UNCERTAINTY IN SOIL-STRUCTURE INTERACTION ANALYSIS OF A NUCLEAR POWER PLANT DUE TO DIFFERENT ANALYTICAL TECHNIQUES*

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SUMMARY

This paper summarizes the results of the dynamic response analysis of the Zion reactor containment building using three different soil-structure interaction (SSI) analytical procedures: the substructure method, CLASSI [1]; the equivalent linear finite element approach, ALUSH [2]; and the nonlinear finite element procedure, DYNA3D [3]. Uncertainties in analyzing a soil-structure system due to SSI analysis procedures were investigated. Responses at selected locations in the structure were compared: peak accelerations and response spectra.

INTRODUCTION

The Seismic Safety Margins Research Program (SSMRP) is an U.S. NRC-funded program conducted by Lawrence Livermore National Laboratory (LLNL). Its goal is to develop a coupled analysis procedure for estimating the risk of an earthquake-induced radioactive release from a commercial nuclear power plant. The analysis procedure is based upon a state-of-the-art evaluation of the current seismic analysis and design process and explicitly accounting for uncertainties inherent in such a process. Uncertainties in each element of the seismic methodology chain were quantified to the extent possible and included in the analysis.

Predicting the seismic response of the structures of a nuclear power plant is subject to uncertainties. One source of modeling uncertainty is due to the SSI analysis procedures used. To quantify one aspect of this uncertainty, we applied two linear analysis techniques, a substructure approach and a finite element approach to the entire Zion Nuclear Power Plant [4]. A second aspect of this uncertainty is presented in this paper, i.e., a comparison of response of the Zion reactor containment building (RCB) as calculated by three SSI analysis procedures.

ZION REACTOR CONTAINMENT STRUCTURE AND SITE CONDITIONS

The Zion RCB is composed of two independent structures--the containment shell and the internal structure (Fig. 1). The shell and the internal structures interact only through the foundation. The foundation was assumed flat

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for our analysis with no additional lateral or vertical resistance due to the sump. The Zion site is characterized by 110 feet of soil overlying a bedrock of Niagara dolomite. The soils are classified into three separate layers. To reduce the number of key parameters in the analysis, the site was simplified to a single equivalent soil layer with pressure dependent soil properties.

SITE MODEL AND STRESS-STRAIN BEHAVIOR OF SOIL

The site was modeled as a set of horizontally layered soils overlying a bedrock halfspace. The computational model consists of 10 to 12 sublayers with layer thicknesses varying from 8 to 10 feet. Each layer was assumed to be a homogeneous isotropic material. The low strain shear modulus of each layer was a function of the effective overburden pressure of each layer. A shear wave velocity of 9000 ft/sec and damping ratio of 2% of the bedrock were taken.

Most soils exhibit highly nonlinear stress-strain characteristics during a cyclic loading. Recently, a number of papers has shown that multiple-yield surface plasticity theories have good potential for accurately characterizing the behavior of soils subjected to cyclic loading. We used Prevost/Hughes pressure independent theory [5] in the nonlinear aspect of this study. In the computer program DYNA3D, we implemented a stress-point algorithm for the theory. A viscoelastic soil model was used for the ALUSH and CLASSI analyses. The strain-dependent equivalent linear shear modulus and damping ratios were derived from the hyperbolic nonlinear stress-strain relationships and the soil characteristics of the site. In addition, the shear modulus and damping ratios used for the ALUSH and CLASSI analyses were computed by equivalent linear techniques. As shown in Fig. 2, these properties are compatible with the shear strain of the soils subjected to the free-field input motion.

FREE-FIELD MOTIONS

A synthetic earthquake motion with peak ground acceleration of 0.3 g and a duration of 10 seconds was specified as input motion at the bedrock within the soil profile. This motion was propagated through the soil column using both the nonlinear and equivalent linear soil models. The input motion at the bedrock and the calculated motions at the surface, based on the assumption of vertically propagating shear waves are shown in Fig. 3. Note, the surface motion calculated by nonlinear techniques exhibits more high frequency content than those calculated by equivalent linear soil models for the frequencies above 7 Hz.

