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Seismic Response of a Nuclear Power Generation Complex Including Structure-to-Structure Interaction Effects

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SEISMIC RESPONSE OF A NUCLEAR POWER GENERATION COMPLEX INCLUDING STRUCTURE-TO-STRUCTURE INTERACTION EFFECTS*

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ABSTRACT

Seismic responses of the Zion nuclear power generation complex accounting for structure-to-structure interaction effects as predicted by CLASSI and FLUSH Codes are presented in this paper. Two aspects of the multi-structure analyses were considered: the effect of structure-to-structure interaction on structure response and the variability in structure response as predicted by different codes, including structure-to-structure interaction.

The effect of structure-to-structure interaction on the response of the Zion reactor building and AFT complex (the auxiliary/fuel-handling/turbine building complex) was assessed by comparing the results of CLASSI analyses with and without interaction between structures. The results show that the reactor building has a very small effect on the AFT complex, but the effect of structure-to-structure interaction on the reactor building from the AFT complex is substantial. A comparison of the reactor building's response as predicted by CLASSI and FLUSH, including structure-to-structure interaction, shows significant differences. Modeling three-dimensional configuration of a complicated power plant structure such as the Zion's with equivalent two-dimensional models for structure-to-structure interaction analysis requires careful consideration.

INTRODUCTION

Predicting the seismic response of a nuclear power generation complex accounting for the effects of soil-structure interaction (SSI) and structure-to-structure interaction is generally subject to a number of uncertainties: definition of the free-field ground motion, variability of soil and structure properties, idealization of the soil-structure system, as well as the difference in SSI analysis techniques. A major source of uncertainty comes from the idealization of the soil-structure system, (Chen et al., 1984). Modeling of soil-structure system is dependent on the capability and limitation of the code used. To address the uncertainty issue comes from differences in SSI analysis techniques, two alternative techniques were used for the SSI analysis of the Zion nuclear power plant, (Maslenikov et al., 1983).

The first technique was a linear direct method of analysis using computer program FLUSH (Lysmer et al., 1975) and the second was a substructure approach using the computer program CLASSI (Wong and Luco, 1980). In each case, due to the complexity of the power plant structure and the limitation of the code capability, significant simplification in modeling the soil-structure system was necessary. These simplifications and the inherent differences in two approaches lead to significantly different prediction of response, especially when multiple structures are included in the model. This paper presents the results of our analyses on the SSI response of Zion reactor building and AFT complex considering the interaction effects of these two structures.

ZION NUCLEAR POWER PLANT

The Zion nuclear power plant is situated on the southwestern shore of Lake Michigan approximately 40 miles north of Chicago, Illinois, USA. The plant consists of two NSSS units with a power rating of 1100 MW(e) each. For SSI, three structures are of interest--two reactor buildings and the auxiliary-fuel handling-turbine building (AFT) complex. (Figure 1).

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The Zion site is characterized by about 110 feet of soil overlying a bedrock of Niagara Dolomite. The soil can generally be classified into three separate layers. The top layer, about 35 feet in thickness, consists of granular lake deposits of dense, fine to medium sands with variable amounts of coarse and gravel. The reactor building foundation was excavated through this material and into the second layer. The second layer, 30 feet thick, is a cohesive, firm to hard, glacial till whereas the bottom layer (45 feet thick), is primarily a cohesionless glacial deposit of dense sands and gravel.

The Zion reactor building is composed of two essentially independent structures--the containment shell and internal structure. The containment shell is a prestressed concrete right circular cylinder topped by an elliptical dome. For this study, the internal structure includes both the reinforced concrete support structure for the NSSS and the NSSS (reactor pressure vessel, steam generators, coolant pumps, piping, etc.) itself. These two structures interact only through the foundation.

Dynamic models of the containment shell and internal structure were considered separately. The containment shell was modeled by a series of beam elements with shear and bending characteristics appropriate for a circular cylindrical shell. Masses and rotary inertias were lumped at nodal points. Inertias affecting bending and torsion response of the shell were included. The internal structure, including a simplified model of the NSSS, was modeled with three-dimensional finite elements. Masses were again lumped at selected nodes.

The second structure, AFT complex, are founded on a common base slab of varying elevation. Common floor slabs in the superstructure provide additional structural connections. A finite element model of the AFT complex was developed, employing the plate and shell elements to represent the concrete shear walls and beam and truss elements to model the braced frames. Masses were lumped at selected nodes, which were chosen so as to minimize the effects of this simplification on the response in the auxiliary building and to suppress local nodes in the turbine building.

FREE-FIELD GROUND MOTION

Specifying the free-field ground motion is one of the most important factors in SSI Analysis. It is essential that a consistent definition of the free-field ground motion be maintained. Three aspects of the free-field motion are important — location of control point, frequency content of the control motion, and the spatial variation of the motions. In our analyses, the control point was located on the ground surface, and vertically propagating shear and compression waves defined the spatial variation of the motion. Two earthquake motions; one real, (recorded at El Centro, Imperial Valley earthquake, May 1940) and one synthetic were considered in our analysis. The synthetic motion was generated to loosely match target pseudo-velocity spectra considered typical of the Zion site. Both earthquake motions were scaled to a maximum acceleration of 0.2 g corresponding to the SSI level at Zion.

STRUCTURE-TO-STRUCTURE INTERACTION

The effect of structure-to-structure interaction on the response of the containment building and the AFT complex was analyzed by CLASSI and FLUSH codes.

