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Influence of Soil-Structure Interaction on Floor Response Spectra

C.J. Costantino[1], C.A. Miller[1] and J.R. Curreri[2]
Structural Analysis Division
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973 USA

Other Affiliations:

1 Professor of Civil Engineering, City University of New York
2 Professor of Mechanical and Aerospace Engineering, Polytechnic Institute of New York.

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Abstract

A study was undertaken to investigate the influence of soil-structure interaction on floor response spectra developed in typical nuclear power plant structures. A horizontal earthquake time history, whose spectra envelops the Reg. Guide 1.60 criteria and is scaled to a 1g peak acceleration, was used as input to structural models. Two different structural stick models were used, representing typical BWR and PWR facilities. By varying the structural and soil stiffness parameters, a wide range of system behaviors were investigated. Floor response spectra, required to assess equipment qualification, were of primary interest. It was found from a variation of parameter study that the interaction soil parameters, particularly radiation damping, greatly affect the nature of the calculated responses.

1. Introduction

Nuclear power plant facilities have been successfully operated for over two decades, most of which are either BWR or PWR systems. As can be expected, many of these plants have common structural and system characteristics. Electrical and mechanical equipment in these plants, which were designed at different times and perhaps to different standards, must now be qualified for seismic loadings, using currently acceptable analysis methods and inputs. The purpose of this study was to develop generic floor response spectra which could be used to assist in this requalification process.

Typical structural models were used for both types of systems and these were subjected to the same wide-banded horizontal earthquake criteria input. The primary parameters varied in these system models were the structural and soil stiffness coefficients. Over 1000 floor response spectra were generated and studied in an attempt to develop generic criteria.

2. Structural Models

Two separate structural stick models were used in this study. The first, representative of a BWR-Mark I containment, was composed of 9 mass points on a single stick, as shown in Figure 1a, and is labeled Model 3 in this paper. The lowest fixed base frequency of the actual model was 2.3 cps. The structural fixed base frequencies were then varied by modifying the elastic moduli of the structural elements such that the lowest fixed based frequency assumed the values of 2, 3, 4, 5 and 10 cps. The total mass distribution was kept constant for all runs.

The PWR structural stick model is shown in Figure 1b and is labeled Model 4. The system is modeled as three separate structures on a common rigid foundation mat, representing the outer shield structure, the steel containment and the reactor internals. A total of 25 mass points were used to represent this structure. The same procedure was used to vary the fixed base natural frequencies of the structure. The original stick frequencies were calculated to be in the ratio of 1:5:6, with the outer shield structure having the lowest value, and the internals the highest. The first set of variations kept this ratio constant and varied the elastic moduli of the entire structure such that the lowest fixed base frequency varied from 1.0 to 6.0 cps. A second set of structural variations was then run, changing the frequency ratio of the sticks to 1:2.5:3. Again the elastic moduli of the structural elements was varied to yield fixed base frequencies of from 1.0 to 6.0 cps.

3. <u>Soil-Structure Interaction Model</u>

Soil-structure interaction effects were modeled by considering simple spring-dashpot models of the interaction process. Both horizontal and rocking parameters were included, and these were obtained from steady state solutions for circular foundations on the surface of an elastic halfspace. Although it is well known that these parameters are frequency dependent, for this study it was considered adequate to consider constant values as shown below:

Horizontal Spring Constant: $K_x = (0.9)\,\frac{32\,(1-\mu)}{(7-8\mu)}\,\rho V_s^2\,a$

Horizontal Dashpot Contant: $C_x = (0.57)\,\frac{32\,(1-\mu)}{(7-8\mu)}\,\rho V_s a^2$

Rocking Spring Constant: $K_\theta = (0.8)\,\frac{8}{3\,(1-\mu)}\,\rho V_s^2 a^3$

Rocking Dashpot Constant: $C_\theta = (0.15)\,\frac{8}{3\,(1-\mu)}\,\rho V_s a^4$

In these equations, V is the shear wave velocity ($=\sqrt{G/\rho}$), G is the shear modulus of the soil, ρ is the soil mass density, μ is Poisson's ratio and "a" is the base radius. The coefficients in parentheses in each equation are average values of the frequency dependent coefficients. For the structural models considered in this study, the horizontal and rocking frequencies are approximately equal.

