BNL Prediction of NUPEC's Field Model Tests of NPP Structures Subject to Small-to-Moderate Magnitude Earthquakes

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ABSTRACT

As part of a verification test program for seismic analysis codes for NPP structures, the Nuclear Power Engineering Corporation (NUPEC) of Japan has conducted a series of field model test programs to ensure the adequacy of methodologies employed for seismic analyses of NPP structures. A collaborative program between the United States and Japan was developed to study seismic issues related to NPP applications. The US Nuclear Regulatory Commission (NRC) and its contractor, Brookhaven National Laboratory (BNL), are participating in this program to apply common analysis procedures to predict both free field and soil-structure snteraction (SSI) responses to recorded earthquake events, including embedment and dynamic cross interaction (DCI) effects. This paper describes the BNL effort to predict seismic responses of the large-scale realistic model structures for reactor and turbine buildings at the NUPEC test facility in northern Japan. The NUPEC test program has collected a large amount of recorded earthquake response data (both free-field and in-structure) from these test model structures. The BNL free-field analyses were performed with the CARES program while the SSI analyses were preformed using the SASSI2000 computer code. The BNL analysis includes both embedded and excavated conditions, as well as the DCI effect, The BNL analysis results and their comparisons to the NUPEC recorded responses are presented in the paper.

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KEY WORDS: seismic, recorded earthquake data, nuclear, reactor structure, analytical models, structural response.

INTRODUCTION

Consideration of the soil-structure interaction (SSI) effects is a key step in seismic response analyses, especially for massive stiff buildings such as nuclear power plant (NPP) structures. Over the past thirty years, considerable efforts have been made to develop both analytical and numerical tools for computing SSI effects, many of which are now being used as standard practice in the nuclear industry to treat the seismic response of structures. Although it is widely recognized that the SSI analysis methodologies and their numerical applications are established on sound analytical bases, assessments of their applications still need to be made against recorded earthquake responses. As part of the Verification Tests for Seismic Analysis Code Program for NPP structures, the Nuclear Power Engineering Corporation (NUPEC) of Japan has conducted a series of field model test programs to ensure the adequacy of methodologies employed for seismic analyses of NPP structures. A collaborative program between the United States and Japan was developed to study seismic issues related to NPP applications. The US Nuclear Regulatory Commission (NRC) and its contractor, Brookhaven National Laboratory (BNL), are participating in this program to apply the industry practice to predict both the free field and structural responses to recorded earthquake events, including various aspects of the SSI effect, including embedment and dynamic cross interaction (DCI) effects.

This paper describes the BNL effort to predict the seismic response of the NUPEC test facilities. Large-scale realistic model structures for reactor and turbine buildings were constructed at a site in northern Japan. Several structural configurations were designed to study various aspects of the SSI effect, including embedment and DCI effects. The NUPEC test program has collected a large amount of recorded earthquake response data from these test model structures, and SSI analyses were preformed for these test models using the substructure method as programmed in the SASSI2000 computer code. The BNL analysis includes both embedded and excavated conditions, as well as the DCI effect, The BNL analysis results and their comparisons to the NUPEC recorded responses are presented in the paper.

DESCRIPTIONS OF NUPEC TEST STRUCTURES AND BNL ANALYSIS MODELS

The NUPEC test site for the field tests was located in Aomori Prefecture in northern Japan, a region which experiences frequent seismic activities. Large-scale models with dynamic characteristics similar to typical NPP structures were constructed on soils representative of actual NPP sites [1, 2]. The DCI field test considered three building construction conditions: a) single reactor as reference for comparison purposes, b) closely spaced twin reactors, and c) a reactor and a turbine building in close proximity to each other. The field tests also consider both excavated and embedded foundations and two types of loading conditions: 1) forced vibrations and 2) observations of the structural response to real earthquake ground motions. The latter was accomplished by pre-installed seismometers in the structures and free field. To complement the field tests, laboratory tests were also performed by NUPEC using a shaking table and smaller scaled DCI soil-structure models. The laboratory tests were used by NUPEC for detailed investigation of DCI effects under strong earthquake motion, which could not be achieved in the field tests.

