PROCEEDINGS OF SMiRT 13 - POST CONFERENCE SEMINAR 16 SEISMIC EVALUATION OF EXISTING NUCLEAR FACILITIES

DYNAMIC ANALYSIS OF WWER-1000 NUCLEAR POWER PLANTS

Alejandro P. Asfura, Ph.D.
EQE International
San Francisco, California, USA

Marin J. Jordanov
EQE International
Sofia, Bulgaria

1. INTRODUCTION

As part of the effort to assess the seismic vulnerability of nuclear power plants in Eastern Europe, a series of dynamic analyses have been carried out for several plants [1, 2, 3]. These analyses were performed using modern analysis techniques, current local seismic parameters, and local soil profiles.

This paper presents a compilation of some of the seismic analyses performed for the WWER-1000 reactor buildings at the nuclear power plants of Belene and Kozloduy in Bulgaria, and Temelín in the Czech Republic. The reactor buildings at these three plants are practically identical and correspond to the standard building design for this type of reactors.

The series of analyses performed for these buildings encompasses various soil profiles, seismic ground motions, and different soil-structure interaction (SSI) analysis techniques and modeling. The analysis of a common structure under different conditions gives the opportunity to assess the relative importance that each of the analysis elements has in the structural responses. The use of different SSI computer programs and foundation modeling was studied for Kozloduy, and the effects of different soil conditions and site-specific seismicity were studied by comparing the responses for the three plants.

In-structure acceleration response spectra were selected as the structural responses for comparison purposes.

2. DESCRIPTION OF REACTOR BUILDING

The reactor building for a typical 1000 MW WWER nuclear power plant consists of four distinctive structures, as shown in Figure 1. The base substructure starts from the foundation basemat and rises up to a second concrete basemat, which supports the reactor containment, the reactor internal structure, and a peripheral auxiliary building called the "outer building."

The substructure is a three-story building, which houses the main control room and the auxiliary systems, and equipment including several large tanks. The building has a square shape of about 70 m by 70 m with orthogonally distributed walls. Most of the interior walls and slabs in the substructure are made of precast concrete panels serving as formwork for cast-in-place concrete.

The containment is a post-stressed concrete shell with an 8-mm-thick steel liner. The posttensioned cables are anchored in a stiff ring girder at the junction of the cylinder and the spherical dome. The containment thickness is 1.2 m for the cylinder and 1.1 m for the dome.

The internal structure is a massive concrete structure supporting the reactor vessel, four horizontal steam generators, the reactor coolant pumps, a pressurizer, accumulator tanks, and other auxiliary equipment. The core of the structure consists of a thick cylindrical shield wall around the vessel and two groups of pools and cavities containing the spent fuel.

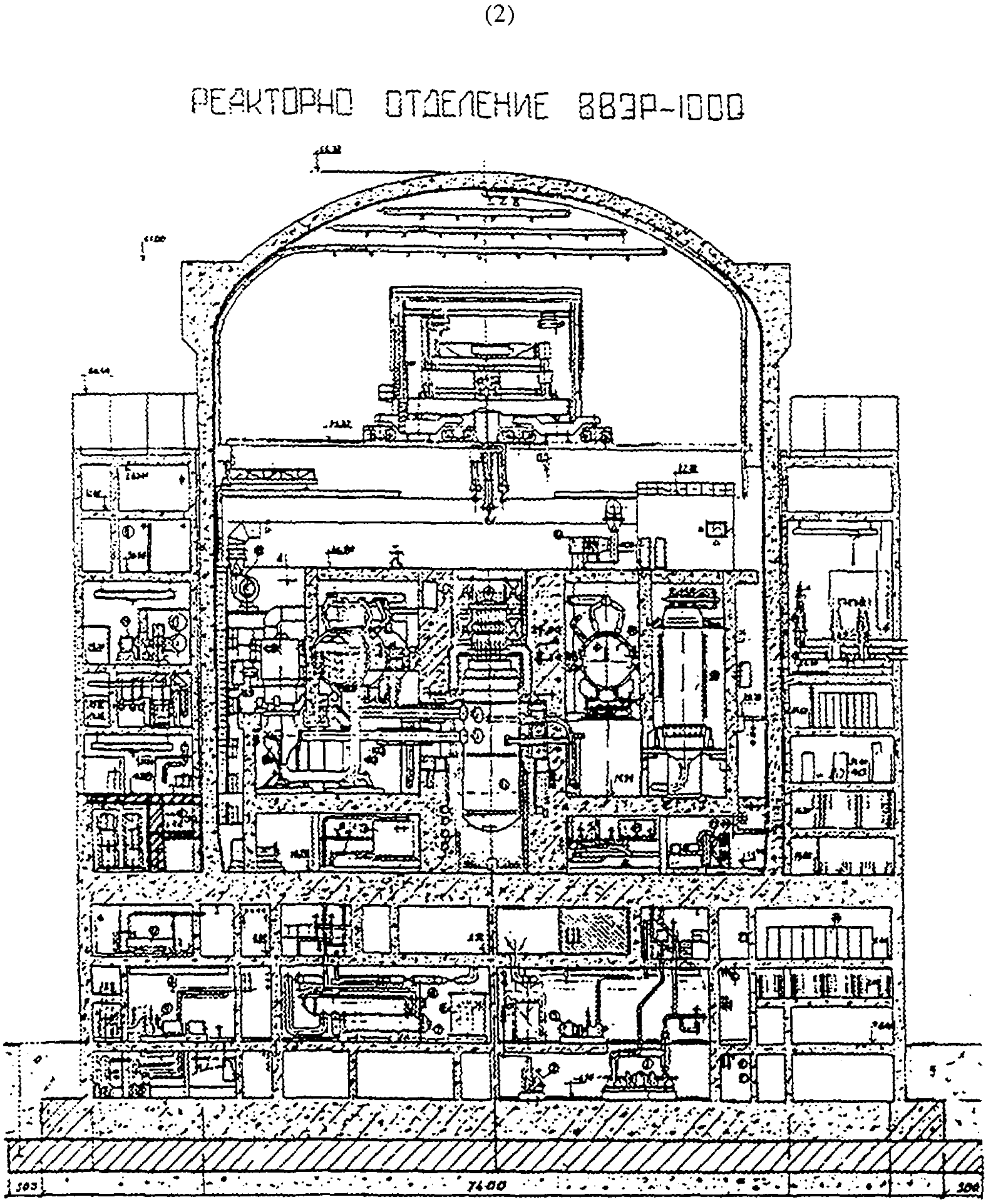

Figure 1: Reactor Building Cross Section

The outer building houses miscellaneous equipment and the main steam piping going to the turbine building. This building is isolated from the containment shell by a seismic gap.

Figure 2 shows the structural fixed-base stick model developed for the analyses described in this paper. Table 1 presents the dynamic modal characteristics of the first 15 modes of this fixed-base model.

(3)

