TRULY THREE-DIMENSIONAL SOIL-STRUCTURE INTERACTION ANALYSIS OF THE HUMBOLDT BAY POWER PLANT

by

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Truly three-dimensional soil-structure-interaction analysis of the Humboldt Bay Power Plant

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ABSTRACT: Until recently, available procedures for three-dimensional soil-structure-interaction analyses have been restricted to structures supported on rigid foundations and founded on the surface of a halfspace. In this paper, the general purpose computer program for three-dimensional soil-structure-interaction analysis, known as SASSI is used to compute the structural response of the Humboldt Bay Nuclear Power Plant to the Ferndale earthquake of June 7, 1975. The computed motions are shown to be in good agreement with those recorded inside the plant. Additionally, the computed motions compare favorably with results obtained from a two-dimensional plane-strain finite-element analysis. The effect of foundation rigidity on the response of deeply embedded plants is also addressed in this paper.

1 INTRODUCTION

In the past several years, soil-structure-interaction (SSI) analysis has played an important role in the design of nuclear power plants and will continue to play an important role in the design of future important structures. Although numerous methods have been proposed to perform these analyses, they have been limited to structures with special conditions. Procedures for three-dimensional analysis have been restricted to buildings assumed to be supported on rigid foundations resting at grade on layered sites. While finite-element methods have been used to compute the response of embedded structures, they have been limited to two-dimensional analyses, due to difficulties in modeling the complete soil-structure system within limited computer storage space.

In this paper, a new computer program for three-dimensional soil-structure-interaction analysis is examined. This program, known as SASSI, makes it possible to analyze three-dimensional embedded structures of arbitrary shapes.

To demonstrate the versatility of SASSI and its applicability to practical seismic problems, results are presented of a truly three-dimensional soil-structure-interaction analysis of the knowledge of the motions recorded at the ground surface in the free-field, computations are made to determine the response likely to develop in the building. The computed responses are compared with motions recorded inside the plant during the same earthquake.

To check the validity of widely used two-dimensional plane-strain analyses in predicting the response of deeply embedded structures, the SASSI results are compared with previously published results (Valera, et al., 1977) computed using the 2-D computer program FLUSH.

Finally, the effects of foundation rigidity on the overall response of the building is investigated by repeating the SASSI analysis, but forcing the plant foundation to behave as a rigid body. The results are compared with those described above.

2 METHODOLOGY

The computer program SASSI (Lysmer, et al., 1981) was used to perform the 3-D analysis. This program uses the flexible-volume method presented by (Tajirian 1981) and by (Tabatabaie 1982). This method is a general substructuring procedure which uses the finite-element method. It is substructuring techniques since the solution steps required are simplified. This is due to the manner in which the soil and the structure are partitioned. In this partitioning, the complete soil-structure system, shown in Figure 1, is divided into two substructures; the foundation and the structure. The mass and stiffness of the structure is reduced by the corresponding properties of the volume of soil excavated, but it is retained within the halfspace. Furthermore, the interaction is assumed to occur over a volume, i.e., at all the nodes in the basement. Thus, the impedance problem is greatly simplified and is reduced to a series of axisymmetric solutions of the response of a layered site to point loads (Tajirian 1981). Furthermore, the scattering problem is eliminated.

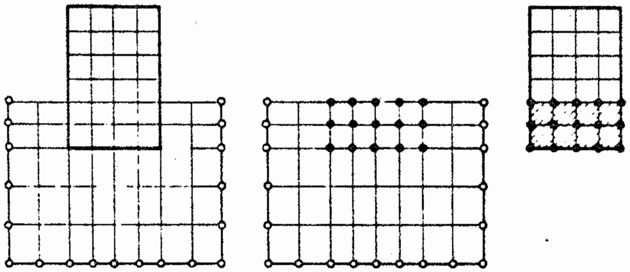
(A) STRUCTURE (B) FOUNDATION (C) STRUCTURE MINUS EXCAVATED SOIL

Figure 1. Substructuring of interaction model

The system is solved in the frequency domain using the complex response method. An efficient interpolation scheme on the complex response functions has been developed for the SASSI program (Tajirian 1981). This significantly reduces the computer time. Material damping is introduced by the use of complex material moduli. These lead to effective soil-damping ratios that are frequency independent and can vary from element to element according to the strains developed.