Figure 1 shows a layout of the NUPEC field test models. Although three different model-building configurations were utilized in the NUPEC tests, there are only two structurally distinct model buildings, namely, the reactor building and the turbine building. The reactor building is a three-story reinforced concrete structure (1/10th scale of the typical reactor building in a commercial NPP in Japan). The building has dimensions of 8m by 8m in plane and 10.5m in height and weighs about 660 metric tons. The turbine building is a two-story reinforced concrete structure and is 6.4m by 10m in plan and 6.75m high and weighs about 395 metric tons. The single reactor building is situated in the base of a pre-excavated pit of trapezoidal shape. For the single reactor building, the excavated pit is 10m by 10m in plan at the base and 20m by 20m in plan at the ground surface. The base of the pit is 5m below the ground surface with the sidewalls inclined at a slope of 45-degree angle with the ground surface. The excavated pit for the twin-reactor building is located to the east of the single reactor building and has a rectangular opening of 10m by 18.6m at the base and 20m by 28.6 at the ground surface, and is 5m deep. The longer side of the pit is in the north-south direction (x-axis). The twin-reactor buildings are situated in the north-south direction at the base center of the pit with a gap of 0.6m between the two reactor buildings. The reactor-turbine buildings are situated in an excavated pit, which is located to the north of the twin reactor buildings and has an opening of 11m by 17.2m at the base and 19m by 25.2m at the surface. The pit is 4m deep and the basemat of the reactor building is embedded into the base foundation by 1m. The gap between the reactor and the turbine buildings is 0.1m.

The BNL SASSI 2000 [3] models were developed based on the information provided by NUPEC. In the BNL models of the reactor and the turbine buildings, the portion of the structure below the ground surface is modeled with explicit finite elements (e.g., 3-D bricks and shells), while the portion above the ground surface is modeled with simple lumped masses and 3-D beams. Figure 2 shows the SASSI model of the single reactor building. Due to the symmetric configuration of the building, only half of the structure was modeled with the plane y=0 (east-west direction) as the symmetry plane. As seen in this figure, the basemat was modeled with brick elements and the sidewalls and internals were modeled with shell elements. The super-structure was modeled with lumped masses and beams. The base of the super-structure is connected to the sidewalls by rigid links to simulate the rigid diaphragm of the floor at grade level. Also as indicated in the figure, a thin layer of soil elements was added underneath the basemat to account for the softening effect induced by the excavation activities. In order to apply the subtraction method, the nodes at the boundary of the excavation need to be identified as the interaction nodes and the volume of the excavated pit also needs to be modeled. In this case, due to the symmetry, only one-half of the volume needs to be modeled and it is done using brick elements in the SASSI model.

Since the twin reactor buildings were arranged in the north-south direction (x-axis), the adjacent building effect or the dynamic cross interaction (DCI) effect is mostly amplified by the ground motion excited in the north-south direction, which is an important aspect of the SSI effect under the BNL study. Therefore, to develop a model for the DCI effect, in addition to the symmetry condition used for the single reactor building, the SASSI model for the twin reactor building also introduces an anti-symmetry plane perpendicular to the x-axis located in-between the two reactors. Furthermore, due to symmetry and anti-symmetry planes introduced in the model for the twin reactor buildings, only one-quarter of the excavated volume is required to be modeled, instead of the one-half volume being modeled for the single reactor.

For the reactor-turbine buildings, which are arranged in the north-south direction (x-axis), only a symmetry condition (y=0) was introduced similar to the single reactor model. Figure 3 shows the SASSI model for the reactor-turbine buildings. Similar to the objective for the twin reactor building for developing a SASSI model for the DCI effect, the reactor-turbine buildings model was developed in which the gap between the two structures was explicitly modeled.

As for the structural models in the embedded condition, the building models are the same as those for the excavated condition. The excavation for an embedded case is the embedment of the structure. Therefore, the volume of the excavation for the embedded cases is substantially less than the volume for the excavated models. The modeling effort is also substantially reduced compared with the excavated case modeling. The SASSI model of the embedded reactor-turbine buildings is shown in Figure 4.