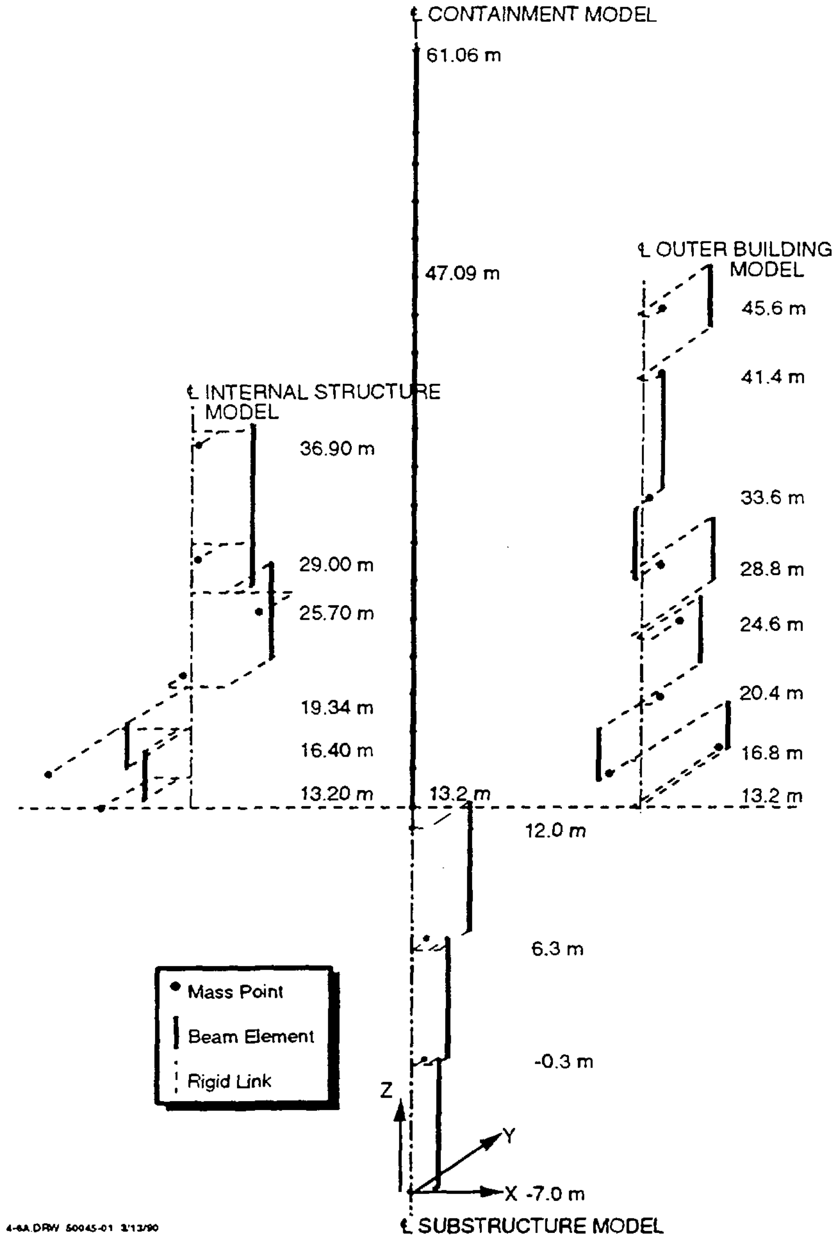

Figure 2: Reactor Building Element Model

Table 1: Reactor Building Model Frequencies and Percent of Modal Mass

Mode Number	Frequency (Hz)	Modal Mass (%)			Description
		X	Y	Z	
1	3.91	42.940	2.140	0.001	CB-x
2	3.91	2.145	42.682	0.003	CB-y
3	5.73	33.008	0.004	0.001	OB-x
4	5.80	0.007	35.220	0.004	OB-y
5	6.29	0.744	0.031	0.000	SS-x
6	8.85	0.089	0.008	0.000	IS-x
7	9.58	6.464	0.006	0.002	IS-x
8	9.62	0.011	4.378	0.069	IS-y
9	10.82	0.014	0.057	53.875	CB-z
10	12.01	0.001	6.184	0.133	IS-y
11	12.18	5.008	0.000	0.050	IS-x
12	12.60	0.273	0.003	0.002	IS-x
13	14.65	0.000	0.338	16.608	CB-z
14	14.84	1.328	0.003	0.117	CB-x
15	14.93	0.008	1.057	12.596	CB-z

CB: Containment Building SS: Substructure OB: Outer Building IS: Internal Structure

3. *DESCRIPTION OF FOUNDATION SOILS*

The foundation mat for each of the 1000 MW WWER reactor buildings is a 2.8-m-thick, approximately 74 m by 74 m concrete slab. Belene and Kozloduy reactor buildings are founded on a layered, relatively soft soil and embedded about 7 m below grade. Figure 3 shows the best estimate strain-compatible shear wave velocity profiles for Belene and Kozloduy.

The reactor building at Temelín is founded on rock-like material with a shear wave velocity of approximately 2030 m/sec. Thus, it was determined that there was no need to include the soil effects in the dynamic analysis for this building.

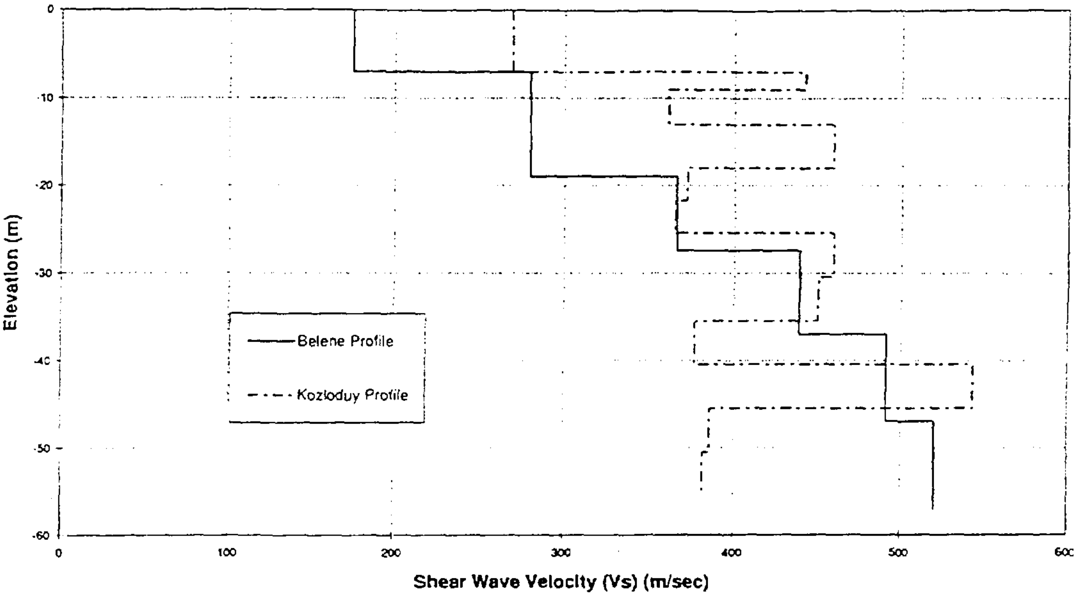

Figure 3: Best Estimate Strain-compatible Shear Wave Velocity Profile

4. DESCRIPTION OF INPUT MOTION

For the three plants, the seismic motions used were consistent with the seismic hazard for the site. Figures 4 and 5 show the horizontal and vertical acceleration response spectra at 5% damping for the three plants. For Belene and Kozioduy, the hazard was dominated by the Vrancea source [1, 2], and the motions were anchored to an equivalent peak ground acceleration of 0.2g. Both seismic motions correspond approximately to a return period of 10^4 years. For Belene and Kozloduy, the specified vertical spectra were defined as half of the horizontal spectra.

The seismicity at the Temelín site was dominated by the local conditions [4]. The intensity and epicentral distances selected for the site resulted in a design peak ground acceleration of less than 0.1g. However, for the Temelín study presented in this paper, the spectra of an actual earthquake considered to be representative for the site [4] anchored to a horizontal maximum peak ground acceleration of 0.1g were used to develop a single artificial earthquake for the analysis. The selected earthquake has its main frequency content coinciding with the main frequencies of the fixed-base reactor building.