The site consists of viscoelastic layers on a rigid base or a semi-infinite halfspace. Structure(s) are idealized by standard two- or three-dimensional finite elements. Primary nonlinear effects in the free field and secondary nonlinear effects in a limited region near the strucutre can be considered by "The Equivalent Linear Method" (Seed, et al., 1969).

The dynamic loading can be either a seismic environment consisting of an arbitrary 3-D superposition of inclined body waves and surface waves or external forces such as impact loads, wave and ice forces, or loads from rotating machinery acting directly on the structure. Transient input time-histories are handled by the Fast Fourier Transform technique.

Within the above limitations and that of available computer capacity, the system can handle embedded structures with flexible basements, structure-structure interaction and the effects of torsional ground motions. Recently, special pile elements described by (Ostandan 1983) and methods to make the program more efficient as described by (Vahdani 1983) were incorporated in the SASSI program.

3 THE HUMBOLDT BAY POWER PLANT

A general view of the plant showing the various structures is shown in Figure 2. The facility consists of two fossil fuel units (1 and 2), one nuclear unit (3), and various other structures. The nuclear unit is housed inside the Refueling Building, which is 30m long, 13m wide, and 10.5m high. It is supported on a massive concrete caisson embedded to a depth of 26.5m below the ground surface. This caisson consists of two major structural portions (see Figure 3): a cylindrical portion which is 18m in diameter, and a rectangular portion which is 12 x 23m.

From previous studies by (Valera, et al., 1977) it was found that the effect of adjacent structures on the unit 3 response was minor and could therefore be neglected. Thus, in this study, the response of unit 3 alone is examined.

3.1 Site conditions and seismic criteria

The soil around the refueling building consists of 7.6m of medium-to-stiff clay; underlain successively by about 9m of medium-dense-to-dense sand, 3m of very stiff clay and then a deep bed of dense sand containing some clay lenses extending to a depth of 122m.

The control motion used was the transverse component of the free-field motion recorded at the ground surface (elevation +3.7m). The response spectrum for this motion, which has a maximum acceleration