CLASSI ANALYSIS

Using the CLASSI code, we first computed the response of the isolated structures, then the response of the multi-structures assuming a single coupled system, the foundation of the reactor containment building was idealized by an embedded cylindrical rigid foundation. The foundation of AFT complex was idealized by the flat surface foundation corrected for embedment and supplemented by the scattering matrix developed for an equivalent embedded cylinder. In our analysis, we assumed that scattering matrixes for the three structures (two containment buildings and the AFT complex) were unaltered by foundation-to-foundation interaction. In the present case, the impedance matrix was an 18 by 18 matrix (for each frequency) with the 6 by 6 off-diagonal blocks representing the coupling terms between foundations. The 6 by 6 diagonal blocks of the impedance matrix were those computed from the isolated foundations. The coupling block were computed assuming idealized surface foundation of the structures supported on soil at the average embedment depth. Coupling between the foundations was assumed to occur only through the underlying soil layers. In the CLASSI methodology, the compliance matrix is computed first and then inverted to obtain the impedance matrix. Figure 2 shows a model of the coupled foundation system, including it's spatial discretization for computation purpose.

Comparison of impedance functions for isolated and coupled foundation models.

Figure 3 shows a comparison of isolated and coupled impedances for the AFT complex. These comparisons show very little difference between the isolated and coupled foundations. The only significant difference occurs in the frequency range of 10 to 15 Hz. Figure 4 shows the comparison for the reactor buildings. Again, with the exception of the horizontal/rocking coupling term, the same observations can be made. The isolated reactor foundation term displays more than double the coupled foundation terms at low frequencies. Examining the off-diagonal blocks provides insight into the magnitude of the coupling between foundations. Figures 5a and 5b show the coupling between foundations. Figure 5a shows the E-W horizontal terms for the AFT complex and the containment building, compared with the term coupling the two foundations for E-W translation. Figure 5b shows the same for the vertical component. In general, the coupling terms for both components are significant when compared with the containment building impedance but not when compared with the AFT complex. Hence, irrespective of the relative mass of the structures, the AFT complex is observed to affect the containment buildings, whereas the reverse is not the case.

Comparison of structure response for isolated and coupled foundation models.

The results of the analysis showed that the containment buildings have a small effect on the response of the AFT complex. This could be anticipated, considering the aforementioned impedance comparison and the large difference (about a factor of 5) between the mass of the AFT complex and of each containment building. In addition, the assumption of a rigid AFT foundation mobilizes its entire mass during interaction. The effect of structure-to-structure interaction on the containment buildings is substantial. In general, motions of the AFT complex induce motions in the containment buildings, in which frequencies associated with the response of the AFT complex response are amplified. Peak acceleration of the containment building foundations increases in by 25 to 30%, and we observed similar of greater increases in spectral accelerations on the foundation and in the structure. Figures 6 and 7 show comparisons of response for the isolated and coupled foundation analyses. Figure 6 shows a point in the AFT complex, where there is little difference in response. Figure 7 shows response at the top of the containment shell, where significant differences are observed.

In this study, we found that structure-to-structure interaction had a significant effect on the amplitude and frequency content of the response of the less massive of the two structures. The magnitude of this effect was as great as differences due to SSI linear analysis procedures. It is well to emphasize that the results presented here assumed linear soil and structural behavior, which may overemphasize the effect of structure-to-structure interaction. Soil behavior in the immediate neighborhood of the structures is likely to be nonlinear and can potentially reduce the effect.

FLUSH ANALYSIS

Four FLUSH models were analyzed in the course of the study--one of the isolated containment building and three representing slices through the Zion facility, identified as A-A, B-B, and C-C in Fig. 8. Elevation views showing the FLUSH model for each cross section are shown in Fig. 9 through 11. Figure 12 shows the FLUSH model of the containment building as an isolated structure.

To model the structures' foundations, it was necessary to idealize their stiffness and geometry. In all of our analyses the foundations were assumed to behave rigidly. This is an excellent assumption for the foundation of the containment building, where effective stiffness is due to the foundation itself and to the stiffening effect of the containment shell and internal structure. The foundation of the AFT complex, however, is expected to behave in a flexible manner, especially with respect to rocking and vertical deformations. The procedure for determining the effective stiffness of the AFT's foundation, accounting for the stiffening effects of the numerous walls and floor slabs, and reducing this three-dimensional behavior to two dimensions is not straightforward. Our initial assumption, therefore, was to model it as rigid. The containment building's foundation was assumed to be a right circular cylinder embedded 36 ft. The foundation width and out-of-plane dimension (slice thickness) were chosen to provide soil shear and rocking stiffness approximately equivalent to those for a circular foundation shape. The geometry of the AFT's foundation depended on the cross-sections. Figures 9 to 12 depicts the foundation geometry and rigidity by showing the idealized foundations as an assembly of rigid, plain strain, finite elements for horizontal portions, interconnected by rigid beam elements that simulate exterior walls.

Simplified Structure Representation

In general, the structural models used in a direct method of analysis represent only the overall dynamic behavior of the structure, and a second-stage structural analysis is usually performed using the results of the SSI analysis as excitation. The simplified structural models for our analysis were developed using a modal equivalence principle. The procedure is to develop a series of single-degree-of-freedom (DOF) models, each designed to represent one mode of the structure. The frequency, mass and moment about the foundation as determined by the detailed model. Judged on the basis of their modal participation factors, only the most important modes are included. Any residual mass or rotary ineritia not represented in the dynamic models is added to the foundation to ensure proper modeling of rigid body behavior. In this study, the internal structure and AFT complex were modeled in this fashion; the containment shell was modeled using a lumped-mass beam model.

FLUSH Models

The complexity of the FLUSH models increased from the isolated containment building to the isolated AFT complex. The isolated containment building model was straightforward and served as a benchmark for the two procedures.