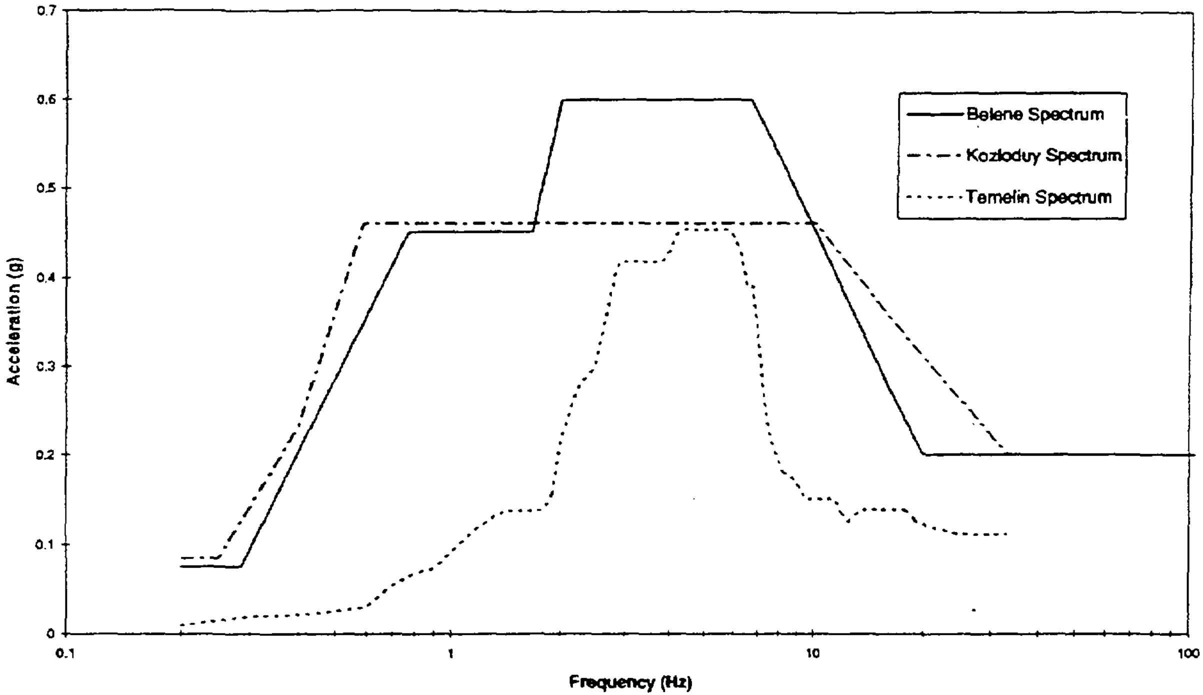

Figure 4: Comparison of Horizontal Input Response Spectra, 5% Damping

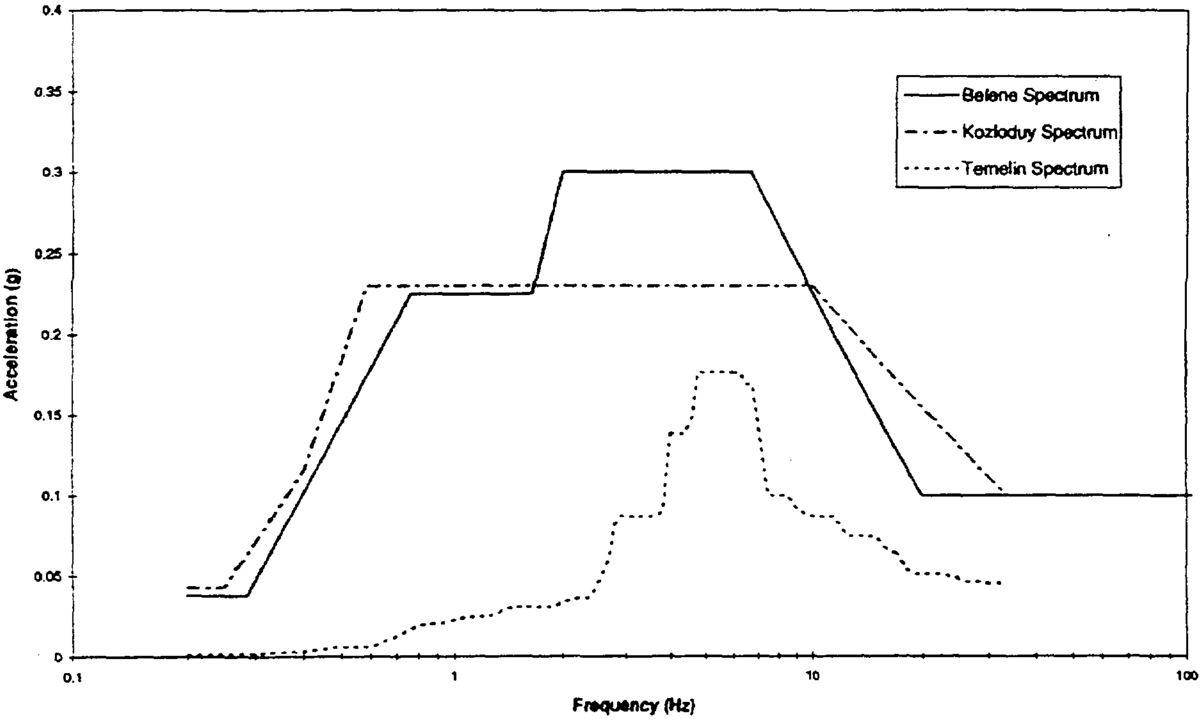

Figure 5: Comparison of Vertical Input Response Spectra, 5% Damping

5. *ANALYSIS*

SSI analyses were performed for Belene and Kozloduy to capture the effects of the foundation soil in the structural responses. For Kozloduy, a series of sensitivity studies were performed to assess the impact that SSI modeling parameters and calculation techniques have in the structural response of these plants.

Since this plant is founded on rock, a fixed-base time-history analysis was performed for Temelín.

5.1 Impedance and Scattering Functions Calculation

To assess the effect that different SSI methods have in the calculation of the impedance and scattering functions, three different codes were used for Kozloduy. The three codes were SASSI (developed by Professor Lysmer at U.C. Berkeley), CLASSI (developed by Professors Wong and Luco at the University of Southern California), and SUPELM (developed by Professor Kausel at MIT). The versions of SASSI and SUPELM used allow for the consideration of the embedment effects. The version of CLASSI used considers only surface-founded conditions.

For the calculation of scattering functions, vertically propagating seismic waves were assumed.

Figures 6 to 8 show the horizontal, vertical, and rocking impedance functions, respectively. Figure 9 shows the horizontal term of the scattering function. For the SASSI and SUPELM cases, it was considered that the foundation was embedded and perfectly bonded to the soil. For the CLASSI case, the foundation was assumed at a free surface at the bottom of the foundation level.

