

Seismic soil-structure interaction behavior at Fukushima Nuclear Power Plant based on multi-point observations

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1 INTRODUCTION

Evaluation of soil-structure interaction effects is one of the most important processes in the seismic design of nuclear power plants. In order to better understand soil-structure interaction effects and to accomplish more safely designed structures it is therefore very desirable to obtain observations of field performance and to perform analytical simulations for both large and small earthquakes. On September 14, 1982, a minor earthquake occurred off the coast of the Tohoku district of the Main Island of Japan. The earthquake was assigned a Richter magnitude of 5.0 with the epicenter being approximately 37km from the Fukushima Daiichi Nuclear Power Station of The Tokyo Electric Power Company and the focal depth being approximately 60km. Acceleration records were obtained at thirteen locations both within and outside the Unit 6 reactor building. Analytical simulations have subsequently performed to study the dynamic response of the reactor building and to examine the adequacy of the analytical methods used in current design practice.

2 DESCRIPTION OF THE REACTOR BUILDING

The reactor building of Unit 6 of the Fukushima Daiichi Nuclear Power Plant (a BWR Mark II type, 1100 MWe) is approximately 73m high from the bottom of base mat (OP-4.0m) to the top of the structure (OP+68.6m). The building is partially embedded and is founded on a mudstone at an elevation of 17m below ground surface. The plan dimension of the reactor building is 68.5m x 68.3m at the bottom and 45.5m x 42.5m at the top. The reactor building is constructed of reinforced concrete and is structurally isolated from the adjacent turbine and radwaste buildings.

3 MULTI-POINT OBSERVATION SYSTEM

Cross-sectional view of the approximate locations of the seismographs are shown in Fig. 1. Two seismographs are installed at the roof level (OP+65.5m, P01 and P11), two at the refueling floor level (OP+51.5m, P02 and P10), one at OP+19m level (P08), and two in the basement floor (OP+1m, P03 and P05), resulting in total of seven seismographs inside the reactor building. Five seismographs are installed outside the reactor building: two (P04 and P13) in the mudstone at a depth of

-31m below ground surface near the reactor building, one (P14) at a depth of -143m below ground surface, one at the surface (P07) and one at depth of -17m (P12). The seismographs P07 and P12 are located 130m north of the reactor building, and are considered to be located in a nearly perfect free field environment. The observed peak acceleration during the earthquake on September 14, 1982 were 26 to 28.6 Gal at the plant roof level and 20.5 to 26.5 Gal at the free field ground surface. The approximate duration of motions was 40 seconds.

4 SOIL-STRUCTURE INTERACTION ANALYSIS

4.1 Outline of analytical approach

Dynamic soil-structure interaction analyses have been performed utilizing the computer program "SuperFLUSH" (EET 1983), which uses the complex response method of computing the response of a finite element model (Lysmer 1975). The recorded motion at the ground surface in the free field was taken as control motion for the analysis. A semi-infinite half space was assumed at depth of 65m at the bottom of the finite element model. A technique for separating incident and reflected components of the incoming motion was used and only incident component is applied at the bottom of the finite element model. The reflected component, including the disturbance due to the reactor building, is absorbed by the half space (Joyner 1975, Udaka 1981). This approach eliminates any uncertainty caused by the assumption of any arbitrary depth for the finite element model. Energy transmitting boundaries (EET 1983, Lysmer 1975, Waas 1972) were attached at the vertical boundaries of the finite element model to simulate the existence of semi-infinite soil layers beyond the finite element model. Soil-structure interaction analyses were performed in both N-S and E-W directions and rocking motion of the reactor building along an axis approximately 45 degrees from the N-S direction was computed by taking the resultant accelerations of the N-S and E-W excitations. Torsional behavior of the structure was also simulated by use of a traveling SH wave concept.