Idealizing the AFT complex introduced a complex modeling issue: how to model the mass and stiffness of an irregularly shaped structure and foundation in two dimensions. This issue arises whenever average properties for the structure cannot be easily established for the analysis slice. In our case, all three cross sections face this dilemma to some extent; however, cross section A-A is particularly difficult because three structures of differing characteristics are modeled simultaneously. In structure-to-structure interaction, the mass ratio of the structures is important in capturing dynamic behavior. In general, the more massive structure has a greater effect on it's neighbor. When only a portion of the foundation is modeled, such as the Zion auxiliary building in cross section A-A, inclusion of the entire mass of the structure will predict disproportionately high stress levels in the soil and will distort structural response. This is especially true when nonlinear soil behavior is being approximated. To maintain reasonable levels of stress in the soil, then, the structure and foundation mass must be proportional to the foundation area. Hence, two alternatives arise: either the mass assumed in the structure and foundation model can be selected to yield the expected soil-bearing pressure; or the horizontal, vertical and rotational inertia of the portion of structure within the analysis slice includes the total mass of the structure, including those portions outside the slice. The former case is deficient, especially in the prediction of structure-to-structure interaction effects. The latter approach overcomes this shortcoming, but clearly leads to shifts in the amplitude and frequency content of the complicated structure-- in our case, the AFT complex. In cross section A-A, the first alternative was selected. Section A-A is a N-S slice taken through the center of the containment buildings and through the west end of the auxiliary building. The out-of-plane dimension of the model was based on the model of the containment building foundation, selected so that the translational and rocking characteristics of the resulting rectangle resting on soil were close to those of the actual cylindrical shape. The shell was modeled by a lumped-mass beam model and the internal structure and AFT complex by modal-equivalent single-DOF models. Modes representing the AFT complex were selected from an eigenvalue analysis of a reduced AFT complex comprising the auxiliary and fuel-handling buildings. As discussed above, the selected mass of the AFT complex was proportional to the foundation area.

Section B-B is a N-S slice taken through the turbine building between the turbine pedestals and the auxiliary building. The out-of-plane dimension was selected so that the foundation area corresponded to that of the turbine building. Similarly, the mass properties of the structure and foundation corresponded to those of the turbine building area of the AFT complex. The structural modes included in the model were identified either with the response of the turbine building alone or with significant overall modes of the AFT complex.

Section C-C extends east and west along the centerline of the AFT complex. The out-of-plane dimension was selected to match the model area with that of the entire AFT complex. Structural modes corresponding to E-W motion were included.

VARIABILITY IN STRUCTURE RESPONSE PREDICTED BY CLASSI AND FLUSH

The results are summarized here for the multiple structure system as predicted by CLASSI and FLUSH, including structure-to-structure interaction. Two components of free-field motion (N-S and vertical) were considered for the synthetic earthquake. Only the response for the containment building are presented here.

Peak acceleration on the foundation and at points in the structure varied on the average by 30%, with the FLUSH results less than those of CLASSI. Figures 13 and 14 show comparisons of response spectra on the foundation and at the top of the containment shell. On the foundation for the CLASSI spectral peaks for N-S translation (Fig. 13a) are from 50 to over 100% higher than those from FLUSH in the frequency range between 2 and 4 Hz. For rocking (Fig. 13c), the CLASSI response is over 150% higher at the primary rocking frequency (2.5 to 3.5 Hz). Vertical response on the foundation (Fig. 13b) appears to agree fairly well. At the top of the containment shell, spectral accelerations for N-S translation (Fig. 14a) reflects the differences seen in the foundation N-S translation and rocking. Here the CLASSI spectral peak is about 135% higher than the FLUSH value. For the vertical response (Fig. 14b), there is a high peak in the CLASSI response spectrum at about 10 to 15 Hz that does not exist for FLUSH.

This comparison of the containment building's response as predicted by CLASSI and FLUSH, including structure-to-structure interaction, shows substantial differences--200% or more in some cases. Poor correlation between the two could be expected, due to the way the AFT complex was modeled in the FLUSH analysis. Only FLUSH cross section A-A included the containment buildings and AFT complex. Modeling the AFT complex in this cross section was difficult, as described earlier. The resulting model properly represented the state of stress in the soil but underestimated the total mass and stiffness of the structure-foundation system. The mass of the containment building was twice that of the AFT complex, and consequently the response of the containment building was virtually unchanged from the isolated case. The response of the AFT complex, however, changed significantly. It is evident that modeling three-dimensional configurations with equivalent two-dimensional models is an issue that requires careful consideration.

SUMMARY AND CONCLUSIONS:

Two aspects of the multi-structure analyses were presented in this paper: the effect of structure-to-structure on structure response and the variability in structure response as predicted by CLASSI and FLUSH, including structure-to-structure interaction. The effect of structure-to-structure interaction on the response of the Zion reactor buildings and the AFT complex was assessed by comparing the results of the CLASSI analyses with and without interaction between the structures. The results show that the reactor buildings have a very small effect on the AFT complex. This is expected due to the large difference between the mass of the AFT complex and each reactor building. Also, the assumption of a rigid AFT foundation means its entire mass is mobilized during interaction. The effect of structure-to-structure interaction on the reactor building is significant. In general, motions of the AFT complex induce motions in the reactor buildings, i.e. frequencies associated with the AFT complex response are amplified in the reactor building. Peak acceleration of the foundation increased up to 30%, and similar or greater increase in spectral accelerations were observed on the foundation and in the structure. The relative size of the foundation and relative mass of the structure are two important characteristics of the foundation-structure system affecting structure-to-structure interaction.

A comparison of the reactor buildings response as predicted by CLASSI and FLUSH, including structure-to-structure interaction, shows substantial differences - 200% or more in some cases. Poor correlation between the two could be expected due to the modeling of the AFT complex in FLUSH analysis. Modeling the AFT complex in this cross section was difficult. The resulting model represented the state of stress in the soil properly but underestimated the total mass and the stiffness of the structure-foundation system. The reactor building mass in the FLUSH model was twice that of the AFT complex, and consequently, reactor building response was not significantly changed from the isolated case. AFT complex response changed significantly. Modeling three-dimensional configuration with equivalent two-dimensional models is an issue which requires careful consideration.