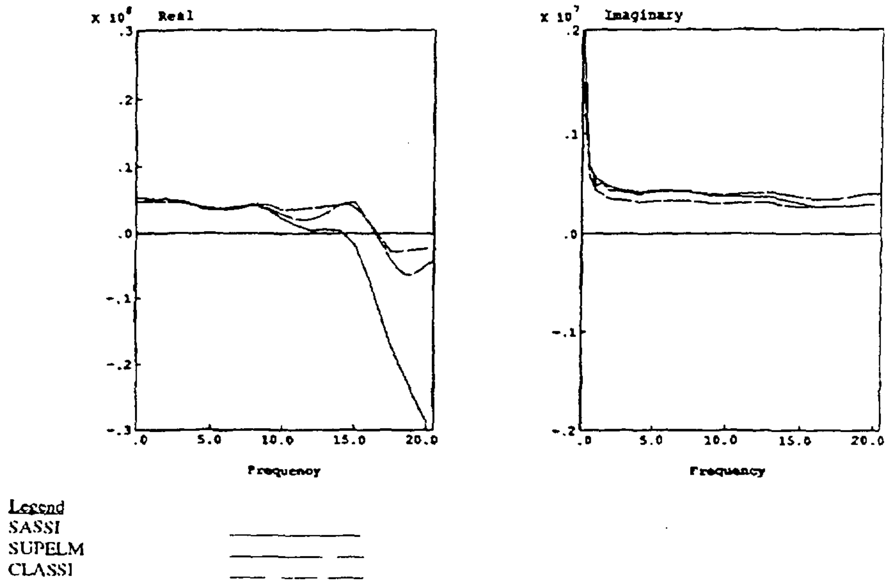

Figure 6: CLASSI/SASSI/SUPELM Comparison Horizontal Impedance

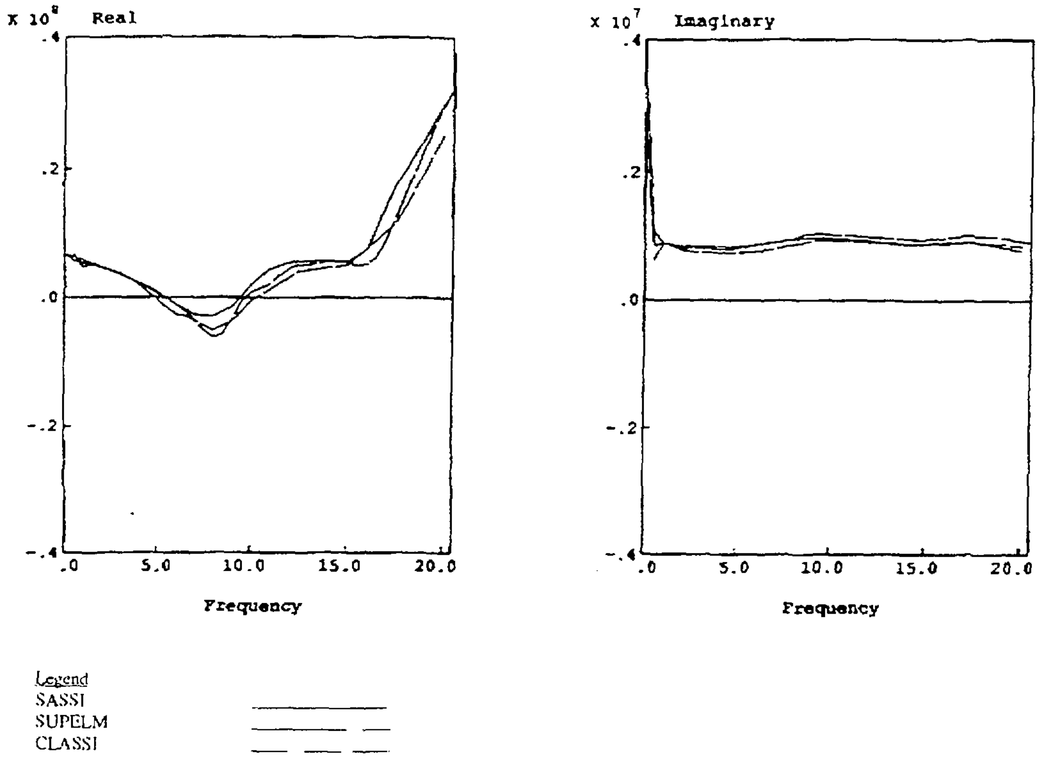

Figure 7: CLASSI/SASSI/SUPELM Comparison Vertical Impedance

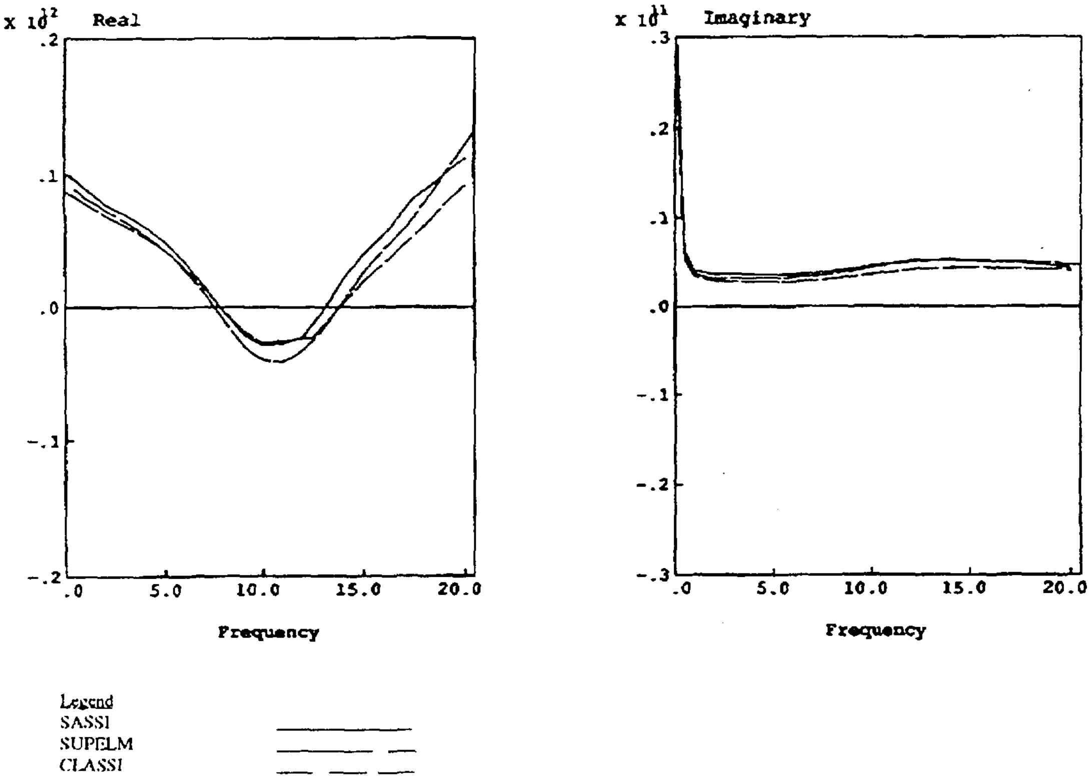

Figure 8: CLASSI/SASSI/SUPELM Comparison Rocking Impedance

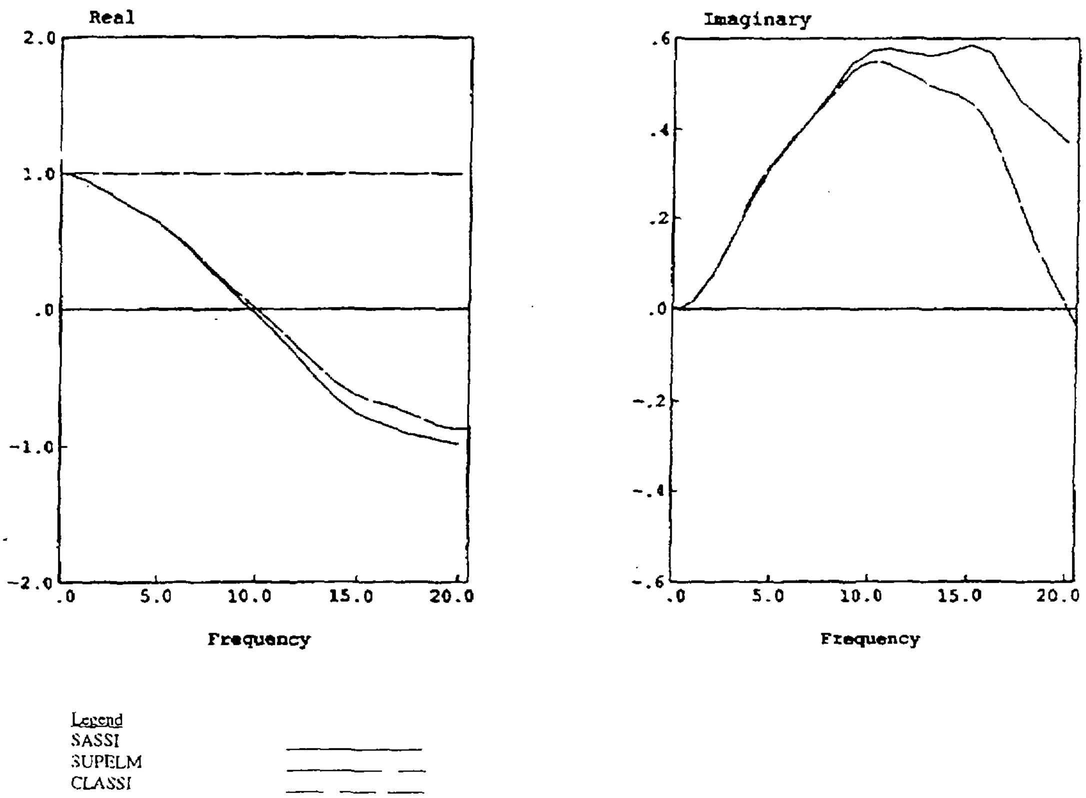

Figure 9: CLASSI/SASSI/SUPELM Comparison Horizontal Scattering

From the impedance figures, it can be concluded that the three programs give similar results in the frequency range of interest. For the horizontal term, SASSI deviates for frequencies beyond those represented by the discretization of the soil layers (about 15 Hz). Also, these figures show that for the calculation of the impedance functions, the effects of embedment are negligible.

From Figure 9, it can be concluded that SASSI and SUPELM give very similar results for the horizontal scattering function. The same is true for all other scattering components. Since it was assumed that the seismic waves propagate vertically, the translational scattering functions calculated by CLASSI are constant and equal to 1.0.

The comparison of the impedance and scattering functions also shows that possible differences between a embedded and surface founded case for Kozloduy will be mainly due to the deconvolution of the motion and not to the stiffening effect of the lateral soil. Due to the similarities between Kozloduy and Belene soils, this is also true for Belene.

5.2 Effects of Building Wall-Soil Bonding

To study the effect that the lateral soil, excavated and then replaced by backfill during construction, can have on the dynamic response of the Belene and Kozloduy reactor buildings, two extreme cases were analyzed for the Kozloduy foundation model. First, the impedance and scattering functions were calculated with program SUPELM considering perfect bonding between the embedded part of the structure and the soil as it is shown in Figure 10. Then, these functions were calculated, also with SUPELM, considering the embedded part of the structure was completely unbonded from the soil as it is shown in Figure 11.

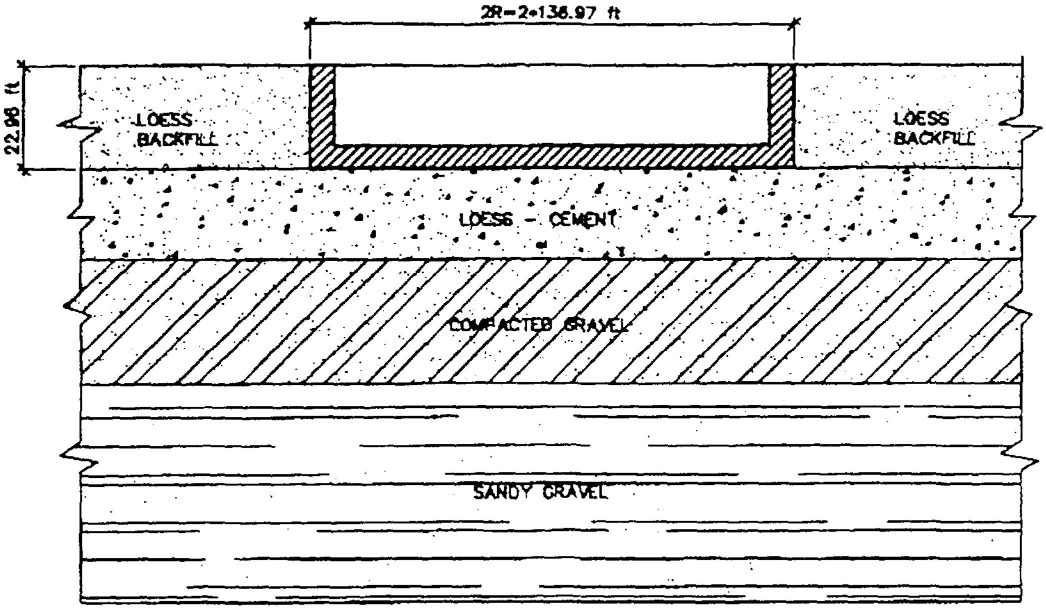

Figure 10: SUPELM Analysis Foundation Model (Bonded Wall)

