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SEISMIC SOIL-STRUCTURE INTERACTION STUDY AT FUKUSHIMA NUCLEAR POWER PLANT

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SUMMARY

This paper describes seismic soil-structure interaction analyses for the Unit 6 reactor building at the Fukushima Daiichi Nuclear Power Plant and examines the suitability of the finite element method for such analyses and the adequacy of current design practice. The responses computed by use of the finite element method were compared with motions recorded during the Miyagiken-oki and South East Tohoku District Earthquakes. An artificial motion fitting the U.S. NRC Reg. 1.60 spectrum was also used in order to further study current design practice. Good agreement is obtained between computed and recorded responses.

INTRODUCTION

An important aspect of the seismic design of safety related structures such as nuclear power plants embedded in soil deposits is the evaluation of the dynamic interaction between the structure and the surrounding soil. The Unit 6 reactor building at the Fukushima Daiichi Nuclear Power Plant complex in Japan is one of the very few nuclear power plant structures for which acceleration responses were recorded at multi-observation points during both strong and minor earthquakes. Analytical simulations based on the finite element approach (Refs. 1,2) have subsequently been performed in order to better understand dynamic behavior of the reactor building and to examine the adequacy of current design practice (Refs. 3,4).

This paper reports the results of a continuation of the soil-structure interaction analyses presented in Refs. 3 and 4, and describes structure-soil-structure interaction analyses of the reactor building of Unit 6. An artificial motion fitting the U.S. NRC Regulatory Guide 1.60 response spectrum was also used for the evaluation of the adequacy of current design practice.

DESCRIPTION OF THE REACTOR AND TURBINE GENERATOR BUILDINGS

The Fukushima Daiichi Nuclear Power Plant complex is located on the Pacific Coast in Fukushima of northern Japan. The reactor building, which houses a 1100 MWe BWR Mark II reactor, is constructed of reinforced concrete and is structually isolated from the adjacent turbine and radwaste buildings. The reactor building is approximately 73m high from the base of the foundation to the roof and is 68.5m x 68.3m in plan at the basement level and 45.5m x 42.5m in plan at the roof level. The reactor building is partially embedded and is founded on a mudstone at an elevation 17m below ground surface.

The turbine generator building located on the east side of the reactor building is about 44m in height and is also partially embedded in a mudstone. The plan dimensions of the building are approximately 104m and 70m in the N-S and E-W directions, respectively.

OBSERVATION SYSTEM AND EARTHQUAKES

On June 12, 1978, the Fukushima Daiichi Nuclear Power Plant experienced a strong earthquake. The earthquake was assigned a Richter magnitude of 7.4 with its epicenter being approximately 140km from the plant and the focal depth being 40km. Only four accelerometers were installed at the time of the Miyagiken-oki Earthqauke. The accelerometers are located under the roof (P01), on the refueling floor (P02), on the foundation mat (P03), and in the mudstone at a depth of 31m below ground surface. The maximum ground acceleration recorded at the Unit 1 site was 128 gal and the duration of strong motion was more than 30 seconds. The peak accelerations observed were 148 to 222 gal at the plant roof and 60 to 84 gal inside the mudstone.

Following the Miyagiken-oki Earthquake, the total number of observation points has been increased. A cross-sectional view of the location of the accelerometers are shown in Fig. 1. Two accelerometers were installed at the roof level (P01 and P11), two at the refueling floor (P02 and P10), one at OP+19m level (P08), and two on the foundation mat (P03 and P05), resulting in total of seven inside the reactor building. Two accelerometers were installed inside the turbine generator building (P06 and P09), and five outside of the structures (P04, P07, P12, P13 and P14). Accelerometers, P04 and P14 were located in the mudstone at a depth of 31m below ground surface, P14 at a depth of 143m, P07 near the ground surface and P12 at a depth of 17m. The accelerometers P07 and P12 were installed 133m north of the reactor building, and are considered to be located in a perfect free field environment.

On September 14, 1982, a minor earthquake, of a Richter magnitude 5.0 with its epicenter located about 37km from the plant and a focal depth of 60km, occured off the coast of the Tohoku District of the Main Island of Japan. Acceleration records were obtained both within and outside the reactor building. Peak accelerations of 26 to 29 gal at the plant roof and 21 to 27 gal at the free field ground surface were observed. The approximate duration of the motion was 40 seconds (Ref. 4).

SOIL-STRUCTURE INTERACTION ANALYSES

Analytical Approach Seismic soil-structure interaction analyses have been performed using the computer program "SuperFLUSH" (Refs. 1,2), which uses the complex response finite element method. A semi-infinite half space was assumed at the bottom of the FEM model (Refs. 1,5) and the energy transmitting boundaries were attached at the lateral boundaries to simulate the existance of semi-infinite soil layers beyond the FEM model (Refs. 2,6).