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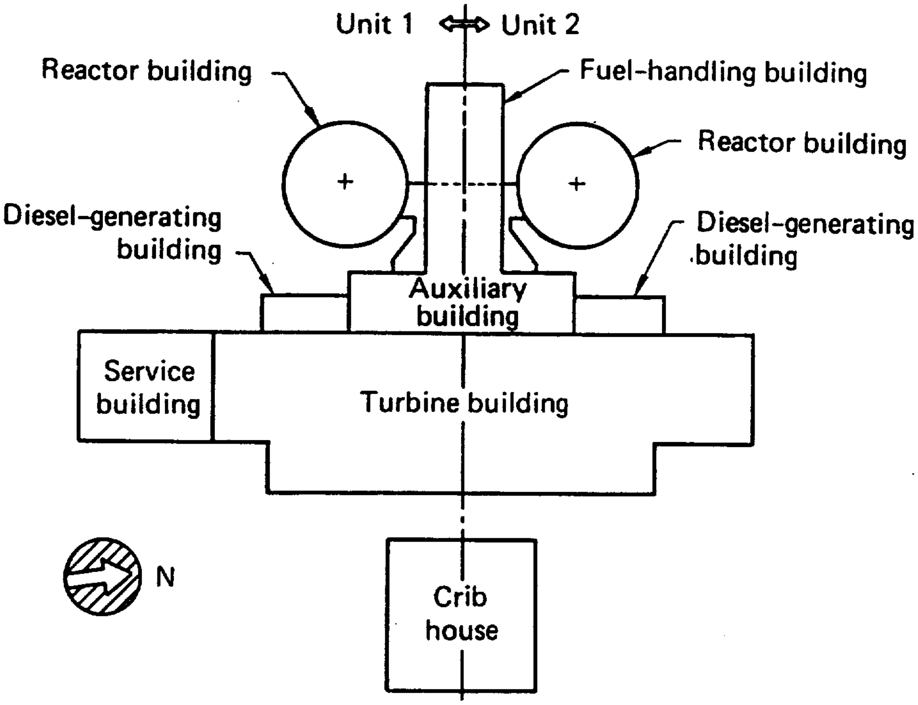

Fig. 1 Plan view of the Zion Nuclear Power Plant

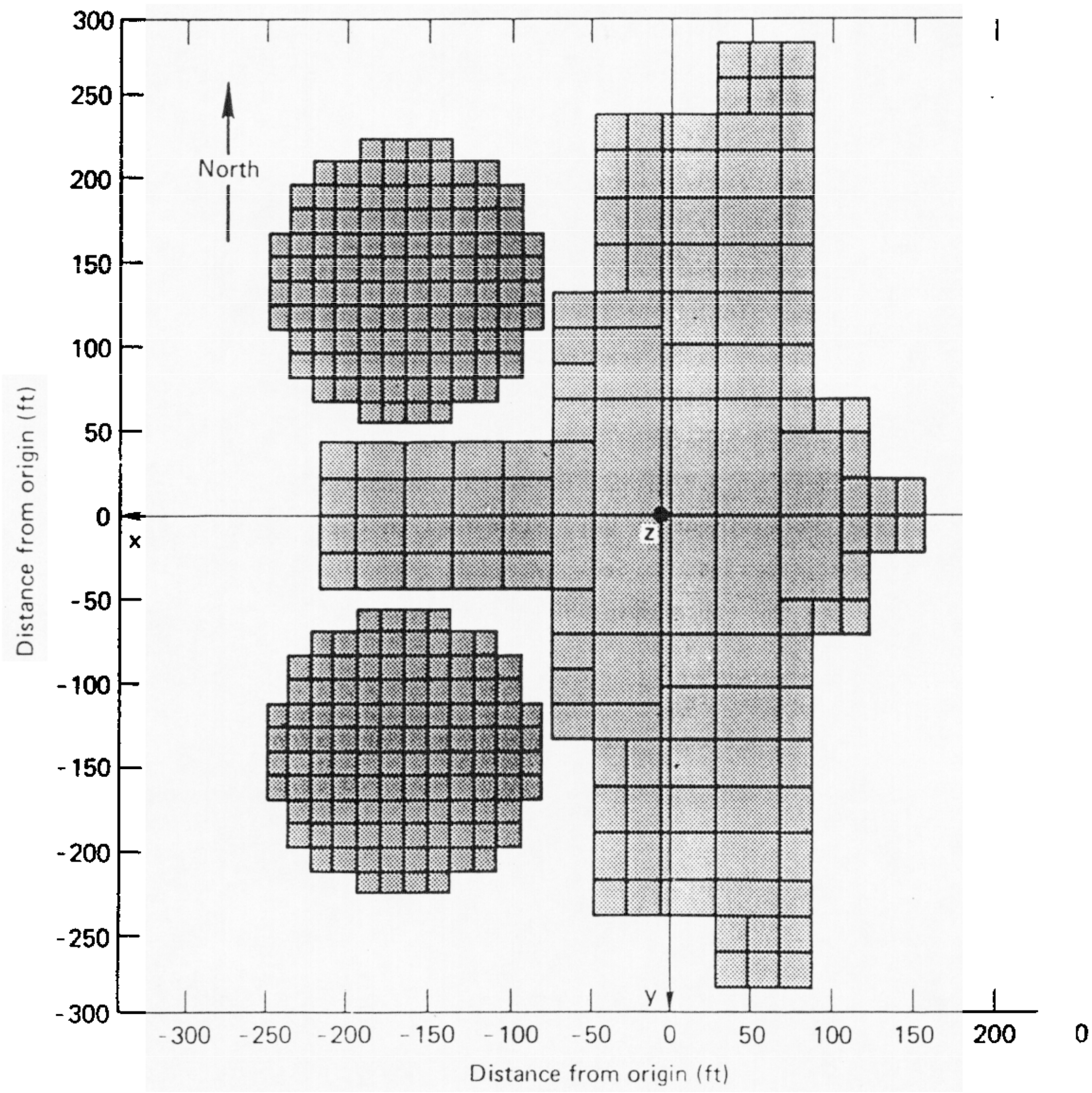

Fig. 2 CLASSI foundation model of coupled AFT complex and containment building foundations, showing the spatial discretization used to compute impedance functions.