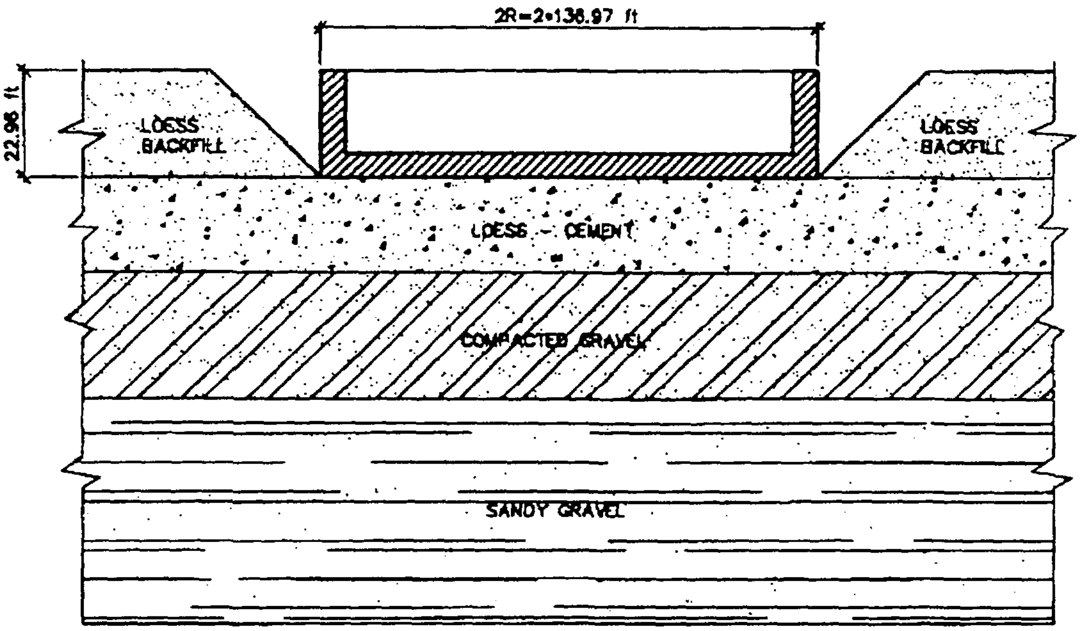

Figure 11: SUPELM Analysis Foundation Model (Unbonded Wall)

Figures 12 to 14 show the horizontal, vertical, and rocking impedance functions, respectively, for the bonded and unbonded cases. Figure 15 shows the horizontal term of the scattering function for these two cases. Some differences exist, but mainly beyond the frequency range of the soil-structure responses. These differences will have only a minor impact in the final dynamic response of the reactor building. Thus, for any practical effect, the SSI analyses for Kozloduy and Belene can be done considering perfect bonding.

