Soil-Structure Interaction Analysis of a Boiling Water Reactor

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SUMMARY

This paper summarizes the results of a soil-structure interaction (SSI) study performed on a Boiling Water Reactor (BWR) plant using both finite-element and compliance-spring approaches. A mathematical model of the BWR/6 type nuclear steam supply system housed in a standard reactor island design was used in the SSI study. For the finite-element analysis, the computer program FLUSH was used. The compliance-spring approach utilized the recently developed computer program CLASSI. The intent of the study was to show that if models and assumptions were used consistently in both the finite-element and compliance-spring approaches, each would provide consistent and comparable results. Four different soil conditions, (from soft to hard soil) were considered in this study. The analysis assumptions made were consistent in both methods of analysis and results compared favorably although the finite element method generally resulted in higher response. Observed differences in the results obtained from the two methods have been interpreted in terms of fundamental differences in the analytical approximations used in the two methods.

1.0 INTRODUCTION

Historically, analysis of Soil-Structure Interaction (SSI) at nuclear power plant structures has been performed using either a finite-element method or a compliance-spring method. Each method has its strong proponents and opponents, both in the industry and within the U.S. Nuclear Regulatory Commission (NRC). Neither method has been identified as preferable. Per latest U.S. NRC position (Reference 1), the SSI analysis needs to be performed using both methods and that the method producing the more conservative result be chosen as the design base. At General Electric (GE), the SSI analysis for the BWR/6 standard plant is being performed using the finite-element method. The BWR/6 standard plant is a standardized nuclear island design. It is designed to be built on any site with minimal licensing review. Hence, for the purpose of comparison, a compliance-spring method of analysis also was performed for the BWR/6 standard plant.

This paper summarizes the results of this comparative study of soil-structure interaction analysis methods for the BWR/6 standard plant. The intent of the study was (i) to determine that if models and assumptions were used consistently in both the finite-element and compliance-spring approaches, each would provide consistent and comparable results, and (ii) to show that using the results from the finite-element method in the seismic design of the BWR/6 standard plant produced an acceptable balance for design loads.

The building arrangement for the standard plant is shown in Fig. 1.0. In this paper, the discussion of results will only focus on the reactor building (RB) structure and the reactor pressure vessel (RPV) housed in this building. Four soil cases were considered which are (i) very soft soil case (AV) with a soil depth of 75 feet and a shear wave velocity (Vs) of 1000 ft/sec at the bottom of the RB basemat, (ii) soft soil case (UB) with a soil depth of 150 feet and a Vs of 1350 ft/sec at the bottom of the RB basemat, (iii) hard soil case (VP3) with a soil depth of 75 feet and a Vs of 1900 ft/sec at the bottom of the RB basemat, and (iv) a rock case (HR) with a soil depth of 75 feet and a Vs of 3500 ft/sec at the bottom of the RB basemat. Details of the soil properties used in the analyses are shown in Fig. 3.0. The embeddment depth of the buildings varied from 20 to 40 feet. The control motion used was 0.15 g OBE consistent with U.S. NRC Regulatory Guide 1.60.

2.0 SSI ANALYSIS USING FINITE-ELEMENT METHOD (FEM)

The SSI analysis was performed for all the four cases using a finite-element approach and the computer program FLUSH (Reference 2). FLUSH has transmitting and viscous boundaries to simulate the infiniteness of the lateral boundaries and the three dimensional nature of the soil profile. In addition, FLUSH can also approximately account for the non-linear behavior of the soil by using an equivalent linear approach. The soil-structure model used in the FLUSH analyses, includes mathematical models of the reactor building, fuel and auxiliary buildings and the turbine building in order to account for the structure-to-structure interaction effects. The control motion was applied in the free field at the finished grade to the SSI model and SSI analyses performed using the vertically propogating shear wave theory. From the FLUSH analysis, translational and rotational responses at the base of the buildings which included the SSI effects were generated. These were then used as input to very detailed structural models of the reactor building (Fig. 2) to generate dynamic responses at all critical locations for use in the stress evaluation of structure and equipment.