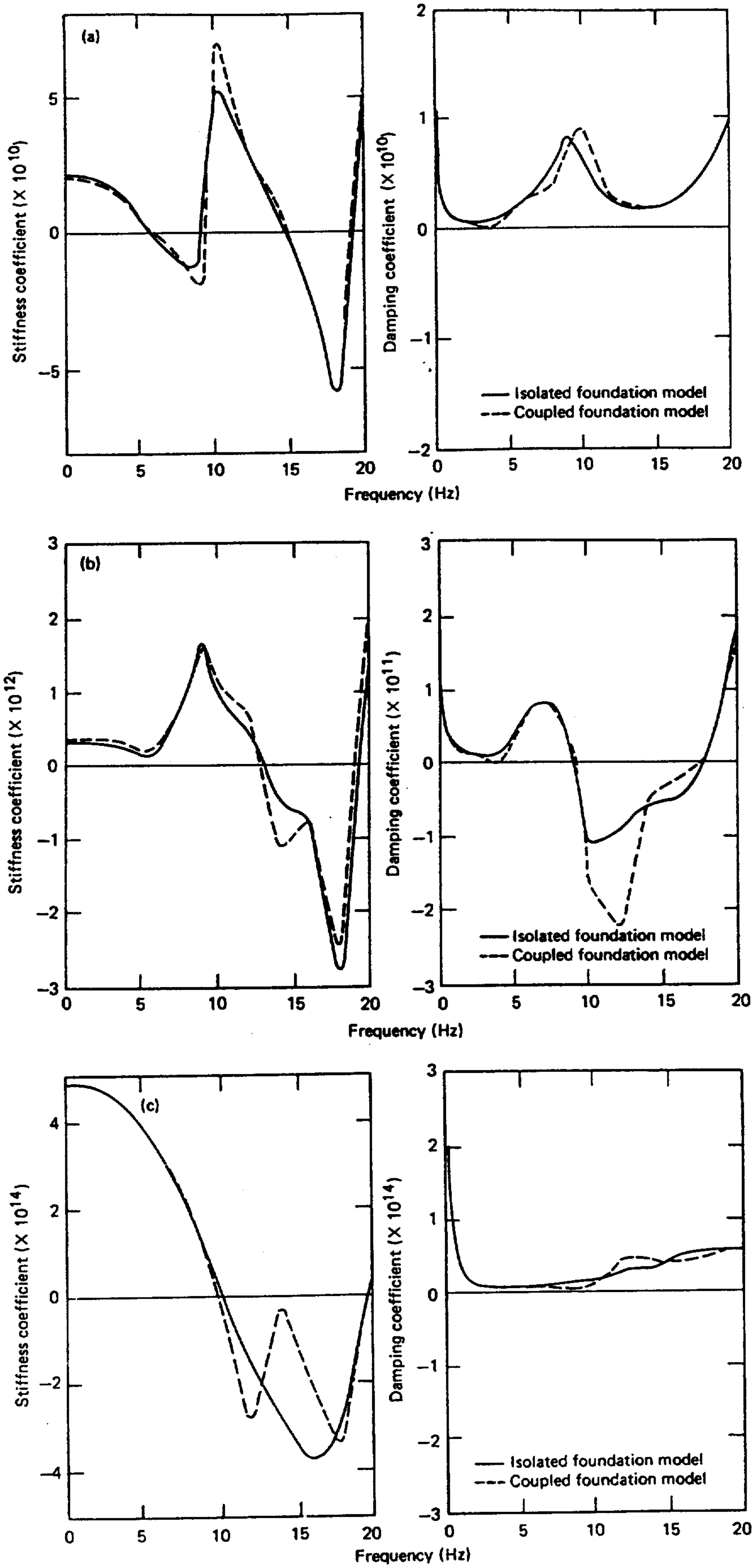

Fig. 3 Comparison of CLASSI impedance functions for isolated and coupled AFT foundation models. (a) E-W translation term K_{11}. (b) E-W translation/rocking coupling term K_{15}, (c) E-W rocking term K_{55}.