BNL ANALYSIS RESULTS AND DISCUSSIONS

Three sets of soil profiles were utilized in the BNL SSI response analyses. These profiles are the mean, mean plus sigma and mean minus sigma iterated velocity profiles. The mean profiles and the corresponding mean surface motions were developed using probabilistic free field analyses [4, 5] using the CARES [7] program for site response. The mean, mean plus sigma and mean minus sigma profiles were calculated by performing a large number (30 to 60) of site response calculations for a given earthquake input at depth to generate iterated site profiles. BNL performed SSI analyses for seven earthquake events provided by NUPEC. Table 1 summarizes these events with respect to their occurrence time, source location, magnitude, epicenter and focal distances from the site, as well as maximum acceleration induced in the free field.

Table 1. Earthquake Events Selected for SSI Analyses

Earthquake No.	Earthquake Occurrence Time	Source Location East Longitude	Source Location North Latitude	Earthquake magnitude (M)	Epicenter/ Focal distance (km)	Max old free field point acceleration GL-1.5m (Gal) NS	Max old free field point acceleration GL-1.5m (Gal) EW	Max new free field point acceleration GL-3.0m (Gal) NS	Max new free field point acceleration GL-3.0m (Gal) EW
89	12-28-1994	143'43.3	40'27.1	7.5	213/213	123.0	174.0		
131	02-17-1996	141'23.0	40'47.0	4.6	43/45	15.9	17.3	15.1	13.3
139	02-20-1997	142'52.0	41'45.0	5.6	140/146	9.3	8.9	11.4	11.6
157	01-03-1998	142'04.0	41'28.0	5.1	66/89	28.5	26.7	20.8	30.2
63	01-15-1993	142'23.0	42'51.0	7.8	294/310	109.0	98.0		
164	11-07-1998	142'03.0	41'34.0	4.6	71/95	8.9	8.5	6.3	10.8
172	05-11-1999	143'55.0	42'57.0	6.4	288/305	13.5	13.6	13.3	10.8

Applying the mean surface input motion and utilizing the mean, the mean minus sigma and the mean plus sigma profiles developed for each earthquake record, BNL performed the SASSI analyses to generate the structural responses for the three structural configurations. These SSI responses were expressed in terms of 5% damped response spectra, which were then compared with the response spectra calculated from recorded motions afforded by NUPEC. Due to the limited space, only typical response comparisons are presented in this paper. For detailed comparisons and complete SSI analysis results, the reader is referred to Reference 6.

For the single reactor in the excavated condition, Figure 5 presents the response spectral comparison between the BNL analysis and the recorded data for Earthquake No. 131 at the roof center. As exhibited in this figure, although a one-to one comparison may not be achieved between the recorded response and the computed response (mean or mean minus sigma or mean plus sigma), the calculated response with all three sets of soil profiles very conservatively enveloped the recorded response. This observation reinforces the belief that the current practice accounting for the uncertainties of the soil properties in the SSI analyses of the NPP structures is not only adequate but possibly over conservative. In practically all of the cases analyzed, the results were shown to be conservative, but not always to the same degree as shown in Figure 5.

To demonstrate the sensitivity of the effect of the disturbed soil in close proximity to the foundation, the SSI response to Earthquake No. 89 was analyzed for a variation of the soil property of the 0.5m thin soil layer underneath the basemat. Two sets of the SSI response calculations were performed, one for the thin soil layer assuming the nominal value of Vs=150m/s, and the other for the soil layer having a reduced Vs=110m/s. Figure 6 shows the SSI response comparison at the roof center for the soil property of the thin soil layer with Vs=150m/s, while Figure 7 depicts the SSI response at the roof center for the soil property of the thin layer with Vs=110m/s. As indicated in these figures, when compared with the recorded data, the computed SSI response with Vs=150m/s for the thin soil layer exhibits either lower response or a frequency shift, while the computed SSI response with a reduced Vs=110m/s for the thin soil layer showed excellent agreement with the recorded data. A similar phenomenon was also observed in the Hualien (Taiwan) field tests. The effect of local disturbance due to the softening by excavation activities may become more pronounced when the media are stiffer.

For the single reactor in the embedded condition, Figure 8 shows the SSI response comparisons at the roof center between the BNL analysis and the recorded responses for Earthquake No. 89. As exhibited in this figure, the BNL SSI analysis both captured the frequency characteristics and predicted the peak responses compared with the recorded responses.