DYNA3D ANALYSIS

DYNA3D is a vectorized explicit 3-D finite element computer program for analyzing the dynamic response of inelastic solids. This program was modified to include the Prevost model for nonlinear soil behavior. The model of the soil-structure system which consists of 3360 solid elements and 4465 nodes is shown in Fig. 4. The reactor containment shell was modeled by 864 3-D solid elements with 1362 nodes. To improve the stability limit, the thickness of the shell was increased threefold while its density and modulus were compensated to preserve the fundamental horizontal frequency of 4.2 Hz. The dominant frequency of the internal structure including the NSSS was simulated by a solid shear cylinder. The concrete was modeled by a visco-elastic standard solid with damping varying from 1 to 3%. Uniform low-strain soil properties were assumed for the elements in the same layer. Ten multiple-yield surfaces modeled the nonlinear behavior of soil for each element. Horizontal input motion was uniformly applied to each node of the bedrock. In addition, free-field motion was applied to the lateral boundaries as determined by a 1-D nonlinear site response analysis. Agreement on shear-stress time histories of the boundary elements and those of the corresponding soil layers showed that the location of the lateral boundary was adequate for the analysis.

ALUSH ANALYSIS

The computer program ALUSH is an axisymmetric finite element program for analyzing axisymmetric soil-structure systems. Horizontal and vertical control motions can be specified at the rigid base. Because of the non-axisymmetric loading, the displacement vector is expanded into Fourier series in the tangential direction. This method reduces the 3-D problem into a series of 2-D problems. In the case of vertically propagating waves, it is sufficient to consider only the first and second term of the Fourier series. The nonlinear dynamic stress-strain behavior of the soils and the frequency independent nature of the damping characteristics of the soils are taken into account by equivalent linear techniques. The response to the earthquake excitation is first computed in the frequency domain with complex moduli representing the hysteretic material behavior of the structure and soils. The time domain response is then obtained by inverse Fourier transformation.

The soil structure model is shown in Fig. 5. The model consists of 272 elements with 326 node points. The vertical lateral boundary was set at a distance of 404 feet from the center of the shell. Boundary conditions at this boundary were assumed free in the horizontal direction. The adequacy of the boundary location was verified by comparing the motion at each boundary node with the free-field motion of the soil column analysis.

CLASSI ANALYSIS

CLASSI is a set of computer programs for analyzing the effects of SSI on the dynamic response of structures using a substructure approach. This approach solves the SSI problem in three steps: determination of the foundation input motion; determination of the foundation impedances; and analysis of the coupled soil-structure system. The foundation input motion is the response of a massless foundation to the specified free-field motion. The effects of the rigid foundation on the incident wave are taken into account by introducing a wave scattering matrix. Foundation impedances characterize the force-displacement behavior of the foundation soils. Their amplitudes depend on the soil properties, the geometry of the foundation and the frequency of excitation. For a viscoelastic material, the impedance is both complex valued and frequency dependent. For a rigid foundation, the impedance functions are defined by a 6 x 6 matrix. The final step of the CLASSI procedure is performing the SSI analysis. The results of the first two steps are combined with a structural model to solve the equation of the coupled soil-structure system. Structural response is calculated from the resulting motion of the foundation including SSI effects, using the modal coordinates. All calculations are performed in frequency domain. Time domain solutions are obtained by inverse Fourier transformation.

The same structural model used for DYNA3D was also used for the CLASSI analysis. Two fixed-base modal analyses were performed separately for the containment shell and internal structure. The analysis includes 30 modes. Figure 6 shows two representative impedances (horizontal and rocking terms) for the rigid cylindrical foundation of the Zion RCB structure embedded to a depth of 36 feet. The vertical and coupling terms of the impedance matrix were also computed but not shown here. The left part of the figure represents the stiffness of the soil-foundation system while the right half represents radiation and material damping.