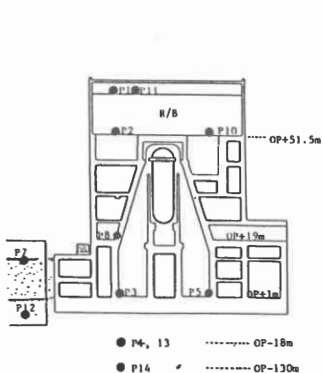


FIG. 1 SEISMOGRAPH LOCATIONS

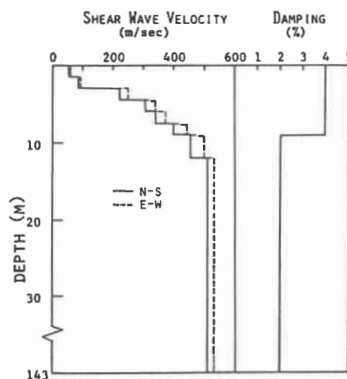


FIG. 2 SOIL PROPERTIES

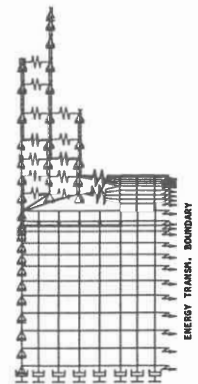


FIG. 3 MODEL

4.2 Material properties

The soil properties used in the analyses are shown in Fig. 2. The reactor building was modeled in the N-S direction by three shear beams whose properties were obtained by computing effective shear areas, mass moments, moments of inertia, and masses based on the original blue prints for the reactor building. The base mat was modeled as a rigid beam. A damping ratio of 2% was assumed for all structural components. Fig. 3 shows the finite element model used for soil-structure interaction analyses.

4.3 Comparison of recorded and computed responses

4.3.1 Horizontal motions

Fig. 4 shows comparisons of the recorded and computed responses in the N-S direction at P10, located on the refueling level, at P08, located on OP+19m level, and at P05, located in the basement. Similarly, Fig. 5 shows comparisons of the recorded and computed responses in the E-W direction. All the response spectra are computed for a damping ratio of 5%. The transfer functions shown in Fig. 6 for the N-S direction and in Fig. 7 for the E-W direction are relative to the free field ground surface motions (P07). A comparison of the recorded and computed maximum accelerations is tabulated in Table 1. The computed values are in extremely good agreement with the recorded values.

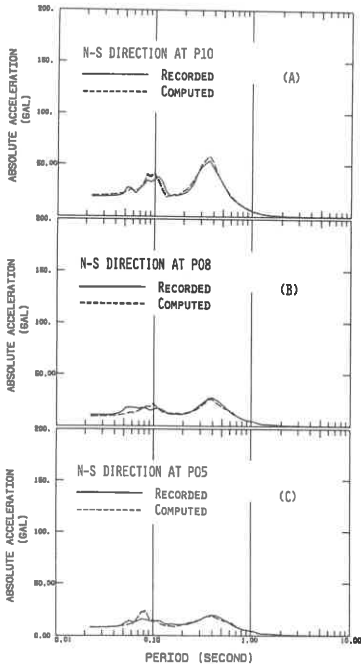


FIG. 4 COMPARISONS OF RESPONSE SPECTRA (N-S)

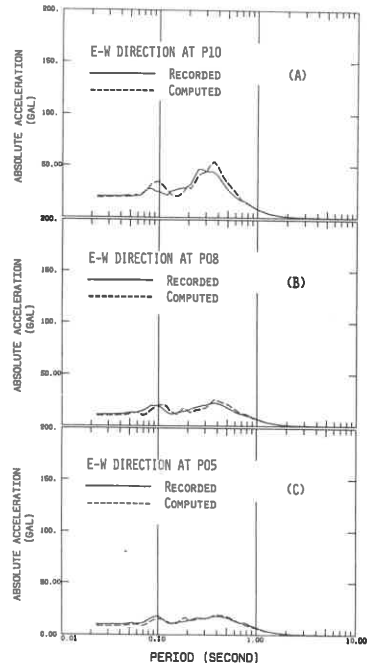


FIG. 5 COMPARISONS OF RESPONSE SPECTRA (E-W)