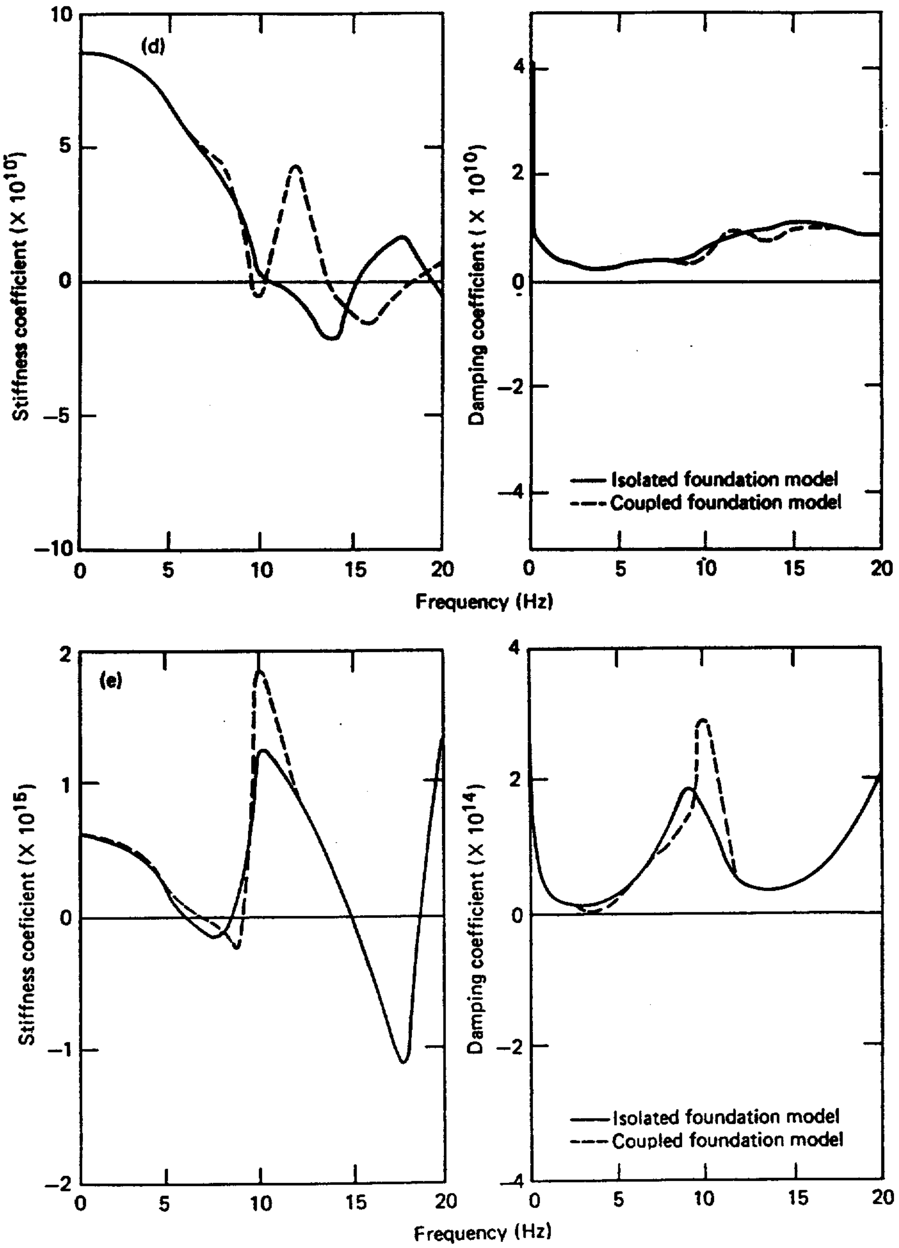

Fig. 3 (Continued). (d) Vertical translation term K_{33}, and (e) torsional rotation term K_{66}.

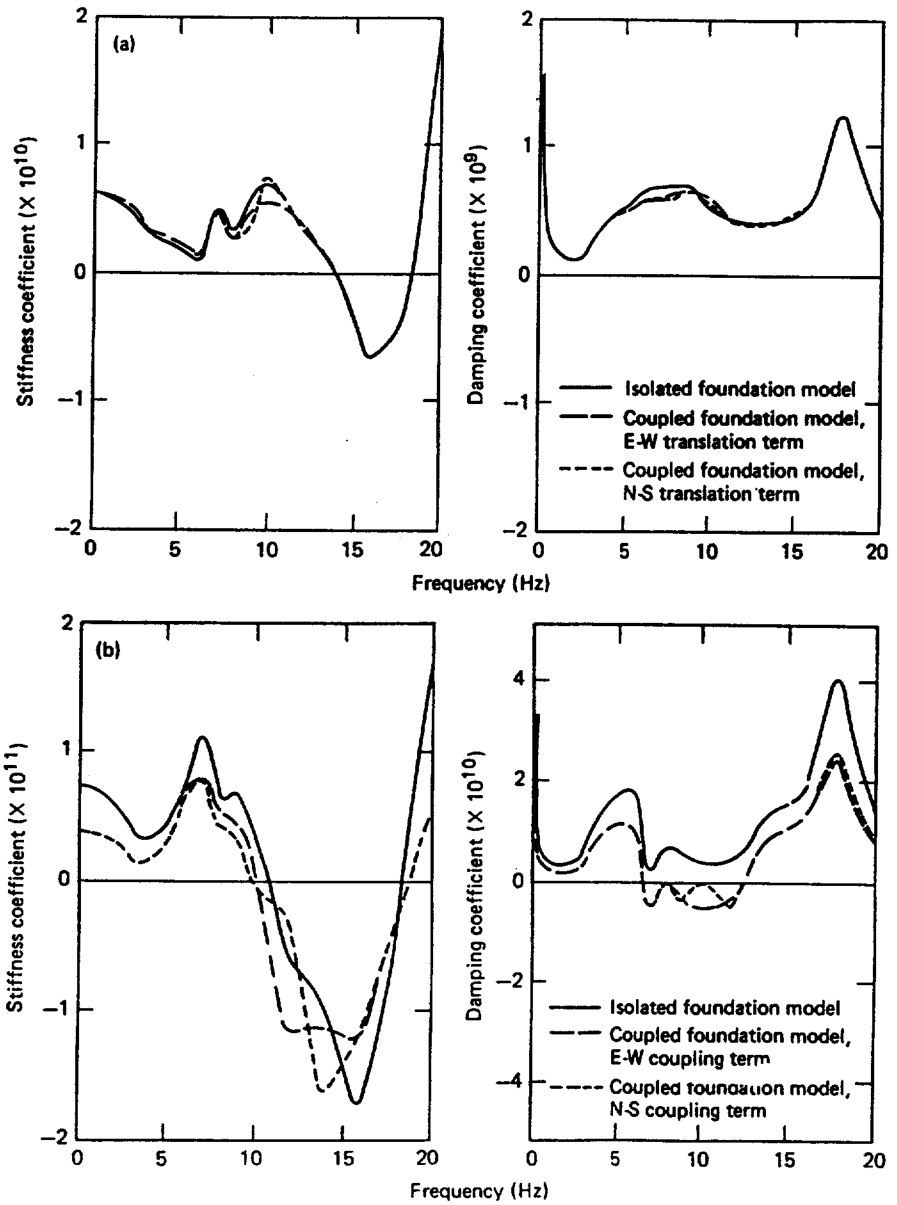

Fig. 4 Comparison of CLASSI impedance functions for isolated and coupled reactor building foundation models. (a) E-W horizontal translation term K_{11} and N-S horizontal translation term K_{22}, (b) E-W horizontal translation/rocking coupling term K_{15} and N-S horizontal translation/rocking coupling term K_{24}.