DISCUSSION OF RESULTS

Uncertainty in SSI analysis is due to two elements: specification of the free-field motion and idealization of the soil-structure system. Different analysis techniques may require the control motion to be put at different control points. The definition of control motion also depends on the assumed soil configuration, soil material behavior, and the wave content. The idealization of the soil-structure system includes idealizing the foundation soil system, dynamic stress-strain characteristics of the soil, modeling of the structure and foundation. Each SSI technique has different assumptions and limitations for modeling soil-structure systems. Uncertainties exist in each part of any SSI analysis. In addition, the method of computing structure response may also contribute to response uncertainty.

For the purpose of this study, the control motion was specified at the rigid base in ALUSH and DYNA3D and, assuming vertically propagating waves and the appropriate linear or nonlinear soil behavior, calculated throughout the soil column. The control motion used in CLASSI was specified at the surface. The scattering matrix calculated with CLASSI related free-field surface motions to foundation input motions. Hence, two possible motions existed and both were used. The resulting surface motions show substantial differences in the high frequency range (Fig. 3). Both surface motions were used for the CLASSI analysis to investigate their effects on structure response. Figure 7 compares the response for three different locations: at the top of the containment shell, at the center of the operating floor, and at the center of the basemat.

The results of the CLASSI analysis using the control motion computed by the equivalent linear soil model are compared with the responses obtained by the ALUSH and DYNA3D analysis at the same locations. The zero period accelerations at the basemat level are almost identical. The maximum difference at the operating floor is 16% and at the top of the containment is 29%. The dominant frequencies predicted by three techniques are between 2.3 to 2.8 Hz at the top of the containment shell. Predicted dominant frequencies are identical at the basemat level. At the operating floor, the first peak frequencies (2.2 to 2.4 Hz) agree, while the second peak frequencies shifted between 3.9 Hz from the DYNA3D analysis to 4.4 Hz from the CLASSI analysis. The peak spectral accelerations at the top of the containment shell show little difference, and at the basemat show 16% difference. At the operating floor, the maximum difference is 29% in the first peak frequency around

2.3 Hz, while at the second peak frequency the difference is significant. This difference may be due to the contribution of rocking which depends on a number of modeling assumptions such as foundation rigidity and soil bulk stiffness. The CLASSI analysis assumes a rigid foundation, whereas DYNA3D uses a 3-D model, and ALUSH uses an axisymmetric model of the foundation. Both include some flexibility. The bulk soil properties in the CLASSI and ALUSH analyses were proportional to the strain dependent shear modulus, while in DYNA3D, they remained constant at the small strain level. The comparison of vertical response at the edge of the RCB structure is not presented here. However, the differences were found significant.

CONCLUSION

Many factors contribute to the response uncertainty of SSI analysis. Each analysis technique has limitations on modeling soil-structure systems, and different assumptions are made in different techniques. In spite of some inconsistency in modeling the soil-structure systems and specifying the control motion for different techniques, the results presented here for a well defined problem lead to reasonably good agreement between responses in the horizontal direction along the center of the RCB structure with the exception at the 4 Hz spectral peak on the operating floor. The difference there and in the rocking response may be attributable in part to foundation flexibility and a number of other factors. Further study would be necessary to resolve these differences.

The effect of rådiation damping for a shallow soil site overlying a bedrock was not fully taken into account because of the rigid base used in the ALUSH and DYNA3D analyses. However, as the bedrock in this site is very stiff, we would not expect the effect of modeling a rigid base for the ALUSH and DYNA3D analyses to be significant.