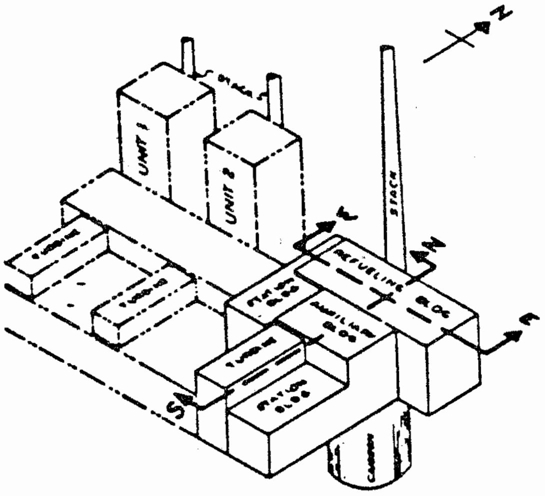

Figure 2. General view of Humboldt Power Plant

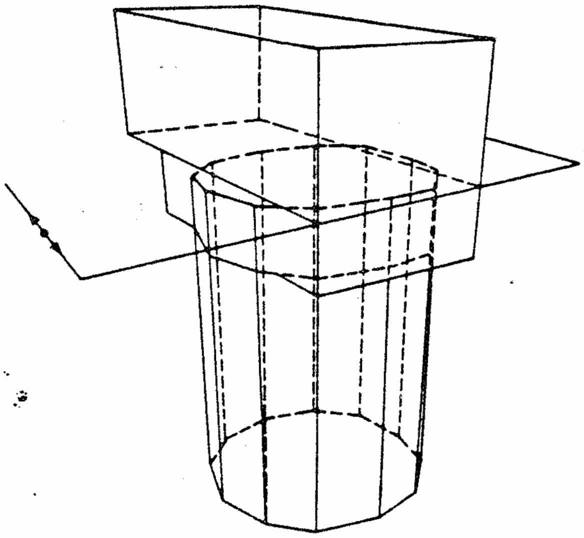

Figure 3. General view of refueling building

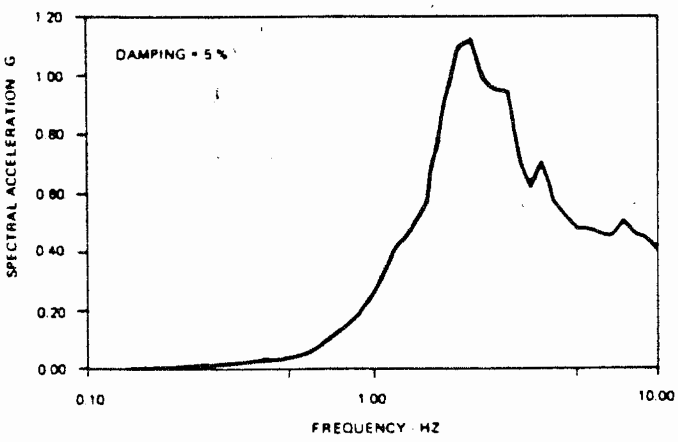

Figure 4. Response spectrum of free

3.2 One-dimensional soil-column study

A one-dimensional column study using the computer program SHAKE (Schnabel, et al., 1972) was performed. The control motion described above was specified at the ground surface, and strain compatible soil properties for the profile were computed to account for primary non-linear effects. The resulting soil shear-wave velocities, damping valves, and maximum accelerations are shown in Figure 5. These iterated properties were used in the SASSI SSI analysis.

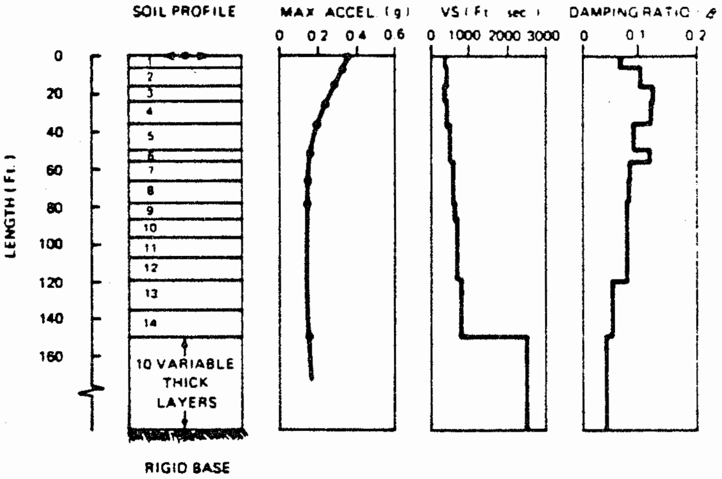

Figure 5. Strain compatible properties from column study

3.3 SASSI model

The 3-D finite element model used in the SASSI analysis is shown in Figure 6. Since the structure and loading are symmetric relative to the one axis, only half the structure needs to be analyzed. The model consists of 384 solid elements and 486 nodes, of which 274 nodes are connected to the ground.