For the variation of parameter runs, the soil shear modulus was varied to yield interaction frequencies which varied from 2 cps (soft soils) to infinite (stiff rock). To develop floor response spectra, four separate damping values must be specified, two associated with the soil-structure interaction process, one with the structural model and one with the equipment system associated with the generation of floor response spectra. The values used in this study are: horizontal interaction damping = 30%, rocking interaction damping = 10%, structural element damping = 5% and spectra damping = 2%. These values are typical for nuclear plant models.

As is well known, the system frequencies (flexible structure and interaction springs) are affected by the coupling between the two. When the structural and soil frequencies are both equal, the system frequency is still lower. When the interaction frequencies are about three times the fixed base structural frequency, the coupled frequencies are essentially unchanged by the soil condition.

4. Input Accelerogram

The process used to generate a ground acceleration time history to match the criteria spectra of Reg. Guide 1.60 is essentially a trial and error procedure. The method begins by choosing an actual measured strong motion accelerogram which has a relatively long duration (say at least 20 seconds) and a relatively wide-banded frequency content. The El Centro record was used to initiate this process. The first step is to calculate the Fourier components of the pulse, calculating each modal magnitude and phase angle from 0 to 60 cps in increments of 0.05 cps. The high frequency content is required to yield adequate numerical results at about 30 cps. Since the measured accelerograms are digitized at 10 to 20 msec intervals (yielding frequency content at less than 15 cps), the enhancement procedure is mainly to add energy at the higher frequency ranges to satisfy the criteria spectra requirements. The enhanced pulse matches the criteria spectra to within 0.15 g's over the frequency range of 0.5 to 30 cps, with over 70% of the spectra values lying above the criteria.

5. Numerical Computations

The structural response of the models was computed using SIM Code (Ref. 1), which determines the dynamic response of the model to a specific time history input. The structure is modeled as a series of lumped masses interconnected by elastic beam elements. Depth of burial effects were not considered for this study. For each stick model, soil conditions were varied from a soft soil to solid rock in seven steps. For Model 3 (BWR single stick model), the fixed frequency was varied from 2 to 10 cps. For Model 4 (PWR multiple stick model), the fixed base frequency range from 2 cps to 36 cps. For each problem, floor response spectra were generated at several different nodes. The complete results of these calculations are presented in Ref. 2. Some of the general response characteristics are presented herein.

The factors which generally affect dynamic response can be summarized as follows: frequency content and magnitude of the input, proximity of a natural frequency to an excitation frequency, modal damping values, model participation factors, and duration of the excitation input. Where the choice of a modal damping value is independent of the stiffness parameters, each of these factors is well understood and can be considered separately. But in the situation involving soil-structure interaction, the situation is somewhat different. Stiffening the soil springs to raise the interaction frequency changes the degree of the participation of the soil damping relative to the structural damping. When modal damping changes in this manner, it is possible, for example, to stiffen the system to avoid a resonance but, by so doing, to increase the peak response. This could happen if the decrease in response that is expected is more than offset by a decrease in modal damping. The net effect of this detuning could be an increase in response rather than the anticipated decrease. The interdependence of the modal damping and soil stiffness makes it sometimes difficult to predict peak response changes.

6. Typical Response Spectra

The large difference between structure and soil damping creates a system wherein the modal damping can vary between the two. Rigid body modes, which emphasize soil properties are highly damped, tending to lower peak responses. On the other hand, structural modes associated with lighter damping can have higher computed responses. Figure 2 presents the computed response spectra at the top of the structure (node 9 of Model 3) for the case of a 2 cps structural model. Seven curves are shown, one for each interaction frequency, varying from 2 cps to infinite. Modal damping values and corresponding coupled frequencies are shown for several of the curves. Large responses are produced in the case where the interaction frequency is high compared to the structural fixed base frequency. By comparing the peak responses for cases ADAA and AEAA of Figure 2 indicates the effects of modal damping on peak amplitudes. Table 1 presents a summary of the peak spectra g's computed at the top of the structure and the frequencies at which they occur for the various problems studied. Table 2 presents a summary for Model 4 of peak spectra responses at the top of each stick element and the frequency at which it occurs.