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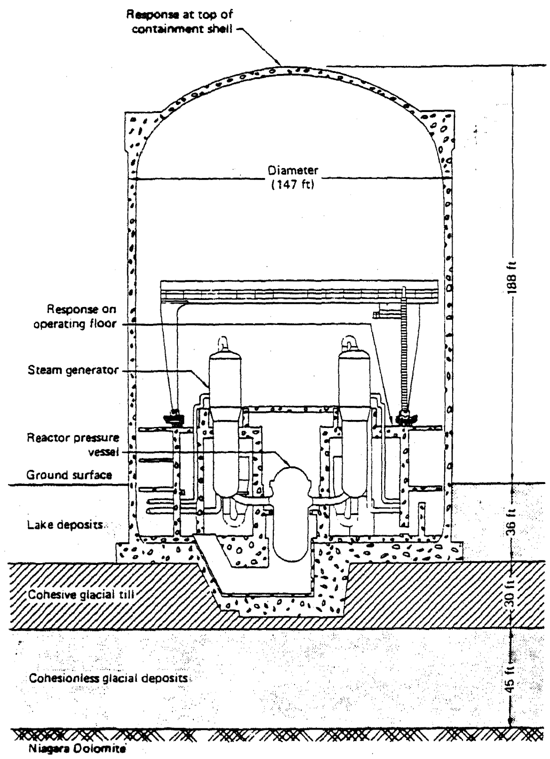

Fig.1 Simplified elevation view of the Zion unit 1 reactor building

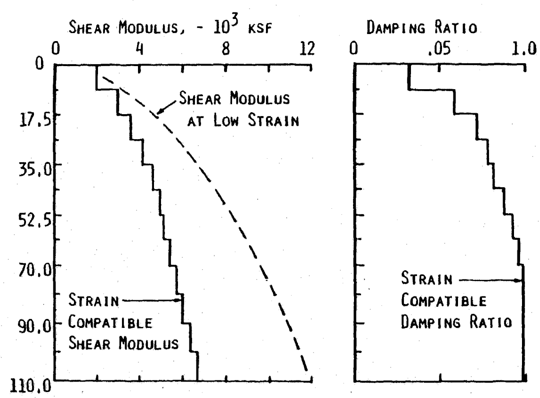

Fig.2 Strain compatible soil properties used for ALUSH and CLASSI analysis

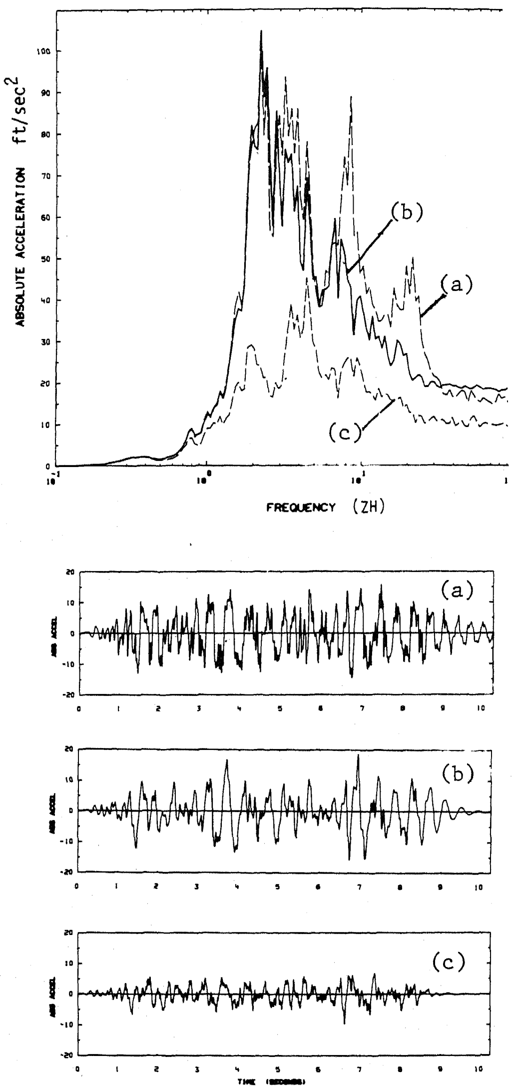

Fig.3 Free field acceleration time histories and response spectra
(a) Surface motion calculated from 1-D nonlinear soil model
(b) Surface motion calculated from equivalent linear soil model
(c) Bedrock input motion