3.0 SSI ANALYSIS USING COMPLIANCE-SPRING METHOD

In addition to the FEM analysis using FLUSH, these four cases were also analyzed using the computer program CLASSI which is based on a frequency-dependent impedance function approach. CLASSI computes the response of a rigid foundation resting on the surface of an elastic half-space, subjected to ground excitation, considering the effects of soil-structure interaction. The program, originally developed by a joint effort between the University of Southern California at San Diego, (Reference 3) is comprised of two subprograms. The first subprogram computes the impedance matrix of a rigid foundation resting on the soil medium represented as an elastic half-space. The properties of the soil medium, which consist of shear wave velocity, shear modulus, and Poisson's ratio are input to the subprogram. These parameters are used to compute an array of four Green's function parameters at equally spaced steps in the frequency domain. These Green's function parameters are used in computing the frequency dependent soil-foundation impedance matrices. The second subprogram performs the computations that lead directly to the response of the soil-foundation system subjected to seismic waves.

The three-dimensional effects, including rocking, were automatically included in the CLASSI algorithm. The embedment effects were taken into consieration using a frequency-independent approach, in which the embedded soil was modeled using a side layer resting on the same half-space as the structure, as proposed in Reference 4. Torsional effects due to horizontally traveling waves were not included in the analysis. The structure-to-structure interaction effects were automatically included within CLASSI using a frequency-dependent approach. Unit dynamic loads were applied at different points on one foundation to obtain the complex displacements at different points on the other foundation, thus providing frequency-dependent coupling terms. These frequency-dependent coupling terms were used in conjunction with the uncoupled terms for the independent foundation to perform the complete soil-structure interaction analysis. The potential nonlinear behavior of the foundation soil was taken into consideration by using an iterative procedure based on the strain-dependent characteristics of the soil.

The elastic half-space analyses were performed using seismic input motions obtained through a deconvolution process. In the deconvolution analyses, the control motion was defined at the free-surface of a soil column and the seismic input motion was recovered at an elevation corresponding to the foundation embedment depth. This procedure was adopted to ensure consistency with the finite element analyses and to allow an unambiguous comparison of results.

4.0 RESULTS AND DISCUSSIONS

The SSI analyses were performed in order to make a detailed comparison between the results from the compliance-spring and finite-element approaches when both methods use consistent assumptions and inputs and, show that the finite-element method used in the standard plant design provides results that are comparable or conservative as compared to the compliance-spring approach. These results are shown in Tables 1, 2 and 3 which provide comparison of forces and acceleration at a few critical locations and in Figures 4, 5, 6 and 7 which provide comparison of response spectra envelopes at a few critical locations. From an evaluation of these results, the following conclusions can be drawn:

1. The forces from the finite-element analysis, in general, were conservative when compared to the forces from the compliance-spring analysis.

2. The envelope of response spectra obtained from the finite-element analysis also envelopes the response spectra obtained from the compliance-spring analysis at all the different locations of the structures considered, particularly in the frequency range of interest for the seismic design of BWR/6.
3. For the rock soil case (HR), the forces obtained using the finite-element and compliance-spring methods were comparable. This was reasonable because for a hard site, with a high uniform shear wave velocity (V_S) of 3500 fps, soil-structure interaction effects were small. The deformation of the soil was small, resulting in very little compliance between the soil and the basemat using either method.
4. The largest difference between the finite-element method and the compliance-spring method was noticed for the softest soil site (AV). However, the results from the finite-element were generally higher, and thus, more conservative. This may be attributed to:

a. The use of a perfectly rigid basemat in the compliance-spring method which, instead of deforming with the soil profile, rotated as a rigid body, causing a larger rocking at the basemat level.

b. The use of the elastic half-space assumption for the soil layer in the compliance-spring method. This did not account for the radiation of the energy from the bedrock below the defined soil-layer depth back into the soil profile.

c. The use of an approximate method, like the frequency-independent spring, to model the embedment effects in the compliance-spring method. This probably overestimated the rocking at the basemat level due to the restraining effects from embedment being neglected.

d. The use of vertically propogating shear waves in the finite-element method. This probably somewhat underestimated the rotation due to rocking because the vertically propogating shear waves do not excite the rocking mode significantly.

e. The use of viscous boundaries in the finite-element method to model the three-dimensional effect probably underestimated the energy that was being dissipated by the viscous boundaries.

5. The effect of increasing the depth of the soil layer to 150 feet was to reduce the differences between the forces obtained using the finite-element and compliance-spring methods. This was valid because the compliance-spring method assumed the soil was represented by a linear elastic half-space and was more realistic for deeper soil layers.