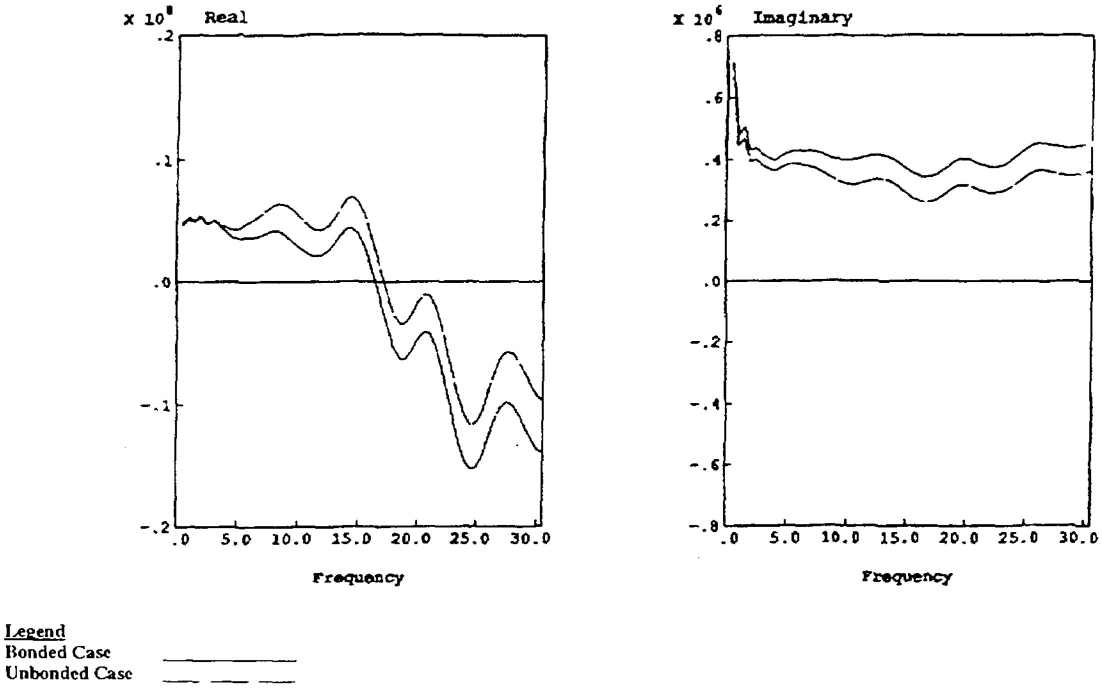

Figure 12: SUPELM Bonded/Unbonded Case Comparison of Horizontal Impedance

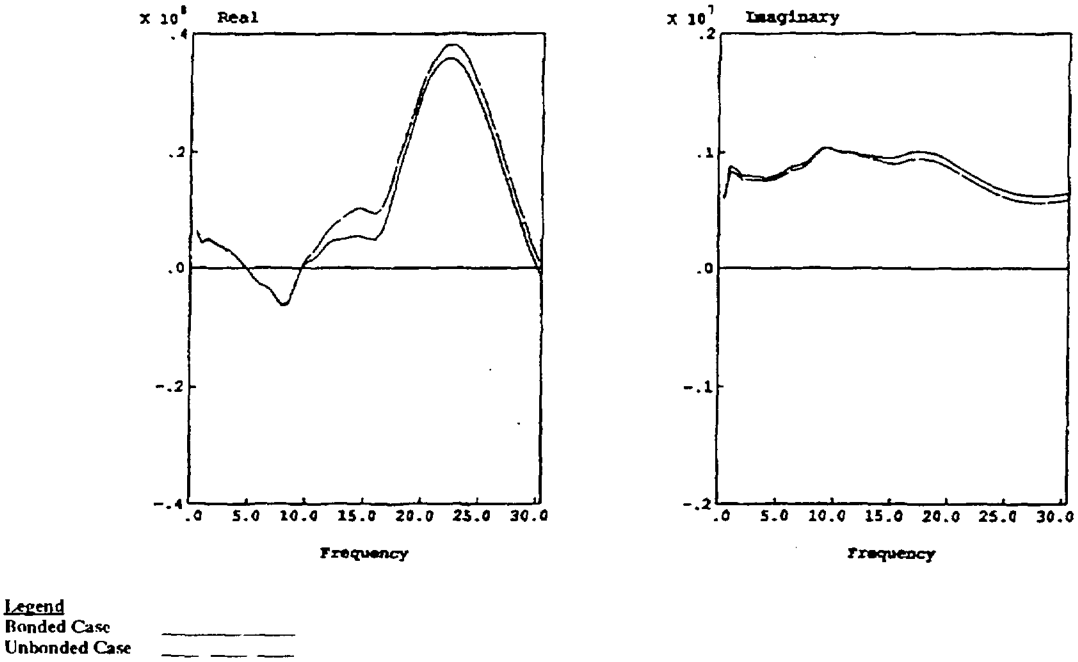

Figure 13: SUPELM Bonded/Unbonded Case Comparison of Vertical Impedance

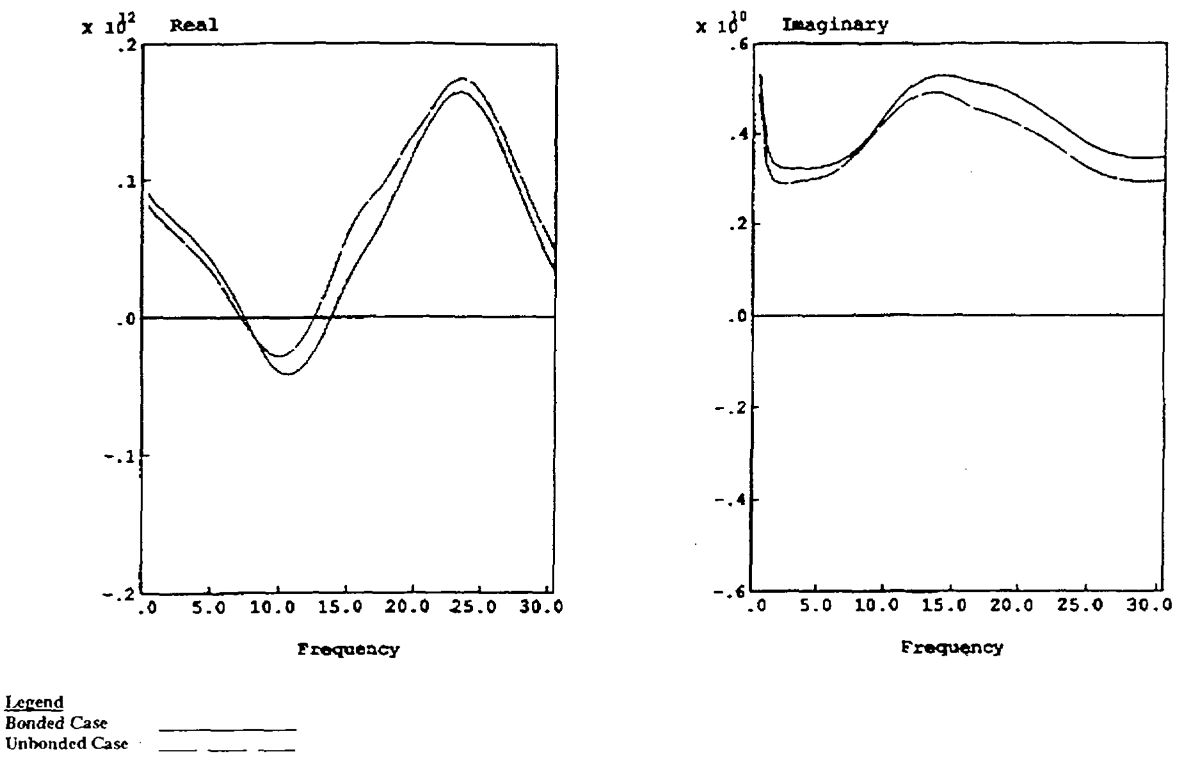

Figure 14: SUPELM Bonded/Unbonded Case Comparison of Rocking Impedance

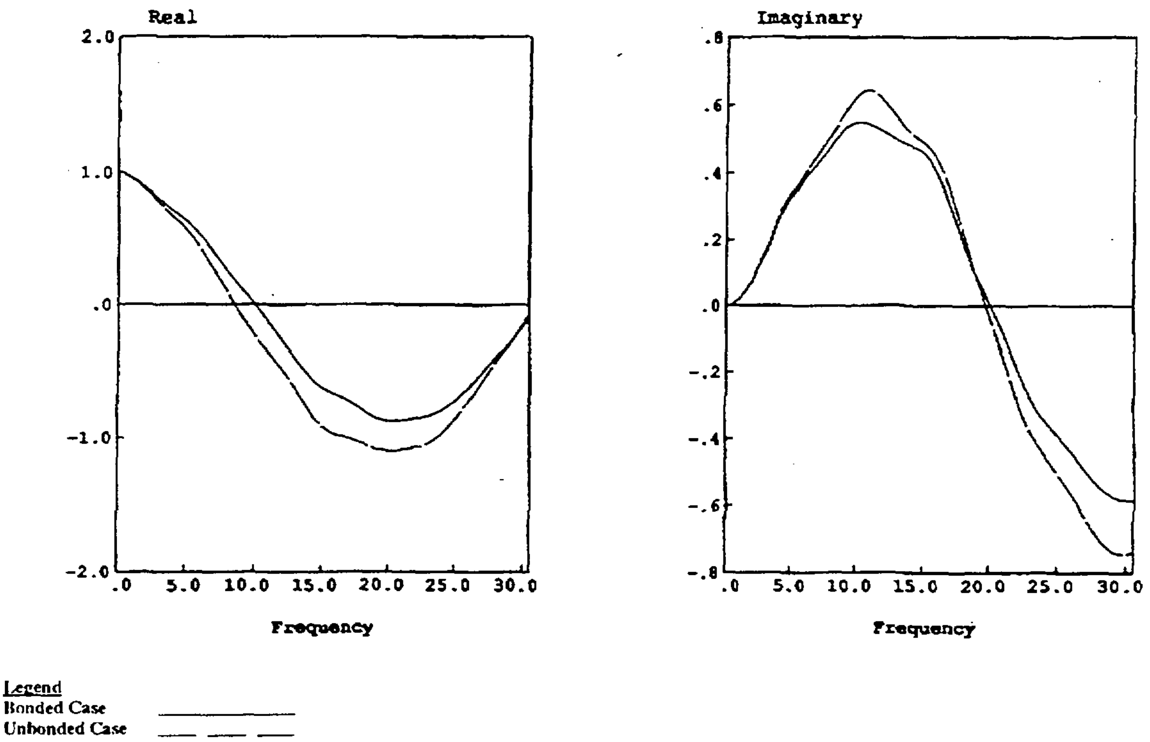

Figure 15: SUPELM Bonded/Unbonded Case Comparison of Horizontal Scattering

5.3 Effects of Embedment

The acceleration in-structure response spectra for Kozloduy were calculated for the embedded, perfectly bonded case (SUPELM) and for the surface-founded case (CLASSI) to quantify the differences in the dynamic responses in the reactor building. Figures 16 to 19 show acceleration in-structure response spectra at 5% damping for selected locations at the containment, internal, outer, and substructure portions of the reactor building, respectively. These figures show that the differences between the embedded and the surface-founded cases are in general of the order of 10% to 15% at some particular frequency ranges. The results for the surface-founded case are, as expected, higher than the results for the embedded case.

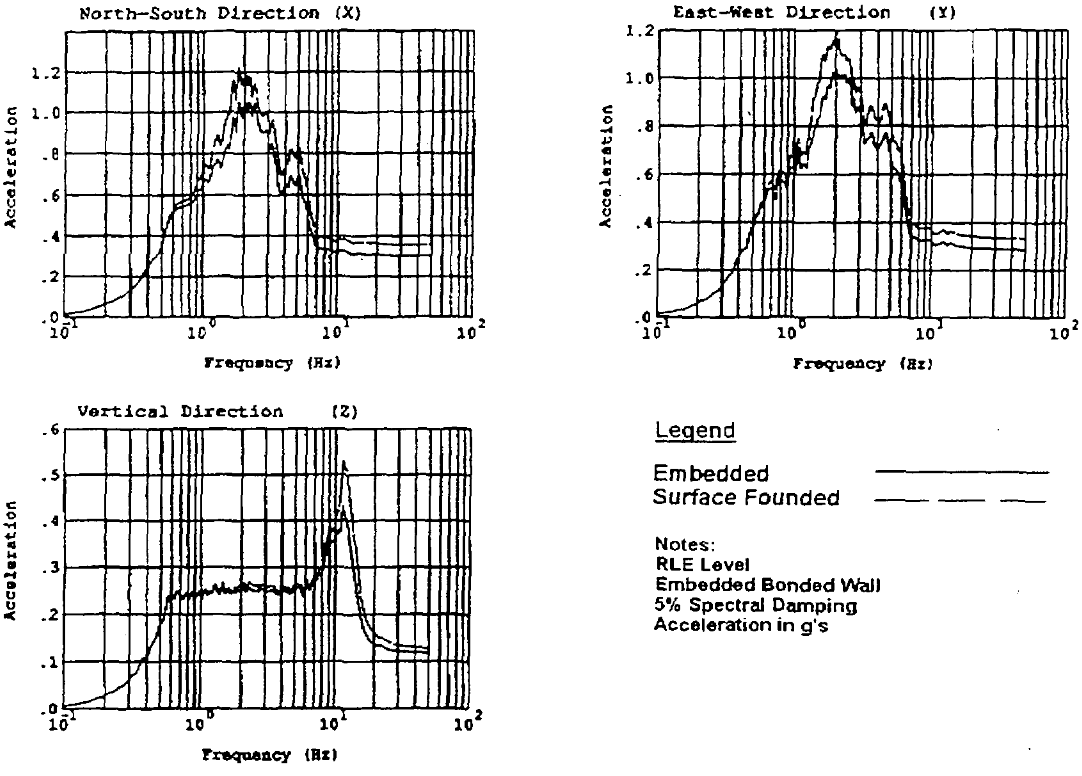

Figure 16: Comparison of Surface Founded to Embedded Structural Model, Top of the Containment Response

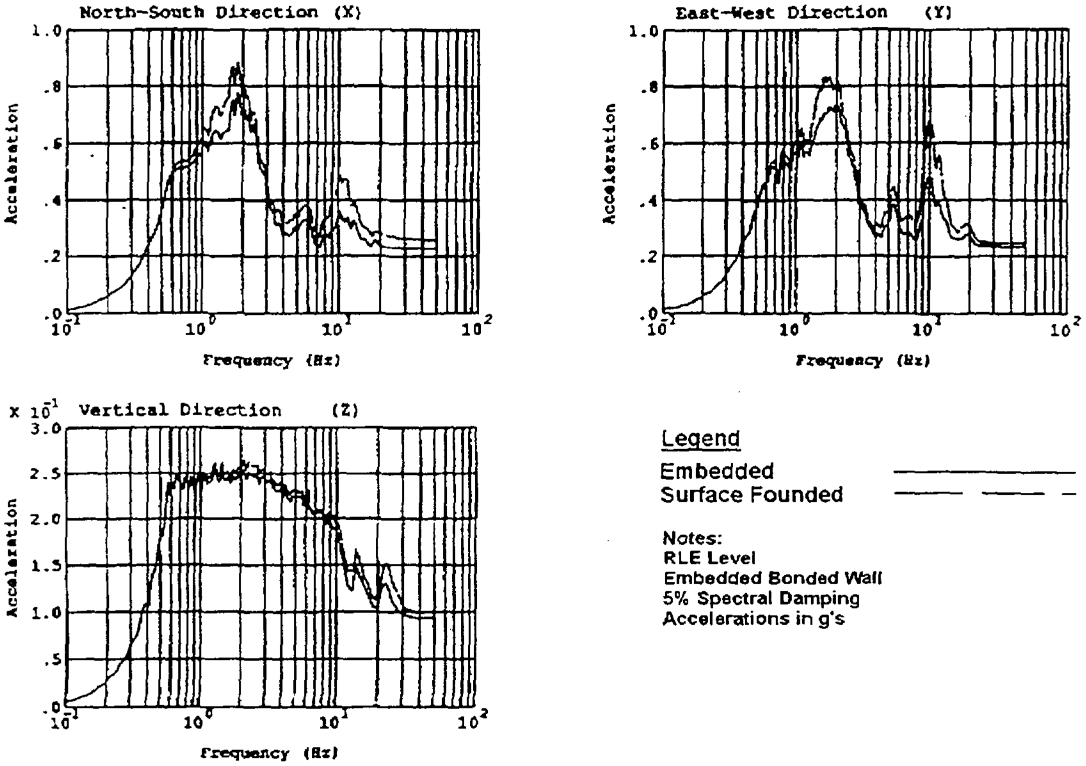

Figure 17: Comparison of Surface Founded to Embedded Structural Model, Top of the Internal Structure Response