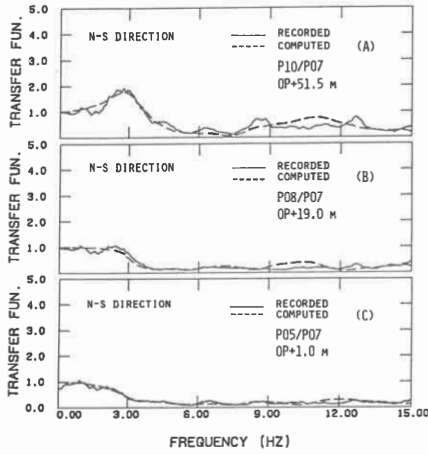


FIG. 6 COMPARISONS OF TRANSFER FUNCTIONS (N-S)

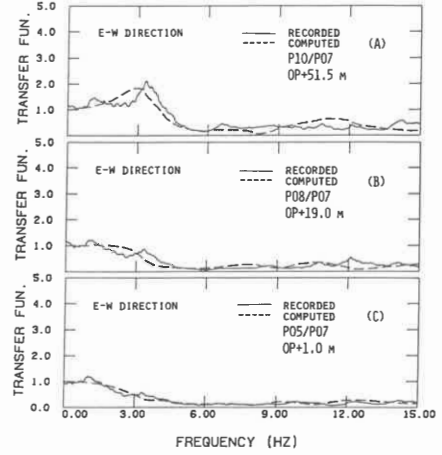


FIG. 7 COMPARISONS OF TRANSFER FUNCTIONS (E-W)

Table 1 Comparison of Maximum Accelerations

	P01	P02	P10	P08	P03	P05	
N-S	RECORDED	26.0	23.3	18.8	10.1	8.7	7.8
	COMPUTED	25.6	20.4	20.4	9.2	8.1	8.1
E-W	RECORDED	28.6	21.8	20.2	11.0	11.1	9.7
	COMPUTED	32.7	19.3	19.3	10.2	8.5	8.5

Unit Gal

4.3.2 Rocking

The seismographs P03 and P05 are located on a line which is nearly 45 degrees from the N-S axis. Therefore, the accelerations obtained by the subtraction of the observed vertical components at P03 from P05 can be assumed to be twice the rocking component of the foundation along this axis. Likewise, the computed vertical responses due to both N-S and E-W horizontal excitations at the foundation level are simply combined to obtain the rocking response on the axis 45 degrees from the N-S direction. A comparison of the recorded and computed rocking response spectra is shown in Fig. 8. The computed response is again in excellent agreement with the recorded response. The minor differences that can be seen may be due to the assumption in the analysis that the structure is perfectly symmetric when this is not actually true.

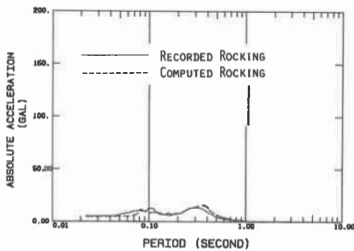


FIG. 8 COMPARISON OF RESPONSE SPECTRA FOR ROCKING AT BASEMENT LEVEL

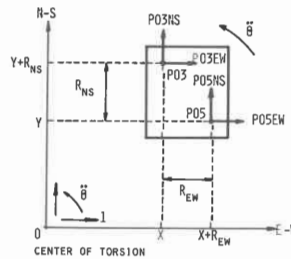


FIG. 9 TORSIONAL MOTION ON RIGID FOUNDATION

4.3.3 Torsional behavior

In order to evaluate the torsional response of Fukushima Unit 6, the base foundation was assumed to be perfectly rigid as shown in Fig. 9. The torsional components with respect to the N-S and E-W directions can then be expressed as follows:

$$\begin{aligned}\ddot{\theta}_{NS} &= (P03NS-P05NS)/R_{EW} \\ \ddot{\theta}_{EW} &= (P05EW-P03EW)/R_{NS}\end{aligned}\quad \text{Eq. (1)}$$

If $\ddot{\theta}_{NS}$ is equal to $\ddot{\theta}_{EW}$, because of the assumption of rigidity, the foundation has a torsional movement with angular acceleration of $\ddot{\theta}_{NS}$.

The observed torsional motions were then computed using Eq. (1) and the response spectra for $\ddot{\theta}_{NS}$ and $\ddot{\theta}_{EW}$ multiplied by a factor R_{NS} as shown in Fig. 10. It is apparent that the reactor building has a rigid body torsional component in the order of 10% of the translational component.