For structures adjacent to each other, the DCI effect may impact SSI responses. To study the DCI effect and to confirm that the state of analytical tools can adequately capture the DCI effect, BNL performed SSI analyses for both twin reactors and reactor-turbine configurations. Figure 9 shows a comparison between the BNL analysis and the recorded response for the reactor-turbine configuration in the excavated condition for Earthquake No. 157. The comparison for the reactor showed that the BNL predictions captured the overall characteristics of the SSI response for the reactor-turbine configuration. For the embedded condition, SSI response comparisons were also made between the recorded data and the BNL analyses. Figure 10 shows a comparison of the computed vs. recorded responses for the embedded reactor-turbine configuration for Earthquake No. 164. As depicted in this comparison, the computed results enveloped the recorded response. Overall, BNL SSI analyses and their comparisons with recorded responses demonstrated that the practice for SSI calculations used by the nuclear industry is capable of capturing recorded responses from real earthquake events.

CONCLUSION

The SSI response analyses performed in this study covered three structural configurations, which include the single reactor building, twin reactor buildings and reactor-turbine buildings. BNL analyzed these configurations for both the excavated and embedded conditions. By applying the current approach for the SSI analyses of the NPP structures, BNL performed the seismic response calculations in terms of mean, mean minus sigma and mean plus sigma values to account for uncertainties in the soil properties. As described in this paper, the BNL SSI response results either closely matched or exceeded the recorded responses, which further substantiated the conservatism in the analytical procedures as many have suggested. The BNL analyses have demonstrated the application of the current approach for addressing uncertainties for SSI analyses, and the consideration of soil uncertainties in the SSI analyses is a necessary step to assure conservatism in the computed structural response.

DISCLAIMER NOTICE

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, D.C. The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the U.S. Nuclear Regulatory Commission, Brookhaven National Laboratory or the Nuclear Power Engineering Corporation.

REFERENCES

1. Kitada, Y., et al., "Model Test on Dynamic Cross Interaction of Adjacent Buildings in Nuclear Power Plants – Overview and Outline of Earthquake Observation in the Field Test," Trans. 16th SMiRT, Session K10/5, Washington D.C, 2001.
2. Suzuki, A. et al., "Evaluation of Seismic Input Motions and Responses of Buildings in Nuclear Power Plants", Proceeding of the OECD/NEA Workshop on the Engineering Characterization of Seismic Input, Brookhaven National Laboratory, Upton, New York, November 15-17, 1999, NEA/CSNI/R(2000)2/Volume 2, January 2001.
3. Lysmer, J., et al., "SASSI2000 – Theoretical Manual," Revision 1, Geotechnical Engineering, University of California, Berkeley, 1999.
4. Xu, J., et al., "Identification Of Free-Field Soil Properties Using NUPEC Recorded Ground Motions", SMiRT-16, Washington, D.C., August 12-17, 2001.
5. Xu, J., et al., "Probabilistic Site Identification Analysis Using NUPEC Recorded Free-Field Motions", ASME PVP Conf., British Columbia, Canada, August 2002.
6. Xu, J., et al., "Collaborative Study of NUPEC Seismic Field Test Data for NPP Structures," NUREG/CR, to be published in 2003.
7. Miller, C.A. and C.J. Costantino, "CARES: Computer Analysis for Rapid Evaluation of Structures, Version 1.3", CE Dept., City College of New York for US Nuclear Regulatory Commission, May 2000.

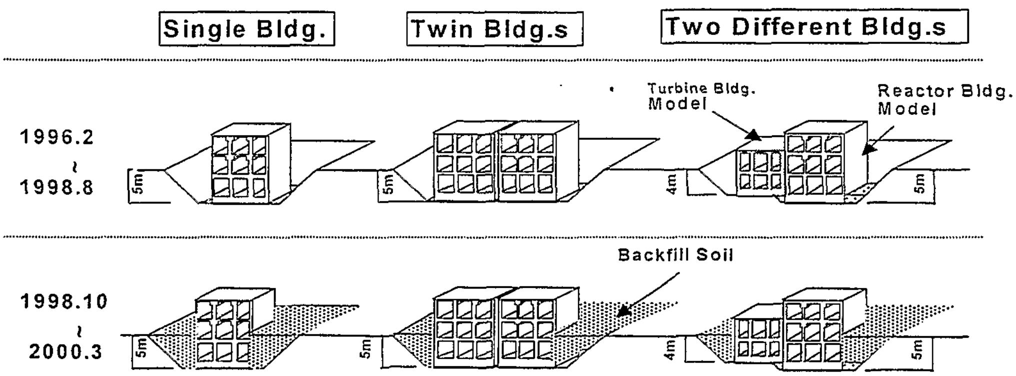

Figure 1. Layout of NUPEC Field Test Models.