Based on these results and discussions, it may be concluded that the finite-element soil-structure interaction analysis which was used in the seismic design of the BWR/6, was more conservative, in general, than the soil-structure interaction analysis using the compliance-spring approach, for reasons which can be explained by differences in the fundamental approximations and assumptions underlying each method. Hence, the finite-element method forms a valid and conservative basis for the seismic design of the BWR/6 standard plant.

5.0 REFERENCES

1. U.S. NRC Standard Review Plant, NUREG-0800, Rev. 1, July 1981.
2. J. Lysmer, T. Udaka, C.F. Tsai, and H.B. Seed, FLUSH - A Computer Program for Simplified 3-D Analysis of Soil-Structure Interaction Problems, University of California, Berkeley, November 1975 (EERC 75-30).

3. H.L. Wong and J.E. Luco, The Application of Standard Finite Element Programs in the Analysis of Soil-Structure Interaction, paper presented at the second SAP Users Conference, University of Southern California, Los Angeles, California, June 1977.
4. M. Novak, Vibrations of Embedded Footings, paper presented at the ASCE National Structural Engineering Meeting, San Francisco, California, April 1973.

TABLE 1.0

COMPARISON OF MAXIMUM ACCELERATION RESPONSE (ft/sec^2)

	V_s = 1000 fps AV Case		V_s = 1900 fps VP3 Case		V_s = 3500 fps HR Case		V_s = 1350 fps UB Case	
Node Number (See Figure 2.0)	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**
1	17.9	6.61	18.15	13.89	32.5	21.1	20.4	10.86
18	5.35	3.84	6.65	6.86	10.01	8.47	6.41	5.50
22	13.50	6.24	17.19	11.22	19.7	19.7	31.1	9.18
42	10.20	5.10	12.56	9.73	23.4	15.2	12.9	7.59
46	8.45	3.82	7.57	6.97	14.2	10.10	6.82	5.65
60	5.09	3.92	6.56	6.65	7.50	8.81	7.93	5.59
64	3.71	3.41	5.55	5.55	6.00	6.69	4.59	4.59
71	4.80	4.80	4.80	4.80	4.80	4.80	4.80	4.80
105	11.20	4.86	13.44	8.67	17.60	17.64	19.8	6.93
109	8.70	4.43	10.66	7.78	13.8	14.3	14.9	6.18
119	4.80	3.71	5.85	6.32	7.6	8.59	6.63	5.03

TABLE 2.0

COMPARISON OF SHEAR FORCE (x10^3 Kips)

	V_s = 1000 fps AV Case		V_s = 1900 fps VP3 Case		V_s = 3500 fps HR Case		V_s = 1350 fps UB Case	
Element Number (See Figure 2.0)	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**
41	11.7	6.08	12.3	11.7	21.2	15.9	13.9	9.26
55	12.7	5.47	11.5	10.0	21.7	14.96	10.2	8.05
70	0.95	0.75	1.81	1.32	1.54	1.79	1.39	1.06
73	0.03	0.01	0.033	0.015	0.05	0.03	0.03	0.01
92	0.08	0.03	0.1	0.053	0.12	0.12	0.15	0.04
101	0.27	0.11	0.34	0.23	0.45	0.37	0.38	0.16
126	0.58	0.36	0.73	0.67	0.99	0.99	0.90	0.52

TABLE 3.0

COMPARISON OF MOMENTS (x10^6 ft/lbs)

	V_s = 1000 fps, AV Case		V_s = 1900 fps, VP3 Case		V_s = 3500 fps, HR Case		V_s = 1350 fps, UB Case	
Element Number (See Figure 2.0	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**	**Finite Element**	**Compliance Spring**
41	1525	691	1614	1382	2774	1953	1787	1090
55	1027	420	953	778	1791	1197	897	619
70	59.7	42.1	71.8	75.0	96.4	106	89.7	60.5
73	0.50	0.11	0.61	0.29	0.86	0.51	0.51	0.21
92	0.91	0.32	1.03	0.58	1.32	1.33	1.50	0.45
101	4.70	1.85	6.05	3.69	7.57	7.01	7.66	2.72
126	23.35	12.25	26.54	22.5	37.0	37.1	36.51	17.8