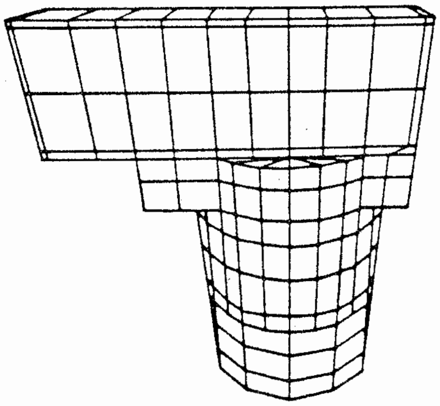

Figure 6. Three-dimensional finite-

4 RESULTS OF ANALYSIS

The results of the 3-D SSI analysis (assuming vertically propagating shear waves) obtained from SASSI are compared with 2-D FLUSH results. The computed responses at the base of the caisson located 26m below the ground surface and, likewise, at the ground surface, are compared with motions recorded at these locations during the earthquake.

Table 1 compares the maximum accelerations at the above locations. The SASSI peak accelerations come within 2% of the recorded peak at ground level and within 6% at the base of the caisson, while the FLUSH results are off by 9% and 26%, respectively.

Table 1. Comparison of recorded and computed maximum accelerations

	Refueling Bldg.(g)	Base of Caisson(g)
Recorded motions	.251	.143
SASSI results	.256	.135
FLUSH results	.228	.106

Comparisons of response spectra are shown in Figures 7 and 8. The largest differences in spectral accelerations occur around 4.0 Hz at the ground level and between 4-7 Hz at the base of the caisson. These discrepancies can be attributed to many factors, such as uncertainties in the building and soil properties, the actual wave field, and the effects of adjacent structures.

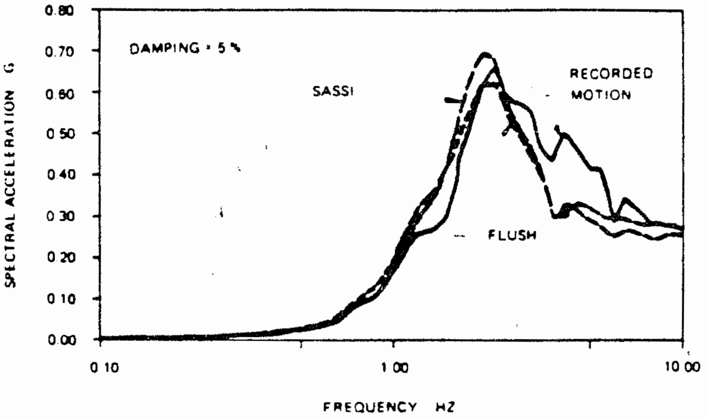

Figure 7. Comparison of spectra in refueling building at grade (+3.7 m)

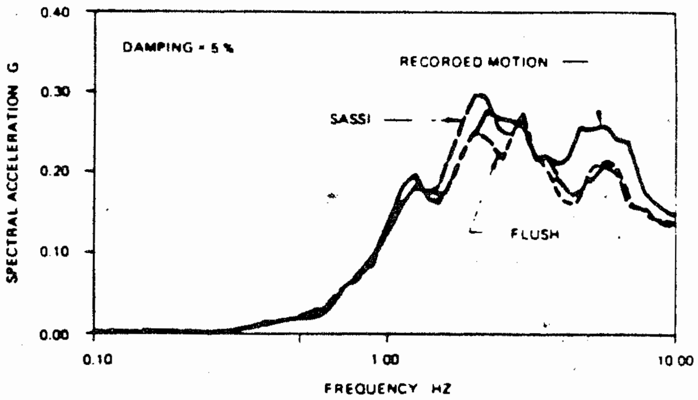

Figure 8. Comparison of spectra in refueling building at base of caisson

The extent of SSI in this plant can be seen in Figure 9. The peak spectral acceleration inside the building is 38% lower than at a point with the same elevation in the free-field, and the maximum acceleraton is 28% lower. These reductions are typical for heavy and stiff structures embedded in soft sites.