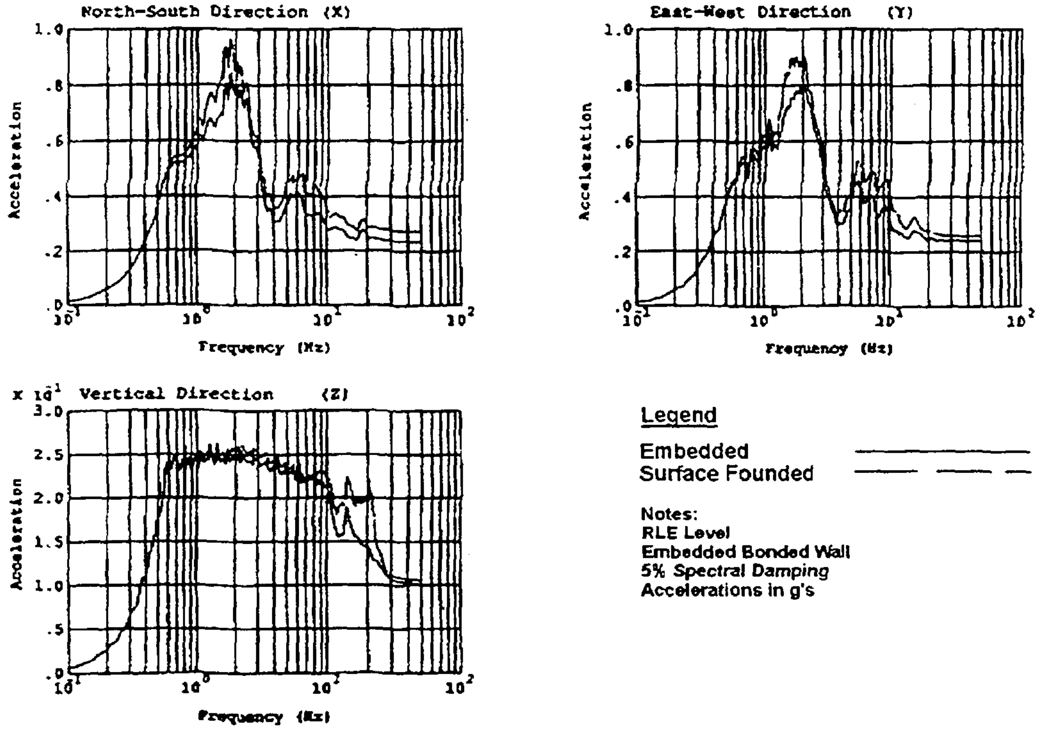

Figure 18: Comparison of Surface Founded to Embedded Structural Model, Top of the Outer Building Response

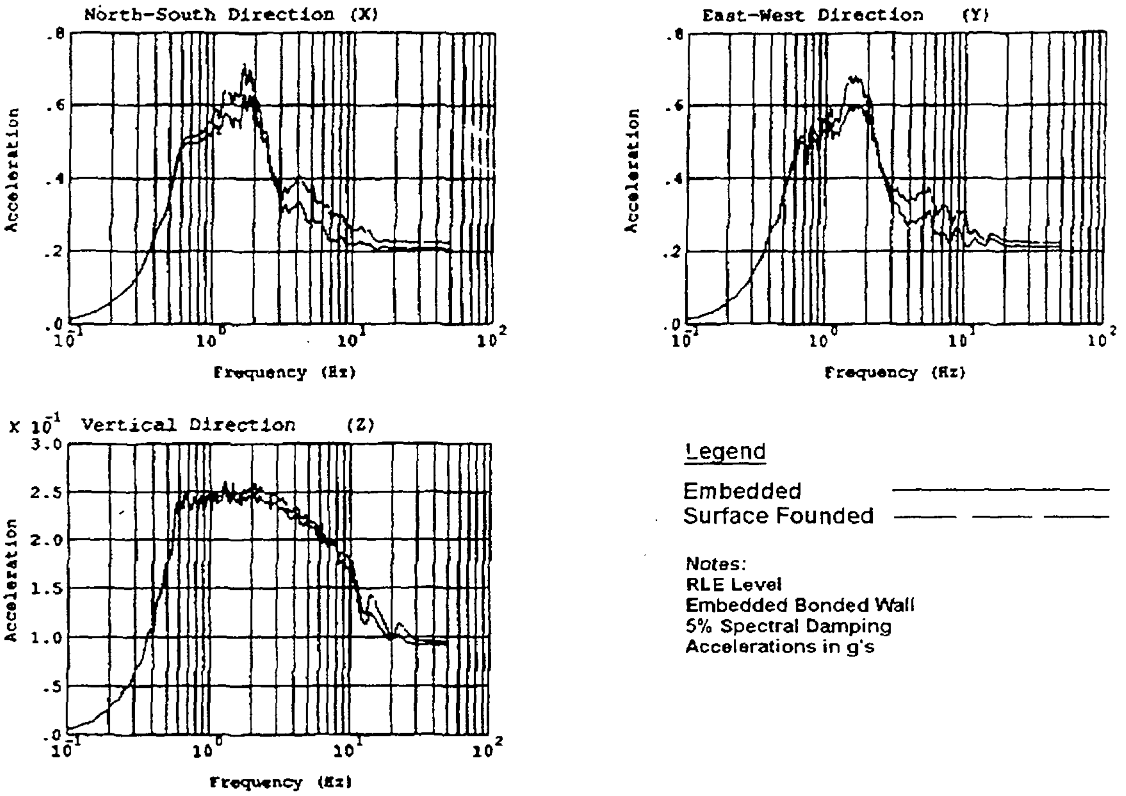

Figure 19: Comparison of Surface Founded to Embedded Structural Model, Top of the Substructure Response

5.4 Effects of Site-specific Conditions

To quantify the effects that site-specific conditions, soil, and seismicity have in the dynamic response of these three "standard" reactor buildings, the results of the dynamic analyses for them were compared. For Belene and Kozloduy, the SSI analyses had been performed assuming embedment and perfect wall-soil bonding. For Temelín, a fixed-base analysis was performed.

Acceleration in-structure response spectra at 2% damping are compared in Figures 20 to 23 for the containment, internal, outer, and substructure portions of the reactor building, respectively.

The in-structure response spectra compared in Figures 20 to 23 correspond to the envelopes of the two horizontal directions at the selected locations. The spectra for Temelín were broadened by 15% to cover structural and analysis uncertainties. Belene's spectra were broadened 25% to also cover soil uncertainties. Kozloduy spectra were broadened by 15% to cover only structural and analysis uncertainties, but three soil cases were considered to cover the soil uncertainties. This difference in the treatment of uncertainties does not prevent a meaningful general comparison between the three sets of results.

The comparison in Figures 20 to 23 shows that the acceleration in-structure response spectra for Belene and Kozloduy are similar. This similarity results from their seismic input in the frequency range of interest being comparable, as well as (on average) from the foundation conditions.

The in-structure response spectra for Temelín are very different from those for Belene and Kozloduy. As expected, the three plants' spectral peaks occur at different frequencies, and even though the seismic hazard at Temelín is lower than the seismic hazard at Belene or Kozloduy, the in-structure response spectra at that plant are much higher than those at Belene or Kozloduy. This difference is mainly due to the dissipation of energy through the soil (radiation damping) for the Belene and Kozloduy reactor buildings, which reduces their structural responses, making them much lower than the Temelín responses.

This large difference in the in-structure response spectra results in a large difference between the seismic demands for the equipment at the Temelín and the Bulgarian 1000-WWER reactor buildings.