In general, it was noted that the single stick model (Model 3) for the BWR system had higher spectral accelerations than the multiple model of the PWR. However, the multiple stick model showed a wider frequency range over which the peaks occurred.

7. References

/1/ Miller, C.A. and Costantino, C.J., "Soil-Structure Interaction Methods Summary Report (SIM Code)", BNL/NUREG-51263, NUREG/CR-1717, June 1980.

/2/ Curreri, J., C. Costantino, M. Subudhi and M. Reich, "Seismic and Dynamic Qualification of Safety Related Electrical and Mechanical Equipment in Operating Nuclear Power Plants", September 1983.

NOTICE

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission, Washington, D.C. The views expressed in this paper are those of the authors. The technical contents of this paper have neither been approved nor disapproved by the United States Nuclear Regulatory Commission and Brookhaven National Laboratory.

Table I
Peak G's/Spectra Frequency for Model 3 (Top of BWR Model)

Structural Frequency (cps)

Interaction Frequency (cps)	2	3	4	5	10
2	14.67/1.17	13.13/1.29	12.86/1.34	12.58/1.36	12.05/1.39
3	18.43/1.48	33.12/2.80	50.38/3.53	18.22/2.10	17.43/2.07
10	42.01/1.94	28.50/3.00	54.00/3.94	38.62/4.00	27.01/5.85
20	48.54/1.99	16.29/2.05	17.88/2.10	35.19/4.50	21.01/8.31
30	49.49/5.70	31.10/3.01	58.33/3.94	31.97/4.90	23.84/10.0
50	49.97/5.70	32.70/3.01	59.82/3.94	31.16/5.00	30.82/1.00
INF	50.41/5.70	33.64/3.01	60.34/3.94	31.24/5.00	31.74/10.0

Table II
Peak G's/Spectra Frequency for Model 4 (Top of Each PWR Stick)

Case	Node	2 cps	3 cps	5 cps	10 cps	> 10 cps
1,2.5,3	1	15/1.2	18/1.5	25/1.5	23/1.6	23/1.6
	11	27/2.3	30/2.3	44/2.5	42/2.3	42/2.3
	21	13/2.8	16/2.9	17/2.9	22/3.0	22/3.0
1,5,6	1	19/0.9	16/1.0	17/1.0	19/1.0	19/5.0
	11	15/4.0	30/4.0	39/4.1		
	21	9/2.6	10/3.8	15/4	28/6	38/6.0
2,5,6	1	15/1.2	18/1.5	24/1.5		
	11	16/4.0	23/4.0	35/4.0		
	21	7/2.8	9/3.8	15/4.0	28/4.0	38/4.0
2,10,12	1	12/1.2	15/1.8	19/2.0	28/4.0	32/2.0
	11	8/1.4	10/4.0	16/5.8	26/10.0	35/10
	21	5/1.2	9/4.0	10/5.8	11/12.0	17/12.0
3,7.5,9	1	11/1.5	16/2.0	26/2.6		
	11	9/1.5	12/2.2	2/17.0	33/7.0	45/7.0
	21	6/1.5	8/4.0	9/6.0	14/8.0	21/8.0
3,15,18	1	11/1.5	16/2.0	26/2.5		
	11	8/1.5	9/2.0	11/6.0	17/10.0	
	21	5/1.5	7/2.5	9/6.0	9.5/9.0	
4,10,12	1	11/1.5	17/2.0	19/2.5	42/4.0	46/4.5
	11	9/1.5	13/2.0	13/95	25/10.0	35/10.0
	21	6/1.5	8/2.0	8/2.5	13/10.0	17.5/12.(
4,20,24	1	10/1.5	17/2.0	20.2/8	42/3.8	46/4.0
	11	9/1.5	12.5/2.2	12/2.9		
	21	5/1.5	7.7/2.0	7/2.8		
5,12.5,15	1	10/1.5	16/2.2	21/3.5	32/4.5	
	11	9/1.5	14/2.2	13/3.5	18/10.0	29/12.0
	21	6/1.5	9/2.2	7/3.0	9/4.0	10.0/15.0
5,25,30	1	11/1.5	17/2.3	21/4.0	32/4.5	
	11	9.5/1.5	13.5/2.0	12/3.8		
	21	6.5/1.5	8.6/2.2	8/3.8		
6,30,36	1	10/1.5	15/2.5	23/3.5	30/4.5	44/6.0
	11	9/1.5	15/2.5	15/3.5		
	21	6.5/1.5	9/2.5	9.5/4.0		