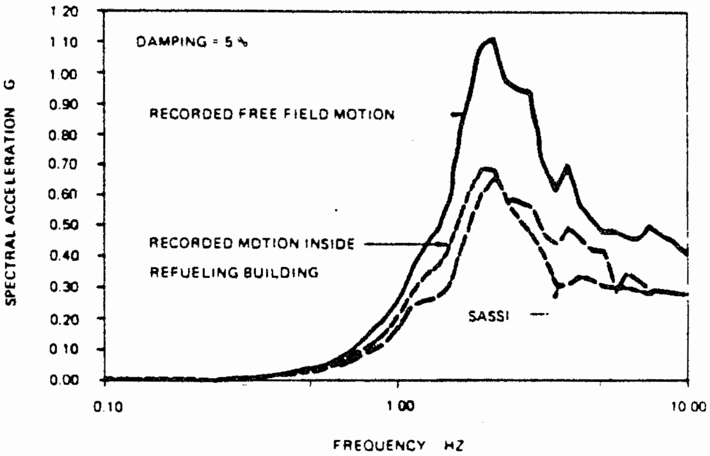

Figure 9. Comparison of spectra refueling building and free field (+3.7 m)

A comparison is also made in the response spectra at the top of the refueling building in Figure 10. Unfortunately, no motions were recorded at that level, thus the SASSI results could only be compared with the FLUSH results. As expected, the difference between the two results was greater than at points in the ground. The peaks computed in FLUSH were significantly lower. However, the frequency at which the peaks occurred were accurately predicted. This discrepancy occurs since it is difficult to duplicate the response characteristics of an actual superstructure using a lead to unconservative results, as was shown by (Luco, et al., 1974).

The closeness of results between the SASSI and FLUSH analyses indicates that for engineering purposes good results can be obtained for points in the ground from performing a 2-D analysis. Furthermore, studies (Maslenikov, et al., 1980) have shown that excellent agreement can be obtained with 3-D analysis at points in the superstructure when ground motions are obtained from a 2-D investigation and are fed as base motions to a 3-D substructure model of the superstructure, as long as all the rigid components of the motion, including rocking, are included in the input. This significantly reduces the cost and effort for performing the required analyses.

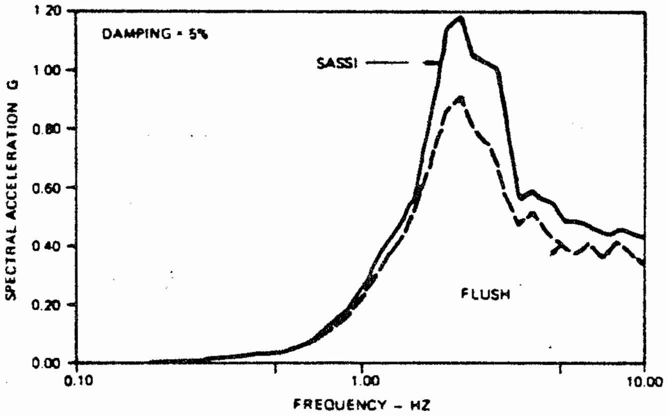

Figure 10. Comparison of spectra at top of refueling building

4.1 Results of analysis for a rigid caisson

Many 3-D soil-structure interaction techniques have to assume that the foundation is infinitely rigid. To investigate the effect of this assumption on the response of structures similar to the Humboldt Bay Power Plant, the SASSI analysis was repeated but with elements representing the foundation adjusted to be much stiffer. In this manner, the caisson was forced to behave as a rigid body.

A comparison of results between the rigid case and the flexible case is shown in Figures 11, 12, and 13. As can be seen, both the maximum accelerations and the response spectra for the two cases are almost equivalent. This indicates that accounting for the effects of foundation flexibility of massive stiff structures may not be important. However, for many types of foundations, such as large mats, these effects can be