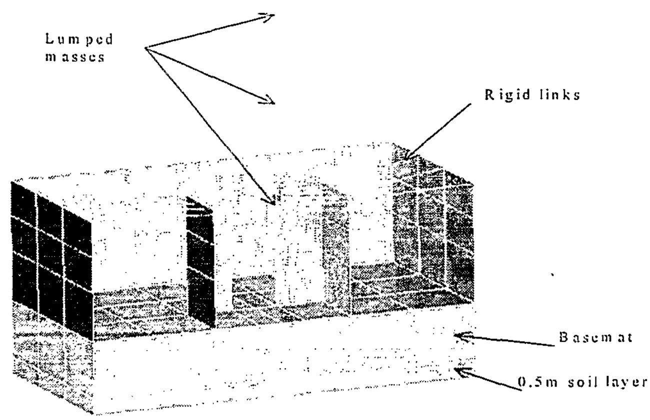

Figure 2. BNL SASSI Model of the Excavated Single Reactor Building.

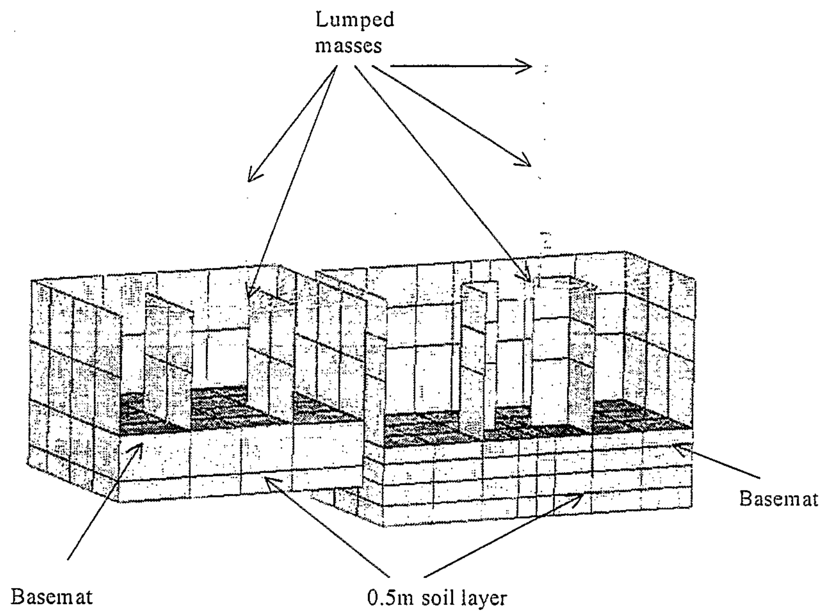

Figure 3. BNL SASSI Model of the Excavated Reactor-Turbine Buildings.