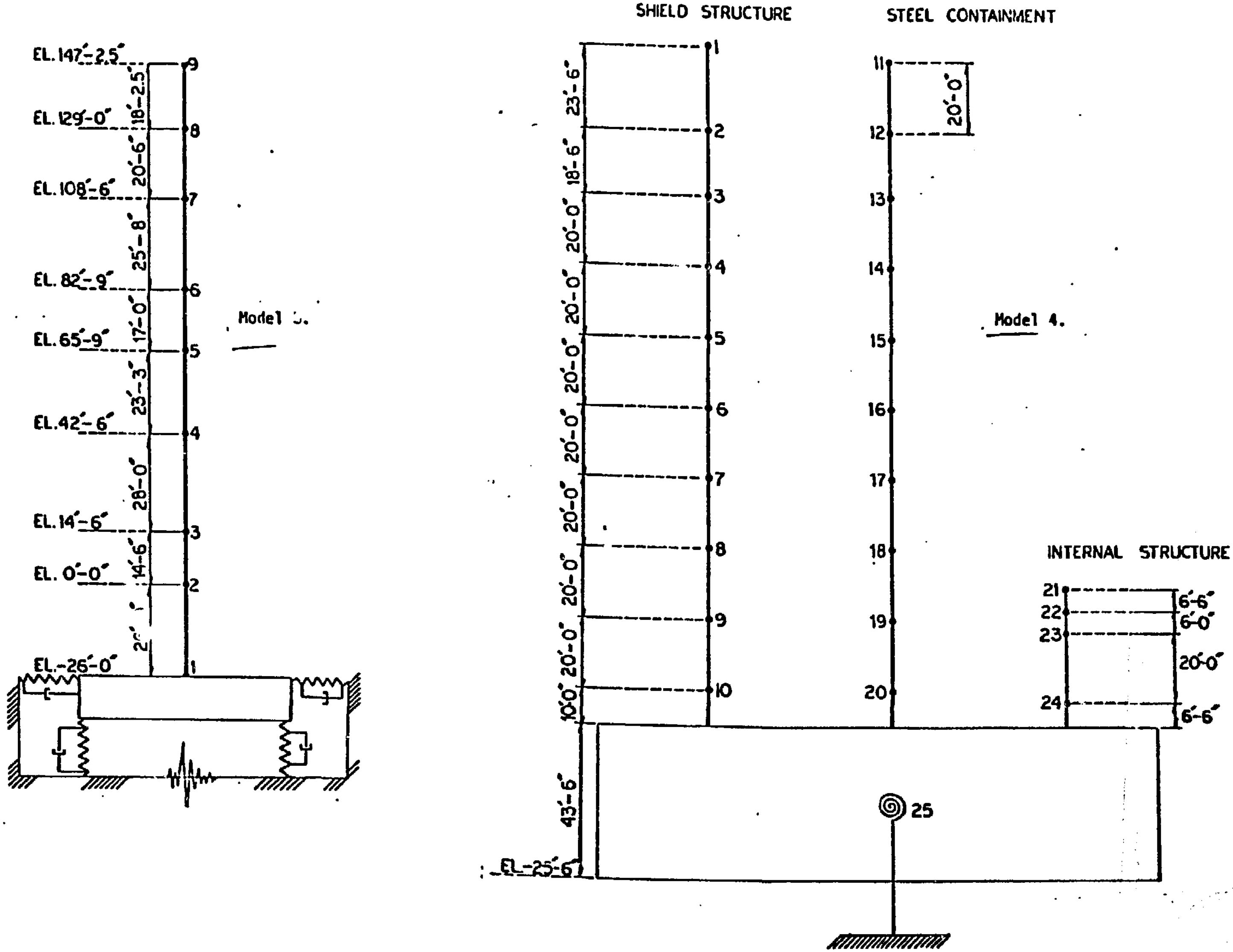

Fig. 1 - Structural RCB Models Considered