Material Properties The soil properties used in the analyses are shown in Fig. 2. The same shear wave velocities are used in both Miyagiken-oki and Tohoku Earthquake analyses. The damping ratios used for the Miyagiken-oki Earthquake, however, are higher than those used for the Tohoku Earthquake because of the higher level of excitation. The reactor building was modeled in the N-S direction by three flexible beams whose properties were based on the original blue prints. A series of rigid beams were used to model the foundation mat. The turbine generator building was modeled by two flexible beams and a series of

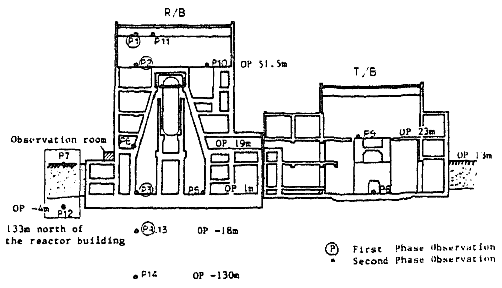


Fig. 1 Accelerometer Locations

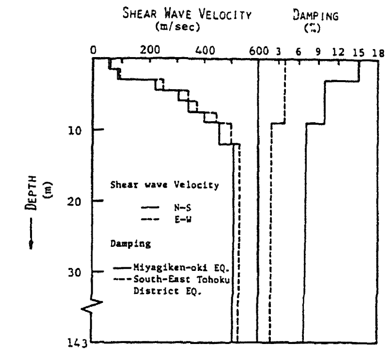


Fig. 2 Soil Properties

rigid beams was used to model its foundation. A damping ratio of 2% was assumed for all structural components.

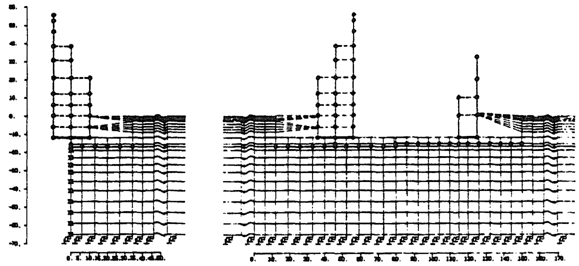
Analyses for South-East Tohoku Earthquake Two analyses were performed using different control motions. The recorded response at P07 was used as the control motion at the free field ground surface, and was then deconvolved to estimate the incident wave at the bottom of the FEM model. The motion recorded at P14 at a depth of 143m was also used as an input motion. The FEM models used for this study are shown in Fig. 3(a). Figs. 4 and 5 show comparisons of the recorded and computed responses in the N-S and E-W directions, respectively. The solid lines show the recorded motions, the broken lines show the computed results using the P07 input motion, and the short-long broken lines show the computed results using the P14 input motion. The computed responses are in extremely good agreement with the recorded responses. The accelerations obtained by subtraction of the recorded vertical components at P03 and P05 can be assumed to be twice the rocking component along the axis 45 degrees from the N-S direction. Likewise, the computed rocking responses were obtained by simply combining the vertical components in the N-S and E-W directions. Fig. 6 shows the recorded and computed rocking responses and excellent agreement is again observed. The fact that the computed responses based on both the P07 and the P14 input motions are very compatible gives support to the adequacy of current design practice as well as the analytical techniques that were used.

Structure-Soil-Structure Interaction Analysis The motion recorded at P07 during the Tohoku Earthquake was used as the control motion at the free field ground surface in this analysis. The cross-section in the E-W direction was modeled as shown in Fig. 3(b). The responses are compared each other in Fig. 7. The solid lines show the recorded motions and the broken lines and short-long broken lines show the computed responses based on use of models of the reactor building only and of the reactor and the turbine generator buildings, respectively. It may be seen that an insignificant difference between the soil-structure and the structure-soil-structure interaction analyses was observed in this study.

Analysis for Miyagiken-oki Earthquake The recorded motion at the foundation mat (P03) was used as the control motion in this analysis and was then deconvolved to estimate the corresponding free field response. Comparisons of the recorded and computed response spectra are shown in Fig. 8 and show excellent agreement (Ref. 3).