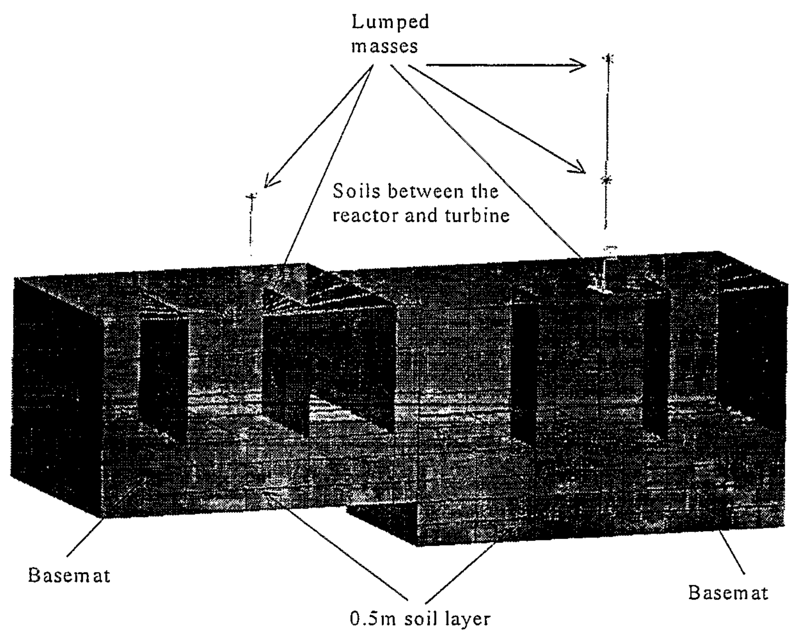

Figure 4. BNL SASSI Model of the Embedded Reactor-Turbine Buildings.

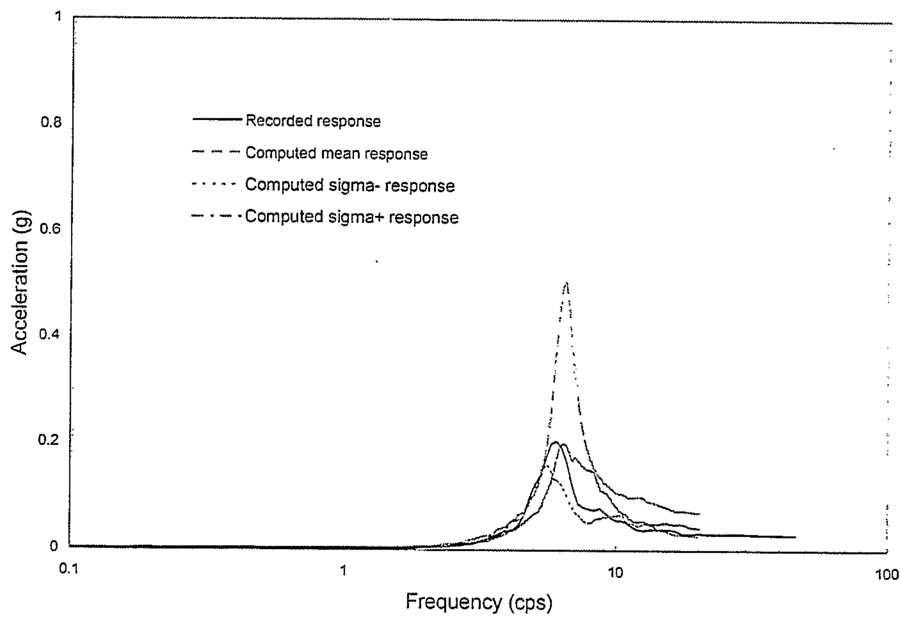

Figure 5. Comparison of Computed vs. Recorded Response at the Roof Center of the Excavated Single Reactor (Earthquake No. 131).

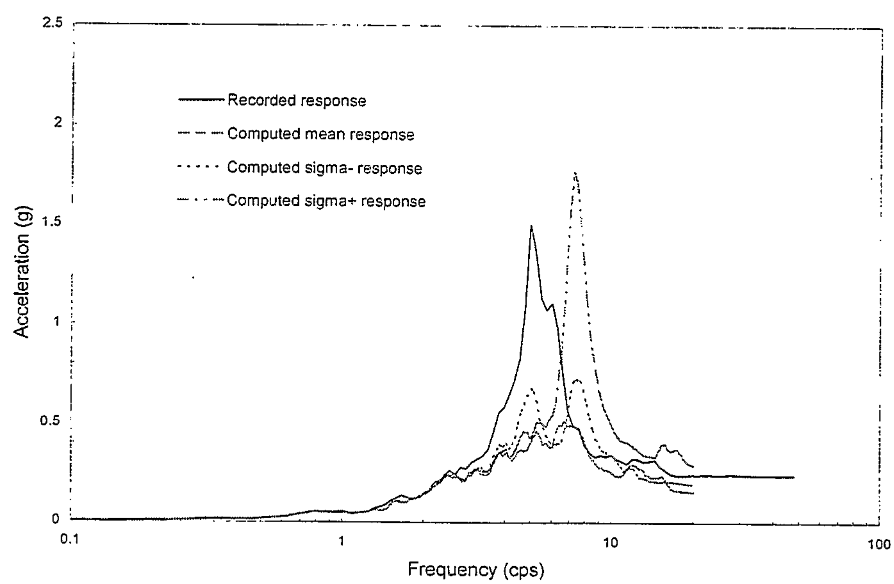

Figure 6. Comparison of Computed vs. Recorded Response at the Roof Center of the Excavated Single Reactor (Earthquake No. 89), Vs=150m/s for the 0.5m Thin Soil Layer under Basemat.