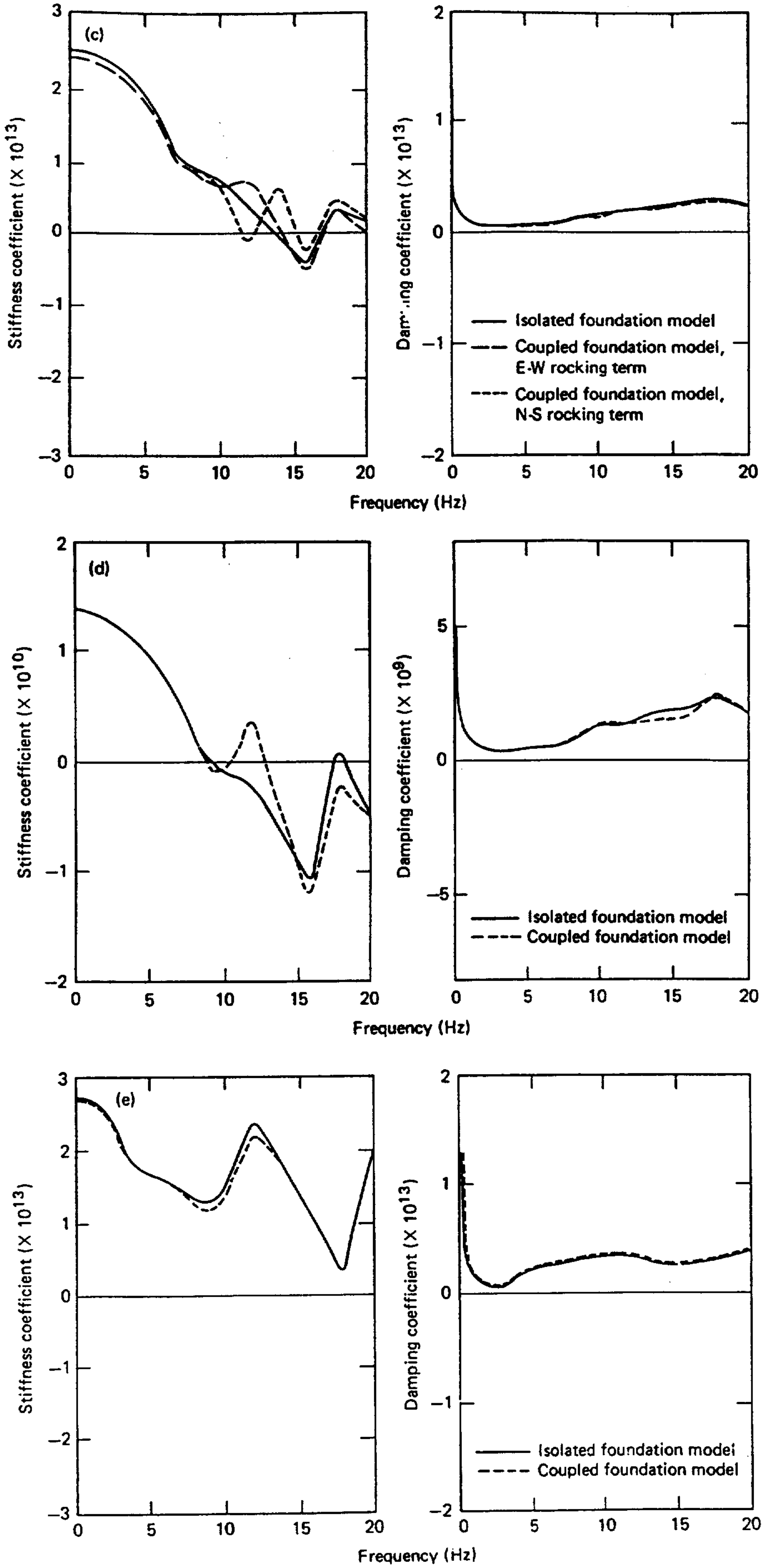

Fig. 4 (Continued) (c) E-W rocking term K_{44} and N-S rocking term K_{15}, (d) Vertical translation term K_{33}. (e) torsional rotation term K_{66}.