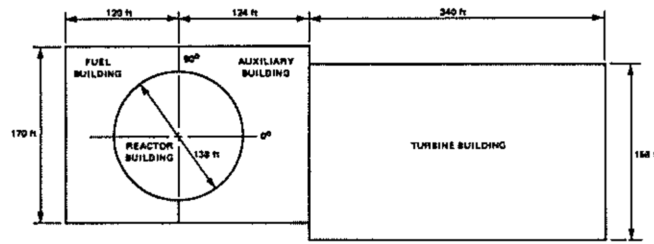

Fig. 1.0: Building Arrangement Plan View

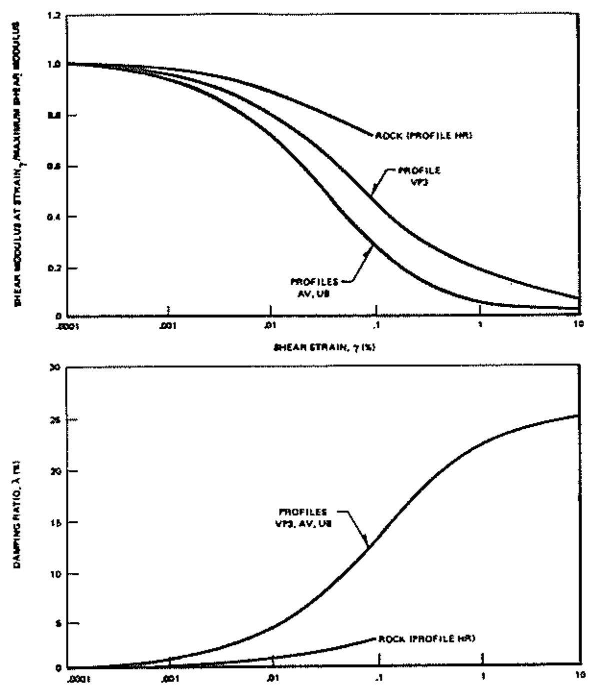

Fig. 3.0: Variation of Soil Properties with Strain

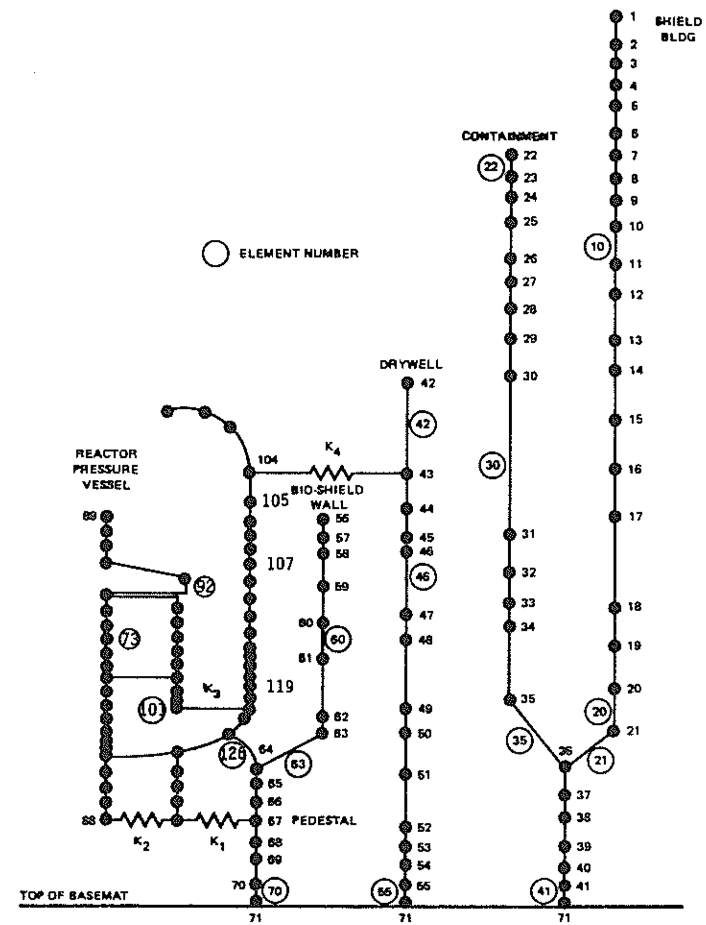

Fig. 2.0: Reactor Building with RPV Model

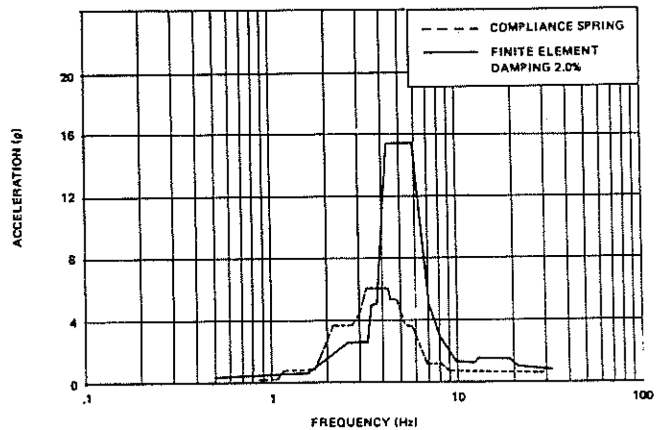