ANALYSES USING ARTIFICIAL MOTION FITTING US NRC REG. GUIDE 1.60 SPECTRUM

The previous section shows the adequacy of the analytical procedure and the model used for the soil-structure interaction analyses. As a next step, it was



a) Reactor Building Only   b) Reactor and Turbine Generator Bldgs

Fig. 3 Finite Element Models

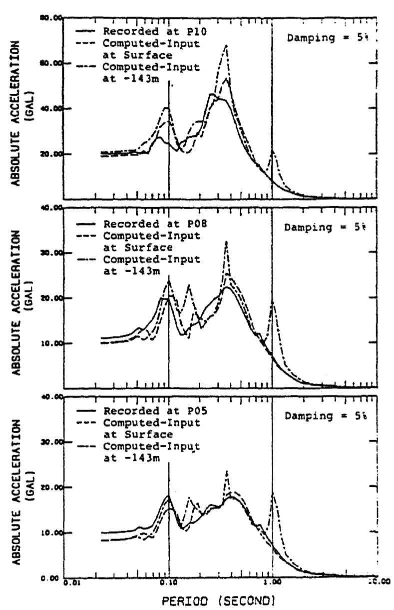


Fig. 5 Recorded and Computed Response Spectra Based on the Tohoku EQ (E-W Direction)

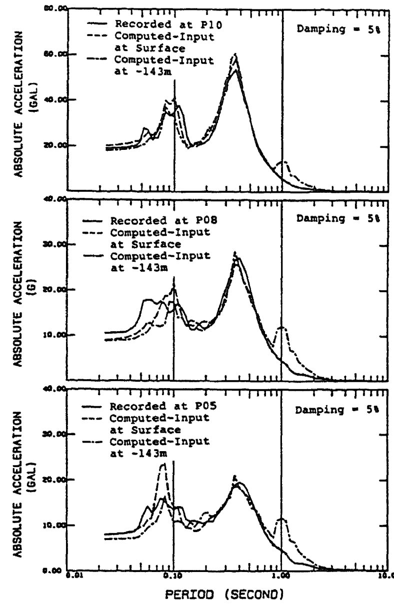


Fig. 4 Recorded and Computed Response Spectra Based on the Tohoku EQ (N-S Direction)

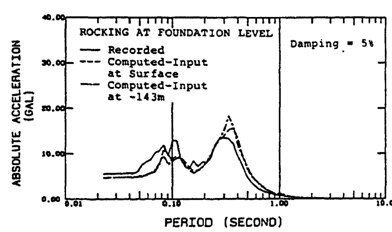


Fig. 6 Recorded and Computed Rocking Responses Based on the Tohoku EQ

desired to evaluate and to better understand the effects of using an artificial motion, such as one fitting NRC Reg. Guide 1.60 spectrum, as the control motion. The motion whose response spectra is shown in Fig. 9 was used in this series of studies. Four commonly used control points are considered in the free field:

1) the free field ground surface with a peak acceleration of 140 gal,
2) a depth of 12m below the ground surface as an "outcropping" motion with a peak acceleration of 70 gal,
3) a depth of 12m as a "within" motion with a peak acceleration of 65 gal,
4) a depth of 70m as an "outcropping" motion with a peak acceleration of 103 gal.

The peak accelerations given in each case were obtained by back calculating the free field responses using the Miyagiken-oki Earthquake motions. The computed maximum acceleration of 140 gal at ground surface of the free field is compatible with observed value of 128 gal at Unit 1 site.

The computed responses obtained at the refueling floor (P02) and foundation mat level (P03) are compared with the recorded responses in Figs. 10 and 11. The cases for the control motion specified at the free field ground surface and at a depth of 70m are shown in Fig. 10. The cases for the control motion specified at

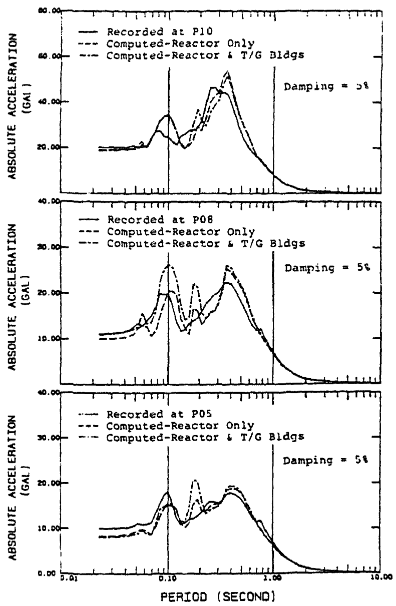


Fig. 7 Recorded and Computed Response Spectra Based on the Tohoku EQ (E-W Direction)

