing the analysis results with the observation records.

Since the observation records had been obtained during operation, the analyses were performed on changing the weight of the model and the stiffness of S/G support to those when operating.

The input earthquake motion was that observed at EL-50m directly underneath the reactor building, and direct inputting was done with this earthquake motion as the model. The accelaration record and the acceleration response spectrum of the input earthquake motion are shown in Fig. 10.

The acceleration records in the simulation analysis results and the observation record are compared in Fig. 11. These were the results at the top of PCCV and at a height of EL 35.3m. The response spectrum at these locations with the damping coefficient of 5 percent are shown in Fig. 12. As for the I/C, the observation records were not in good condition because of high level of background vibrations due to the plant having been in operation.

According to the figure, the response spectrum from simulation coincide almost with the response spectrum from the observation record with respect to amplitudes and peak frequencies. The small peaks in the high-frequency range seen in the observation record are thought to be from background vibrations due to the plant.

As described in the foregoing, observation records can be approximately simulated by analyses using the model made up in this study, and it has been shown that the model correctly evaluates the vibration characteristics of the actual building.

CONCLUSION

A technique for modeling the complex structure of an actual nuclear power plant reactor building was established through vibration tests of the building and simulation analyses of earthquake observation records, and knowledge was gained concerning factors to be paid attention in such case. It was succeeded in ascertaining the aseismic safety of the actual building through earthquake response analyses of a model based on this technique. It may be expected that these findings can be effectively utilized by reflecting them in modeling of a complex structure such as a reactor building.

REFERENCES

1. Kato, M. et al., "Forced Vibration Tests on the Reactor Building of Tsuruga Unit No.2 Nuclear Power Station", Transaction of 9th-SMiRT, K9/7, 497-502, (1987)
2. Kato, M. et al., "Forced Vibration Tests on the R/B of Tsuruga Unit No.2 Nuclear Power Station (Part I ~III)", Summaries of Technical Papers of Annual Meeting AIJ, B, 275-280, (1987)