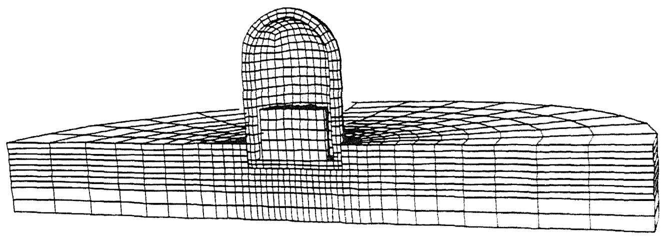

Fig.4 Soil-structure model for DYNA3D analysis

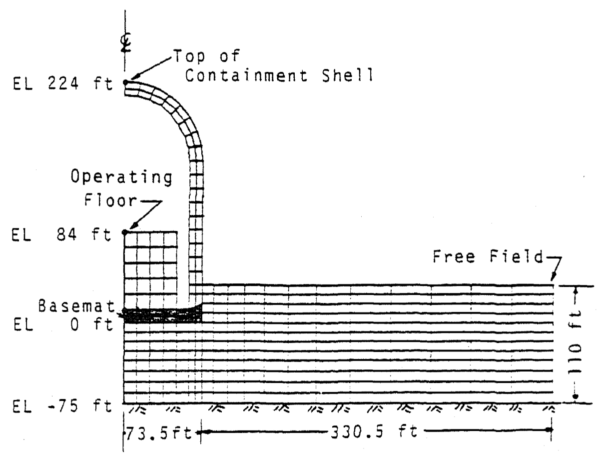

Fig.5 Axisymmetric model for ALUSH analysis

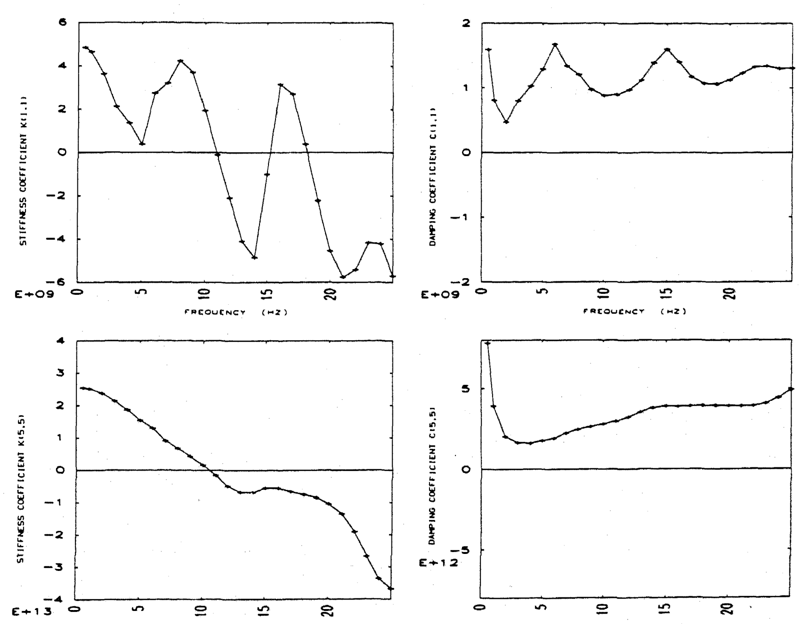

Fig.6 Horizontal and rocking impedance functions for ZION RCB structure