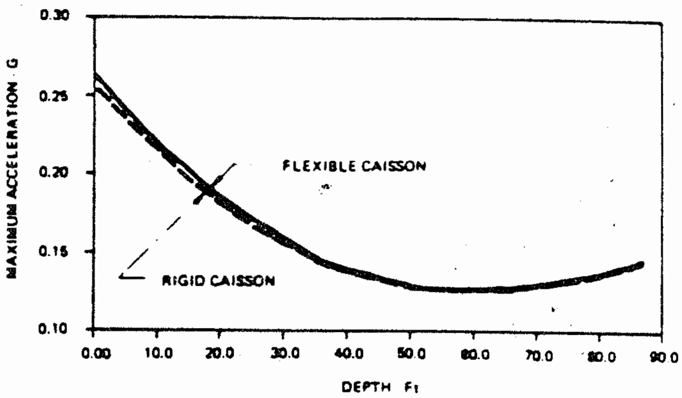

Figure 11. Comparison of maximum SASSI computed lateral accelerations in the caisson

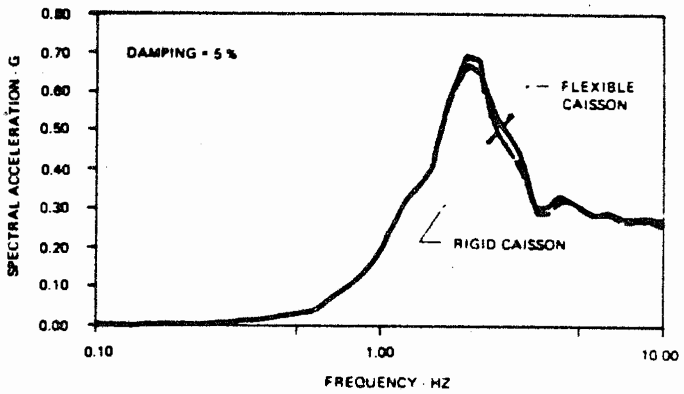

Figure 12. Comparison of spectra of refueling building at grade (+3.7 m)

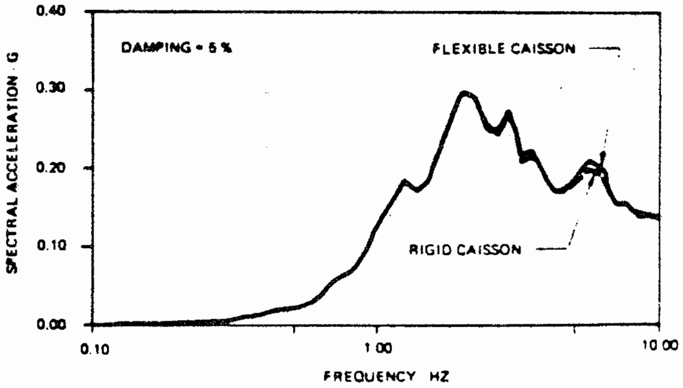

Figure 13. Comparison of spectra in refueling building at base of caisson

5 SUMMARY AND CONCLUSIONS

The computer program SASSI was used to perform a 3-D soil-structure interaction analysis of the Humboldt Bay Nuclear Power Plant. Based on a knowledge of the motions developed at the ground surface in the free-field, computations were likely to develop at the base of the caisson and at the ground surface within the refueling building. The good agreement between the SASSI results and the recorded motions at the same locations are very encouraging. It clearly shows the effectiveness of the new procedure. Although this agreement is for one case only and many more comparisons are required, some general conclusions can be made regarding the response of heavy, stiff, and deeply embedded structures such as nuclear power plants:

1. It is important to perform SSI analyses since the free-field motions would be reduced considerably. Designing structures without accounting for these effects may be too conservative. Furthermore, SASSI is an effective way for predicting this reduction with reasonable accuracy.
2. For this type of structure, a FLUSH analysis is accurate enough for computing responses in the foundation when the wave field is assumed to be composed of vertically propagating waves entirely.
3. Response in the superstructure may not be obtained accurately from a 2-D analysis. However, better agreement can be achieved when ground motions are obtained from a 2-D analysis and used as input to a 3-D substructure model of the superstructure. In this case, all the components of the motion, including rocking motions, should be included.
4. The stiffness of the caisson is relatively unimportant in the interaction analysis. Consequently, the caisson can be assumed to be rigid.

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