STUDY ON VERTICAL SEISMIC RESPONSE CHARACTERISTICS OF DEEPLY EMBEDDED REACTOR BUILDING

H. Morishita\textsuperscript{1}, N. Nakamura\textsuperscript{1}, S. Uchiyama\textsuperscript{2}, A. Fukuoka\textsuperscript{2} and M. Ishizaki\textsuperscript{3}

\textsuperscript{1}Tokyo Electric Power Company, Japan, \textsuperscript{2}Kajima Corporation, Tokyo, Japan, \textsuperscript{3}Takenaka Corporation, Tokyo, Japan

ABSTRACT

This paper describes vertical response characteristics, especially effects of embedment, and analytical methods for seismic design of a deeply embedded reactor building. The influence of embedment on vertical response was found to be minimal by evaluating results of forced vibration tests of a reactor building model and performing simplified analyses. Subsequently, simulation analyses of the forced vibration test and actual earthquake induced response were performed using both the axisymmetric FEM model and the simplified mass and spring model. It was concluded that the analytical models taking the embedment into the consideration closely simulated the observation records, and the omission of embedment in the analyses tended to increase the predicted response which was conservative in respect an actual design consideration.

1. INTRODUCTION

In seismic design of nuclear power plant buildings, the design procedure for vertical motions is primarily based on static method. With the increased availability of test and earthquake data, several studies have recently been performed to establish a dynamic seismic analysis procedure for determining vertical motions in a BWR MARK-II type reactor building\textsuperscript{1)1)}. These studies have indicated that a one-stick model, in which resistance walls have been idealized as masses and springs, has been sufficient to evaluate vertical earthquake responses for seismic design. It has been also reported that the influence of side-wall of embedment foundation on seismic response was small\textsuperscript{1)}.

In this paper, for a deeply embedded reactor building, vertical response characteristics, especially effects of embedment, are evaluated and analytical methods for seismic design are studied by carrying out simulation analyses of both a forced vibration test (FVT) and an actual earthquake induced response.

2. EVALUATION OF EMBEDMENT EFFECT

Vertical forced vibration tests were performed for a reactor building model\textsuperscript{1)}. This model is about one-fifteenth, 1/15, scale of a BWR MARK-II type reactor building. The test was carried out before and after backfill, as shown in fig. 1. The FVT exciter was placed on the second floor.

Figure 2 shows comparisons of the resonance curves before and after the backfill. A resonance peak around 33 Hz, seen in the response at the roof floor, the point Vf, is due to an out-plane local vibration of the slab, and is not much influenced by the backfill. Two resonance peaks are distinctly noted around
15 Hz and 22 Hz before the backfill, but these peaks are not obvious after the backfill. It is inferred that these peaks are due to soil-structure interaction. A reduction of amplitudes is recognized in the lower frequency ranges because of the backfill, however, the backfill effect is smaller than that shown in horizontal characteristics published in the previous study

Impedances and effective input motions for idealized system were calculated to evaluate differences in embedment effects between vertical and horizontal responses. The results are shown in figs. 3 and 4. Variations in the imaginary parts of the impedances due to embedment are large for horizontal response, however, those for the vertical direction are much smaller. Figure 4 shows that a loss of effective input motions attributable to embedment in vertical direction is less than those in horizontal direction. Therefore these analysis results also indicate that the influence of embedment to vertical response is not as large as that to horizontal response, though it is expected that a reduction of vertical response is caused by embedment.

3. SIMULATION ANALYSIS OF THE BUILDING MODEL

3.1 Simulation analysis for forced vibration test

The vibration tests were simulated using both an axisymmetric FEM model and a simplified mass and spring model. A mathematical axisymmetric FEM model is shown in fig. 5. The model was set in reference to studies for horizontal plane
The loosened layer at the bottom of the building model was considered to estimate effects of diminution of the over burden load due to excavation. The backfill portion in the model was ignored when studying before the backfill. Figure 6 represents the mass-spring model, in which the stiffness of the structure is calculated from the axial area of the walls. Slabs are considered as different nodes from the main structure. The base-spring is estimated based on the elastic wave propagation theory. And when only studying after the backfill, a double Novak spring as a side-spring is connected to consider the backfill and the surrounding soil. Therefore, the surrounding soil and effects of the excavation condition are not considered in the mass-spring model before the backfill.

Figure 7 shows the results comparing the calculated values and tests. The solid lines express the analytical results of the axisymmetric FEM. The analytical results represent fluctuations of the test resonance curves well. Two peaks, about 15 Hz and 22 Hz, before the backfill are expressed especially clearly by the analysis. It is confirmed that the axisymmetric FEM provides a good explanation of the resonance curves of both cases before and after the backfill.

The analytical results of the mass-spring model are shown in fig. 8. The computed results correspond approximately to the tendencies of measurements, but it is not enough to represent detail variabilities of the resonance curves. As for before the backfill, only one peak in the low frequency range is expressed. The reason is inferred that the base-spring is estimated on the assumption of ignoring the existences of surrounding soil. It is concluded that the simplified model provides the overall tendency of the resonance curve approximately, though not expressing detail behavior.

3.2 Simulation analysis for earthquake responses

Simulation analyses for the earthquake induced response were carried out using the axisymmetric FEM model and the mass-spring model. In order to grasp the influence of embedment on response analysis results, both the embedded model and the unembedded model were used. Two earthquakes, having difference characters, EQ1 (M 6.7, the epicentral distance 180km, the focal depth 50km) and EQ2 (M 7.3, the epicentral distance 564km, the focal depth 388km), were studied. The earthquakes were observed in the building model after the backfill. Figure 9
indicates the acceleration response spectra of the vertical motions at the ground surface. EQ1 dominates in relatively low period ranges, in contrast, EQ2 does not have such low-period components shown in this figure. These ground surface motions were applied as input to the analytical model. In the mass-spring model, input motions were calculated at each spring level based on the one-dimensional wave propagation theory. In the case of the embedded model, the vertical adjusting force was also input to the base level considering effects of excavated soil.