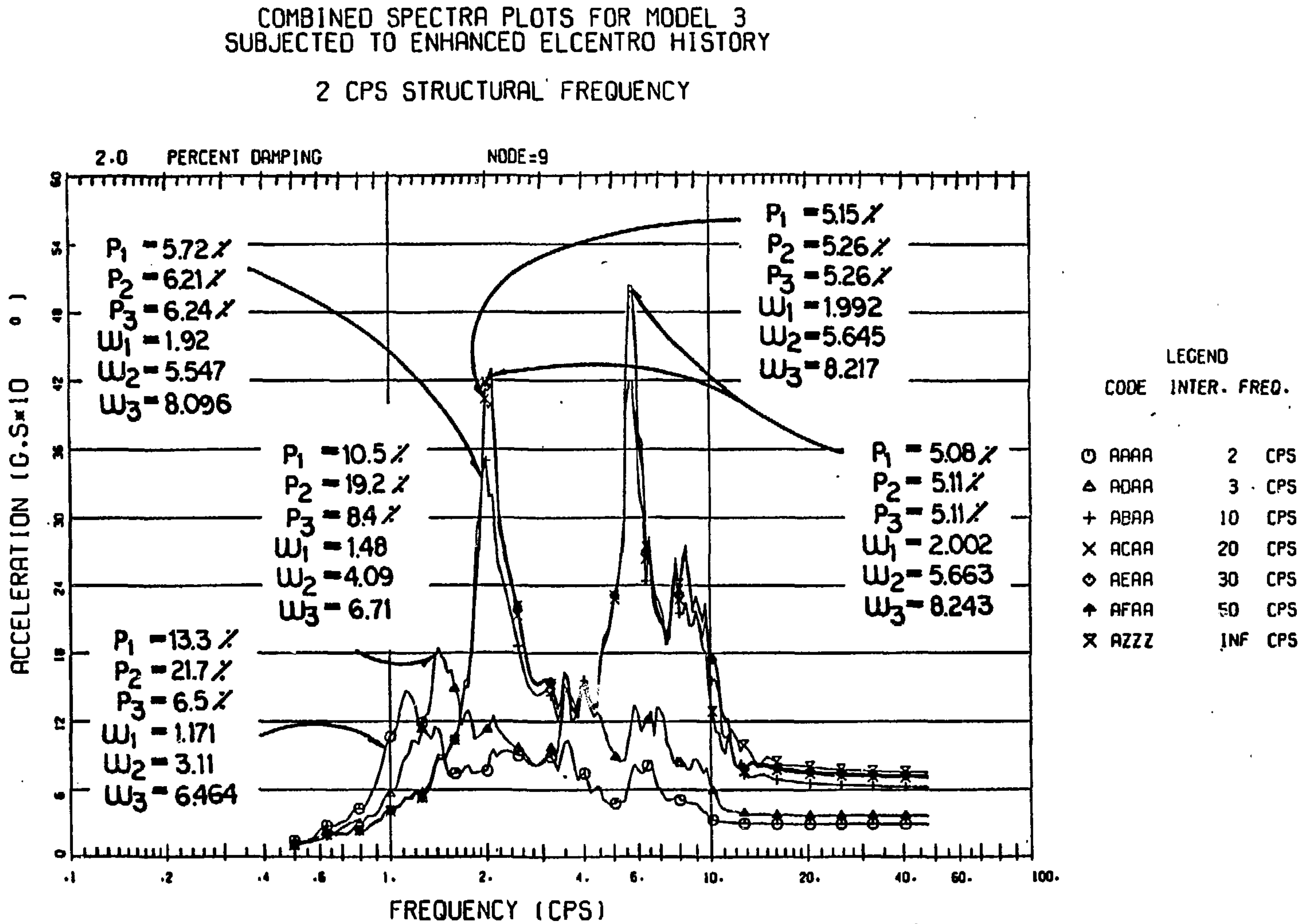

Fig. 2 - Combined Spectra Plot for Model 3 - 2 cps Structural Frequency