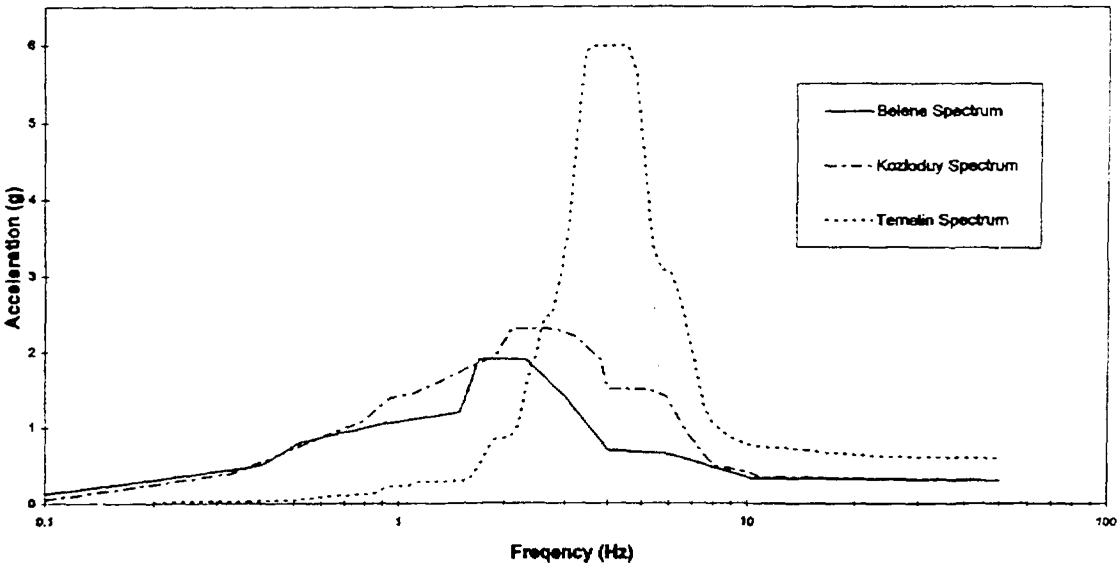

Figure 20: Comparison of Horizontal Floor Spectra; Containment, Elevation 46.8 m

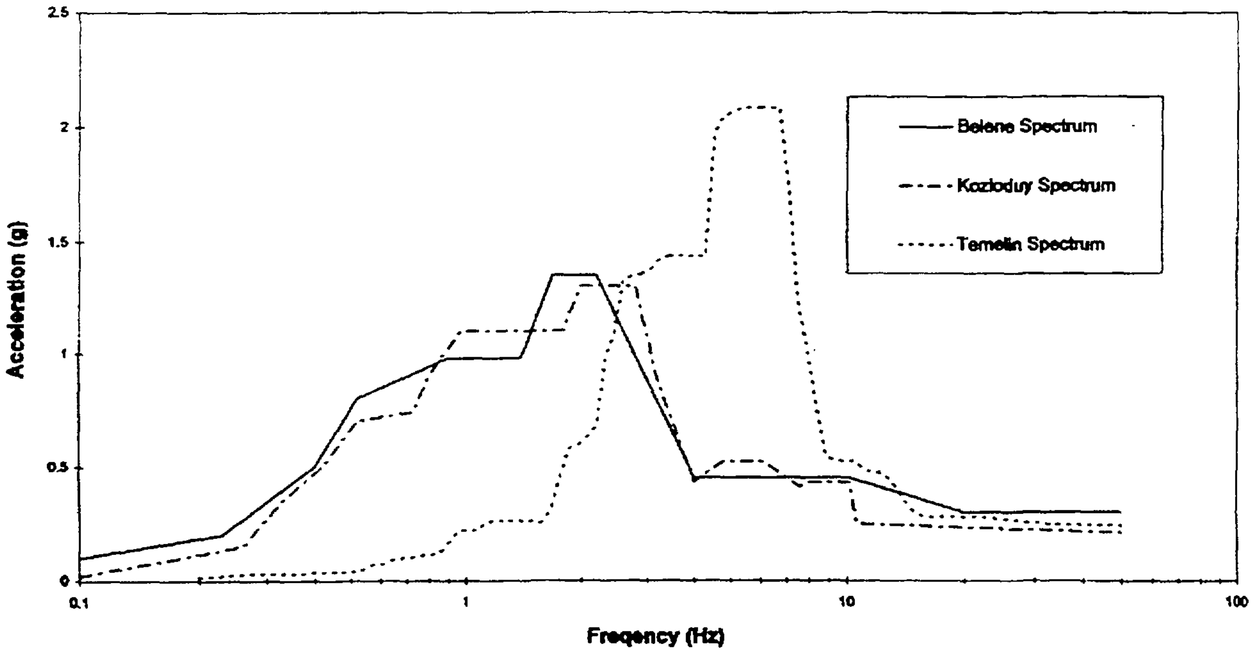

Figure 21: Comparison of Horizontal Floor Spectra; Internal, Elevation 25.7

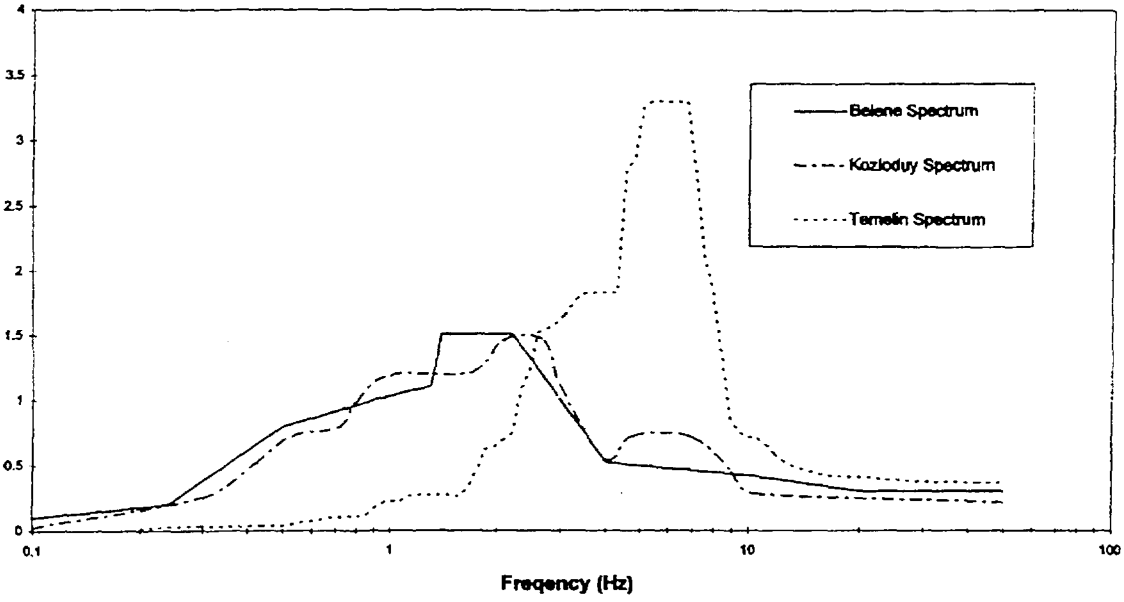

Figure 22: Comparison of Horizontal Floor Spectra; Outer, Elevation 33.6 m

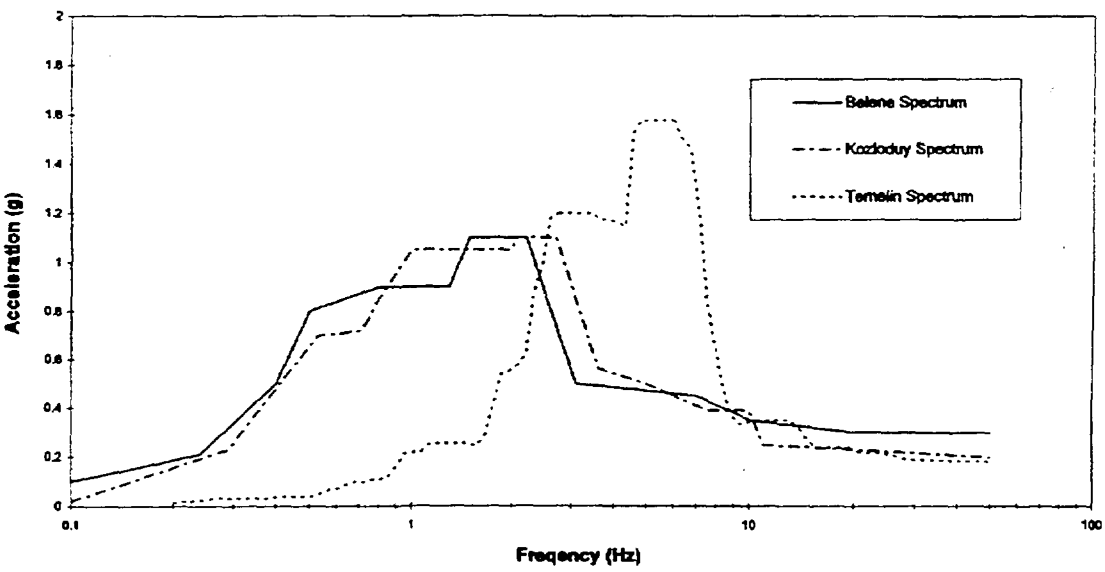

Figure 23: Comparison of Horizontal Floor Spectra; Substructure, Elevation 13.2 m

6. CONCLUSIONS

The results presented in this paper demonstrate the obvious importance of properly considering the site-specific conditions, soil, and input in determining the seismic demand on "standard" plants. For the three studied cases, the effect of the soil and its proper modeling became the most important parameters in determining the structural seismic demands, overcoming the higher seismic hazard at the Belene and Kozloduy plants.

7. *REFERENCES*

1. EQE Engineering/Westinghouse/Geomatrix. March 1990. "Seismic Review of the Belene Construction Project (Units 1 & 2)."

2. EQE International. October 1994. "Structural Response of Kozloduy 1000 MW WWER."

3. Asfura, A. P., J. J. Johnson, and M. J. Jordanov. August 1995. "Dynamic Analysis of Three 1000 MW WWER Reactors in Eastern Europe." 13th SMIRT Conference. Porto Alegre, Brazil.

4. David Consulting, Engineering and Design. "Seismic Hazard Analysis, Ground Response Spectra. NPP Temelín, Probabilistic Safety Assessment for Seismic Events."