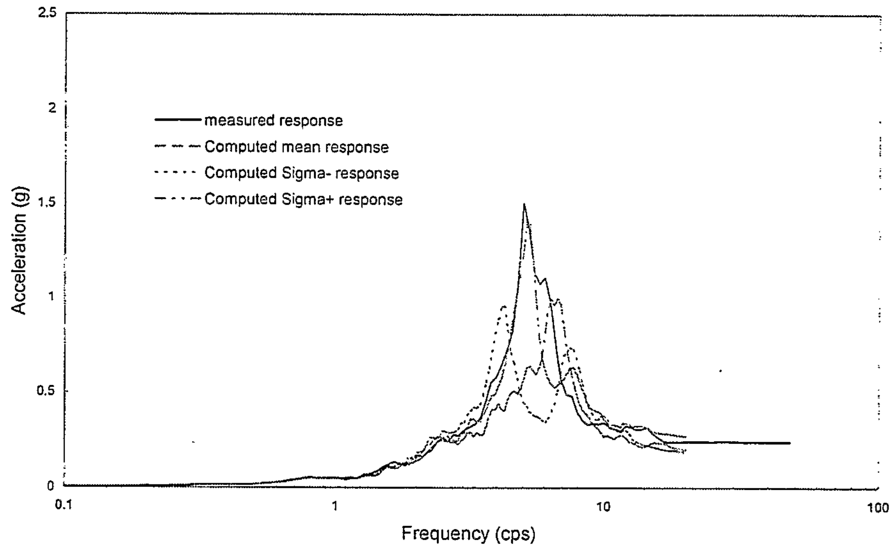

Figure 7. Comparison of Computed vs. Recorded Response at the Roof Center of the Excavated Single Reactor (Earthquake No. 89), Vs=110m/s for the 0.5m Thin Soil Layer under Basemat.

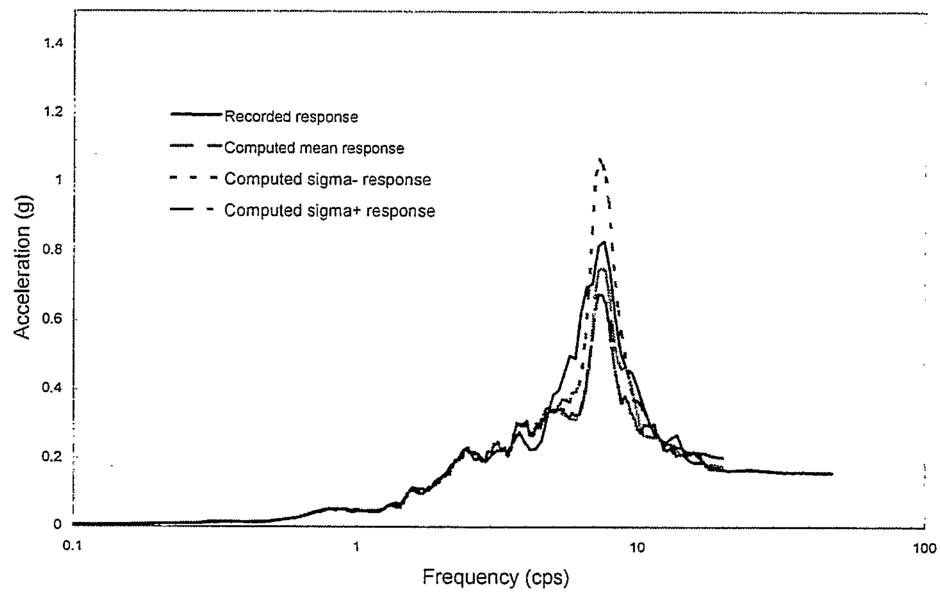

Figure 8. Comparison of Computed vs. Recorded Response at the Roof Center of the Embedded Single Reactor (Earthquake No. 89).