The acceleration response spectra and the distribution of the maximum response acceleration obtained from the FEM analysis are shown with observations in figs. 10 and 11. The results of the embedded model agree excellently with the measurements, though the calculated result overestimates about 0.03 sec at point 1Z in the case of EQ1. It is understood that this peak is due to local vibration and questions remain about modelling the second story. Comparing the calculated results of embedded and unembedded model, it is recognized that the response values without considering embedment are a little larger than those with it. And it is also noticed that the difference of about 0.07 sec in the results for EQ1 is much larger than that for EQ2. It is inferred that the discrepancy is caused by the existence of the dominant periods due to SSI when ignoring the backfill mentioned in Section 2. It is presumed that in the case of EQ1, low-period components are excited by the dominant frequency, because it has more low-period components than EQ2.

Next, the analysis results for EQ1 using the mass-spring model are shown in figs. 12 and 13. For the embedded model, the calculated response spectra correspond reasonably to the observations, except about 0.03 sec at point 1Z the same as the FEM results. The calculated maximum response accelerations, slightly overestimated, show that the overall tendency of observations is reasonable. By ignoring the embedment, the response values tend to become rather larger, except in periods lower than 0.05 sec. Though the influence due to embedment is a little different than that of the FEM, the discrepancy is not so great. It is deduced that the model considering embedment provides response values close to observations and ignoring embedment has no major effect on results.

4. SIMULATION ANALYSIS OF ACTUAL REACTOR BUILDING

For an actual reactor building embedded deeply in rock, simulation analyses for the earthquake induced response were performed. The reactor building was of the BWR MARK-II type and the embedment depth was 36 m, about half of the total height. In the analyses, two one-stick mass-spring models, as shown in fig. 14, were used similar to the building model mentioned above. The models with and without side-springs were idealized to express an embedded and unembedded condition. One earthquake, whose data were M 5.4, the epicentral distance 23km, the focal depth 14km, was studied. For the embedded model, the input motions and the adjusting force were calculated, the same as in the building model, using the ground surface motion. Twice the amplitude of the incident wave on the basis of the one-dimensional wave propagation theory was used as input to the unembedded model.

In fig. 15, the transfer function between the top of the building and the input motion are shown with the Fourier spectral ratios obtained from the observations. Analysis results of both models express well the overall tendency of the records, although at about 0 - 5 Hz and 15 - 25 Hz, there are small differences between the results of the embedded and the unembedded models.

The acceleration response spectra and the distribution of the maximum response acceleration are depicted in figs. 16 and 17. Though the analysis results tend to overestimate response values slightly, it is confirmed that the analysis results coincide with observations overall. It is inferred that the discrepancies between the computed results and the observations are caused by uncertainties included in assumptions of the one-dimensional wave propagation theory and the soil profile used. As a matter of fact, it has been confirmed
that calculated results have agreed very well with the observations by changing an assumption of input motions.

Comparing the results of the unembedded model with those of the embedded model, the former tend to be a little larger than the later for both the maximum response acceleration and response spectra. However, it is understood that the difference is not so distinguished and these simplified models provide sufficient basis for seismic design of an actual reactor building. Further, it is noticed that the response spectra values of the unembedded model exceed those of the embedded model in all period ranges. This is different from the building model results. Though it is inferred that the phenomenon is due to differences of studied frequency ranges because of scaling, it remains to be solved.

5. CONCLUSION

The following results were obtained when vertical response characteristics and analytical methods for seismic design of a deeply embedded reactor building were evaluated;

1) The influence of embedment on vertical response characteristics was smaller in comparison with that to the horizontal ones.
2) The analytical results using an axisymmetric FEM model agreed excellently with observations both for the forced vibration test and earthquake excitation of the building model.
3) The results using the mass-spring model corresponded to observations reasonably, some differences were indicated in analysis results between considering and ignoring embedment in specific frequency ranges. However, the discrepancies were small overall.

Therefore it is concluded that for a deeply embedded reactor building such as the one used in this study, the mass-spring model is sufficient as an analysis model for actual design. The model not considering embedment also provides reasonable response values in a practical sense.

A part of this study has been performed as the joint study. It is titled "Research on Structural Design Method of Nuclear Power Plant Buildings for Dynamic Seismic Load", by ten electric power companies in Japan, namely, Tokyo, Hokkaido, Tohoku, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu and Japan Atomic.

REFERENCE

Fig. 1 Outline of the FVT

Fig. 2 Resonance curves obtained from the FVT

Fig. 3 Comparison of impedances

Fig. 4 Comparison of effective input motion

Fig. 5 Axisymmetric FEM model

Fig. 6 Mass-spring model

Fig. 7 Resonance curves by the axisymmetric FEM model

Fig. 8 Resonance curves by the mass-spring model
Fig. 9 Acceleration response spectra at the ground surface

Fig. 10 Acceleration response spectra of the results by the axisymmetric FEM model

Fig. 11 Distribution of maximum acceleration by the axisymmetric FEM model

Fig. 12 Acceleration response spectra by mass-spring model

Fig. 13 Distribution of maximum acceleration by mass-spring model

Fig. 14 Mass-spring model for reactor building

Fig. 15 Transfer function between the top and the input motion

Fig. 16 Acceleration response spectra

Fig. 17 Distribution of maximum acceleration