The torsional components $\ddot{\theta}_{NS} R_{EW}$ and $\ddot{\theta}_{EW} R_{NS}$ can also be calculated using the recorded responses at P03 and traveling SH wave concepts (Udaka 1979) with phase velocities of 2000m/sec in N-S and 3000m/sec in E-W directions, respectively. A phase velocity of 2000m/sec corresponds to an incident angle of approximately 15 degrees to the vertical while a phase velocity of 3000m/sec corresponds to an incident angle of 10 degrees. Comparisons of response spectra based on the observed motion computed using Eq. (1) and the traveling SH wave concept are shown in Fig. 11. The results shown suggest that torsional behavior at the site may be well explained by the traveling SH wave concept.

Finally $\ddot{\theta}_{NS}$ and $\ddot{\theta}_{EW}$ were computed using the responses computed in the soil-structure interaction analysis and traveling wave concepts with phase velocities of 2000m/sec for the N-S and 3000m/sec for the E-W directions, respectively. Comparison of response spectra for recorded and computed torsional components are shown in Fig. 12. The good agreement that can be seen between recorded and computed results should increase confidence in the concept of traveling SH waves for evaluating the torsional response of structures.

The computed torsional component $\ddot{\theta}_{NS} R_{EW}$ was then added to the computed translational components. The computed response spectra with the torsional component included are shown in Fig. 13. It may be seen that the torsional behavior has no significant effect on the total translational behavior in this case.

5 CONCLUSION

The results of the analyses of horizontal and rocking motions show excellent agreement with the recorded responses. The torsional movement of the reactor building was also studied and was found to have no significant effect on the horizontal responses. These results indicate that the methods used herein are both useful and suitable for evaluation of soil-structure interaction effects and also that analysis based on motions generated by small magnitude earthquakes can be very informative in evaluating the adequacy of analysis and design procedures.

ACKNOWLEDGEMENT

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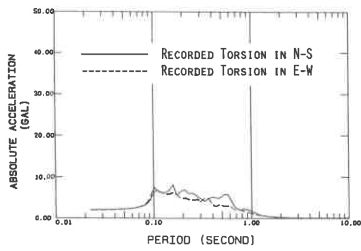


FIG. 10 COMPARISON OF RESPONSE SPECTRA FOR TORSION RECORDED AT BASEMENT LEVEL

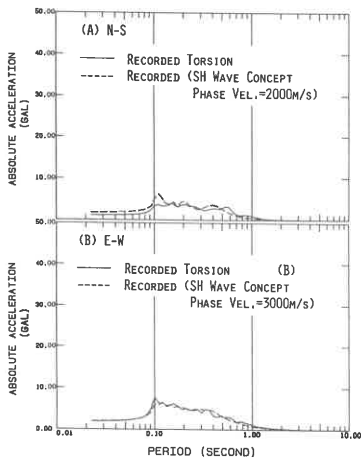


FIG. 11 RESPONSE SPECTRA FOR TORSION OBTAINED FROM SH WAVE CONCEPT

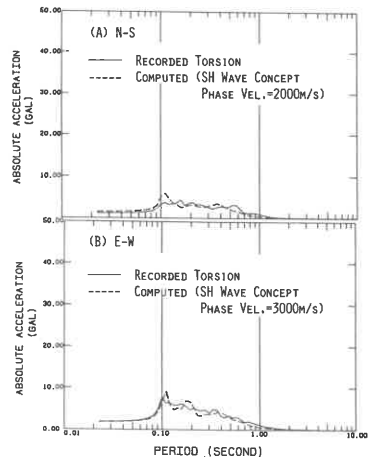


FIG. 12 RECORDED AND COMPUTED RESPONSE SPECTRA FOR TORSION AT BASEMENT LEVEL

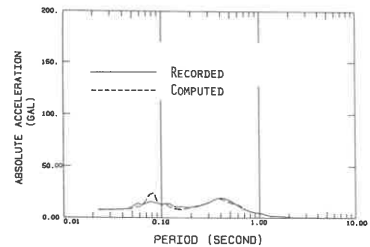


FIG. 13 RESPONSE SPECTRA AT BASEMENT LEVEL WITH TORSIONAL COMPONENT

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