Fig. 4.0: Comparison of Response Spectra at Node 1

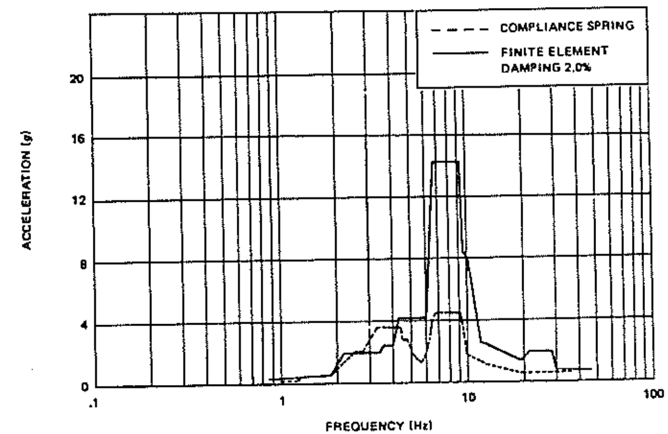

Fig. 5.0: Comparison of Response Spectra at Node 22

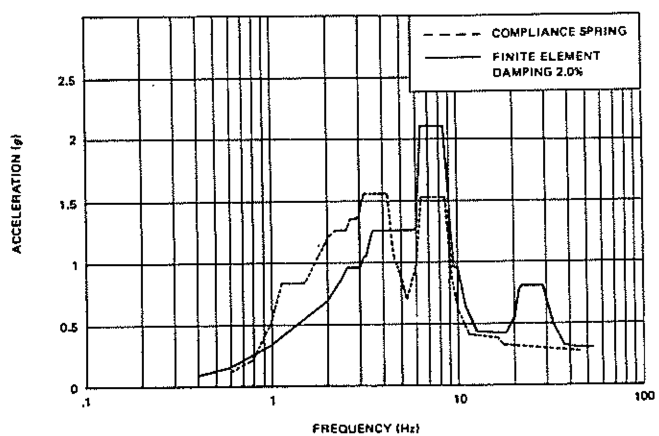

Fig. 7.0: Comparison of Response Spectra at Node 119

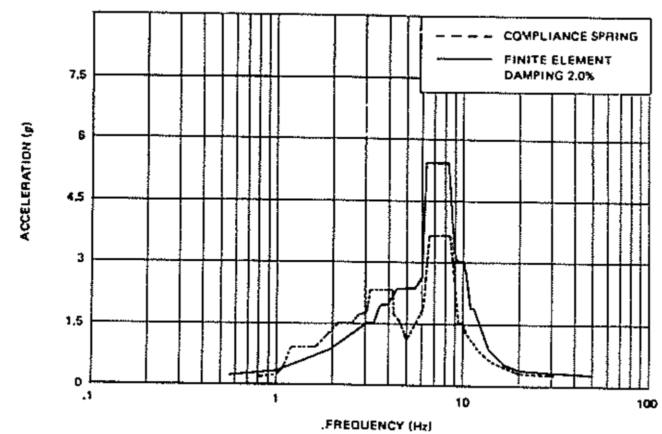

Fig. 6.0: Comparison of Response Spectra at Node 109