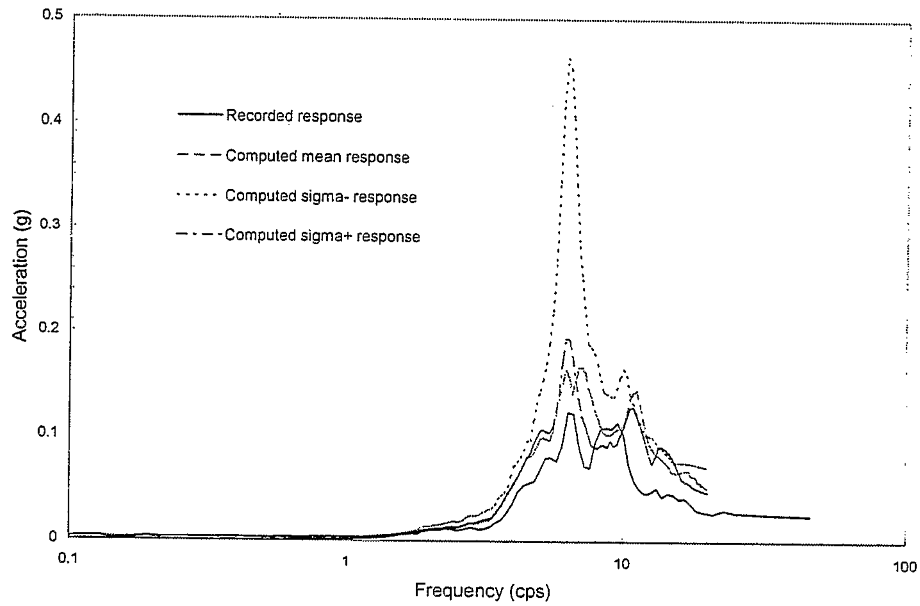

Figure 9. Comparison of Computed vs. Recorded Response at the Roof Center of the Reactor of the Excavated Reactor-Turbine Configuration (Earthquake No. 157).

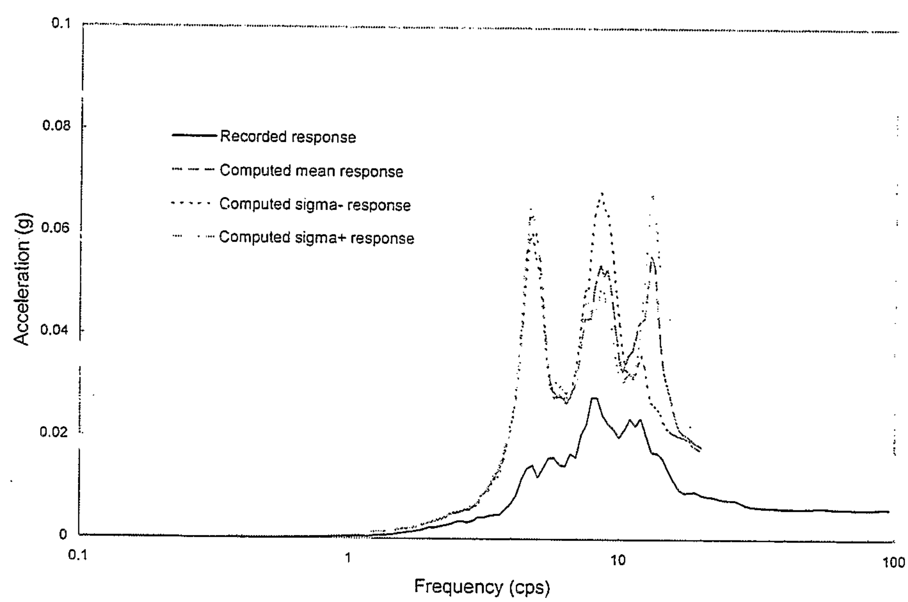

Figure 10. Comparison of Computed vs. Recorded Response at the Roof Center of the Reactor of the Embedded Reactor-Turbine Configuration (Earthquake No. 164).