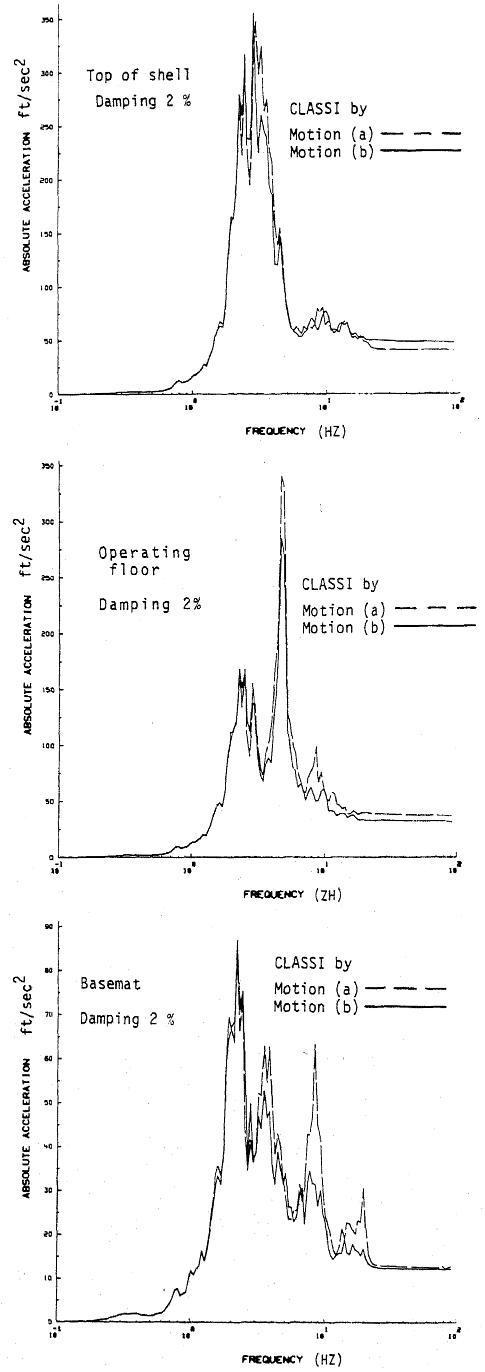

Fig.7 Comparison of response from CLASSI using two different surface motions

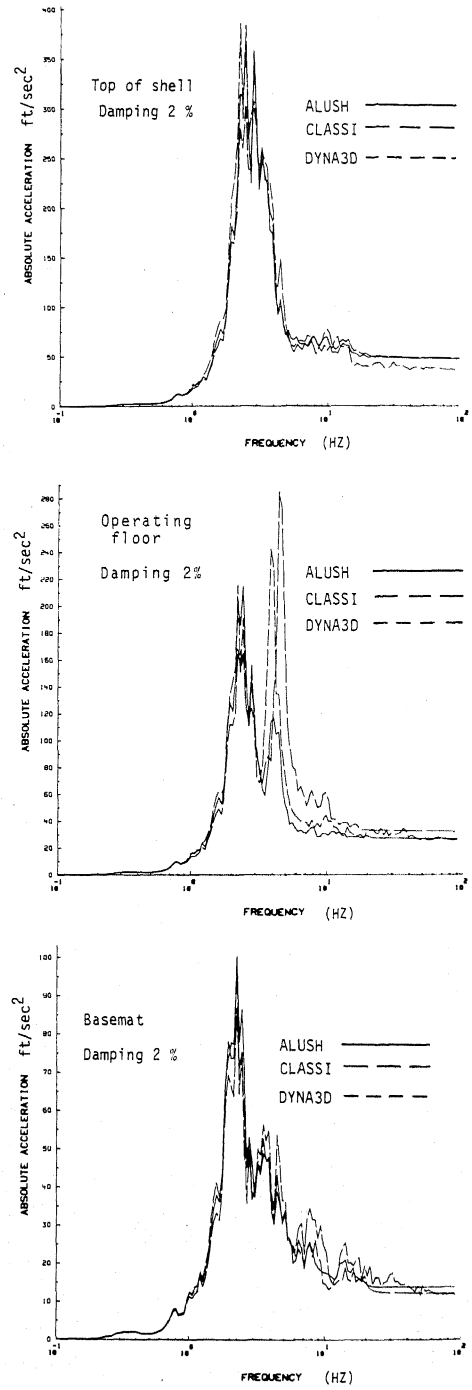

Fig.8 Comparison of response from ALUSH, CLASSI, and DYNA3D analyses