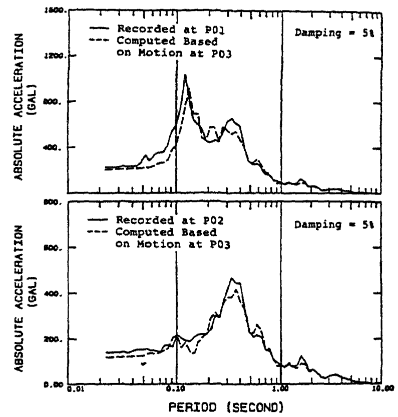


Fig. 8 Recorded and Computed Response Spectra Based on the Miyagiken-oki EQ (N-S Direction)

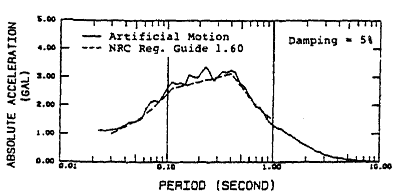


Fig. 9 Artificial Motion and NRC Response Spectrum

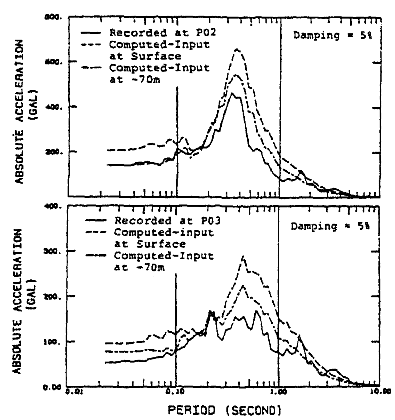


Fig. 10 Miyagiken-oki EQ and Computed Response Spectra Based on the Artificial Motion

a depth of 12m as "outcropping" and "within" motions are shown in Fig. 11. Good agreement was obtained between the recorded and computed responses except for the case where the input control motion was specified as a "within" motion at the foundation level of reactor building. This case tends to overestimate the responses at the frequency corresponding to the natural frequency of the soil column above the control point. The natural frequency computed in the column above control point was 0.18 second. While the incident component may be reasonably assumed to have flat response spectra, a motion whose response spectrum has a relatively flat shape such as the NRC Reg. Guide 1.60 spectrum can not possibly exist at this point.

In order to further examine the adequacy of the frequency content of the computed responses, normalized response spectra are shown in Fig. 12. The shaded area in Fig. 12 corresponds to the cases for which the control motion is given as the incident component. Excellent agreement is observed. On the other hand, the case with the control motion specified as a "within" motion gives relatively poor agreement.

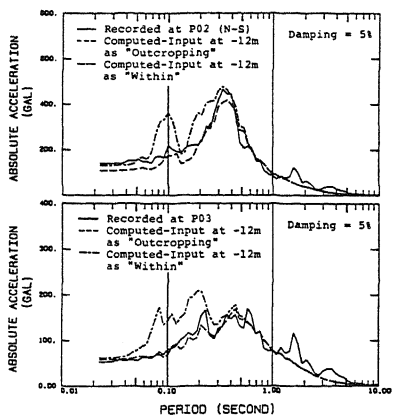


Fig. 11 Miyagiken-oki EQ and Computed Response Spectra Based on the Artificial Motion

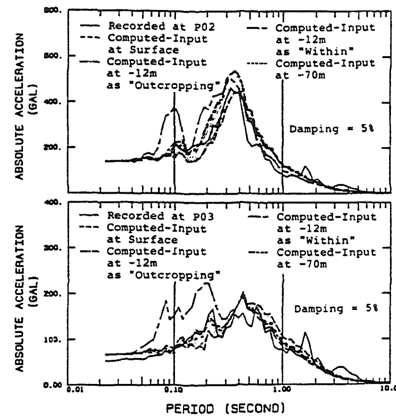


Fig. 12 Miyagiken-oki EQ and Normalized Computed Spectra Based on the Artificial Motion

CONCLUSION

Seismic soil-structure interaction analyses have been performed using motions recorded in the Miyagiken-oki and Tohoku Earthquakes. The computed results show excellent agreement with the recorded responses. The fact that the results based on the recorded free field ground surface motion (P07) and on the motion at a depth of 143m (P14) are very compatible, indicates the appropriateness of deconvolution procedures and the adequacy of present design procedures.

An artificially generated motion fitting the U.S. NRC Reg. Guide 1.60 spectrum was used in order to further study current design practice. Four analyses were performed to examine the effects of different locations of the control points. The results indicate that the cases for which the motion was specified as an incident wave show good agreement with the recorded responses and that the case for which the motion was specified as a "within" motion overestimates the response at the frequency which corresponds to the natural frequency of the soil column above control point. Although this overestimation of the computed response is already well known, it is interesting to observe it in the comparison of computed and recorded responses.

This series of studies indicates that the method used herein is appropriate for the evaluation of the soil-structure interaction effects and provides support for continuing use of current design practice.

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