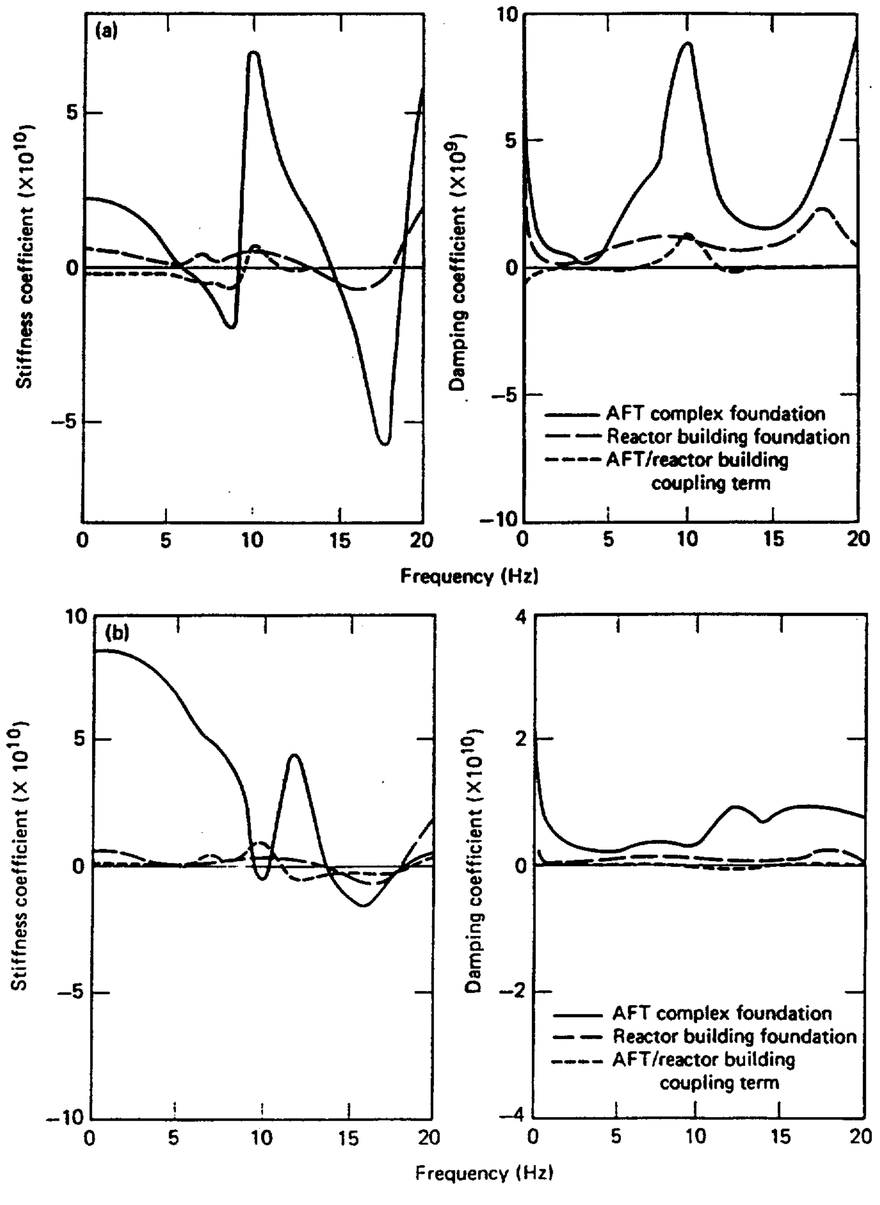

Fig. 5 CLASSI impedance functions for the coupled AFT complex and reactor building foundation system. Shown are the structure-to-structure coupling terms compared with diaganol terms for (a) the E-W coupling term and (b) the vertical translation coupling term.

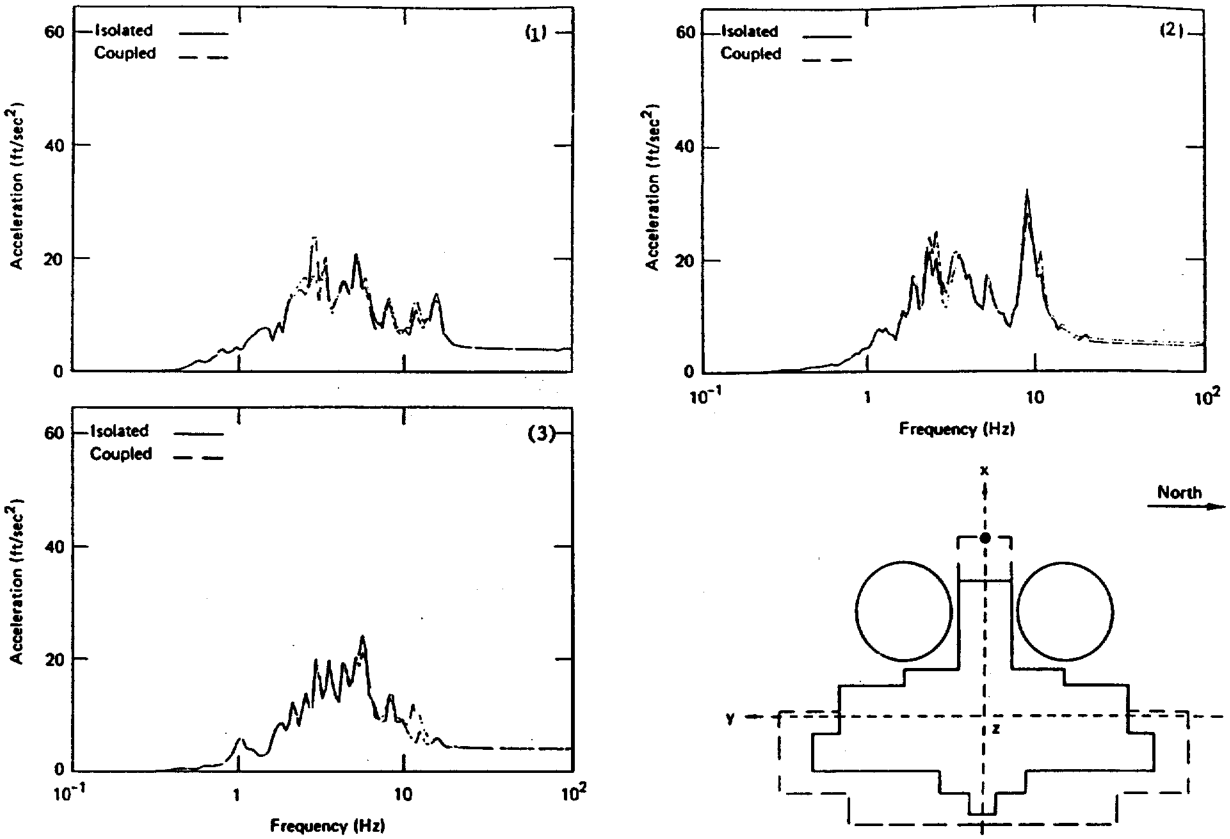

Fig. 6 Comparison of isolated and coupled foundation response at the west wall of AFT complex. Shown are (1) E-W translation, (2) N-S translation, (3) Vertical translation.

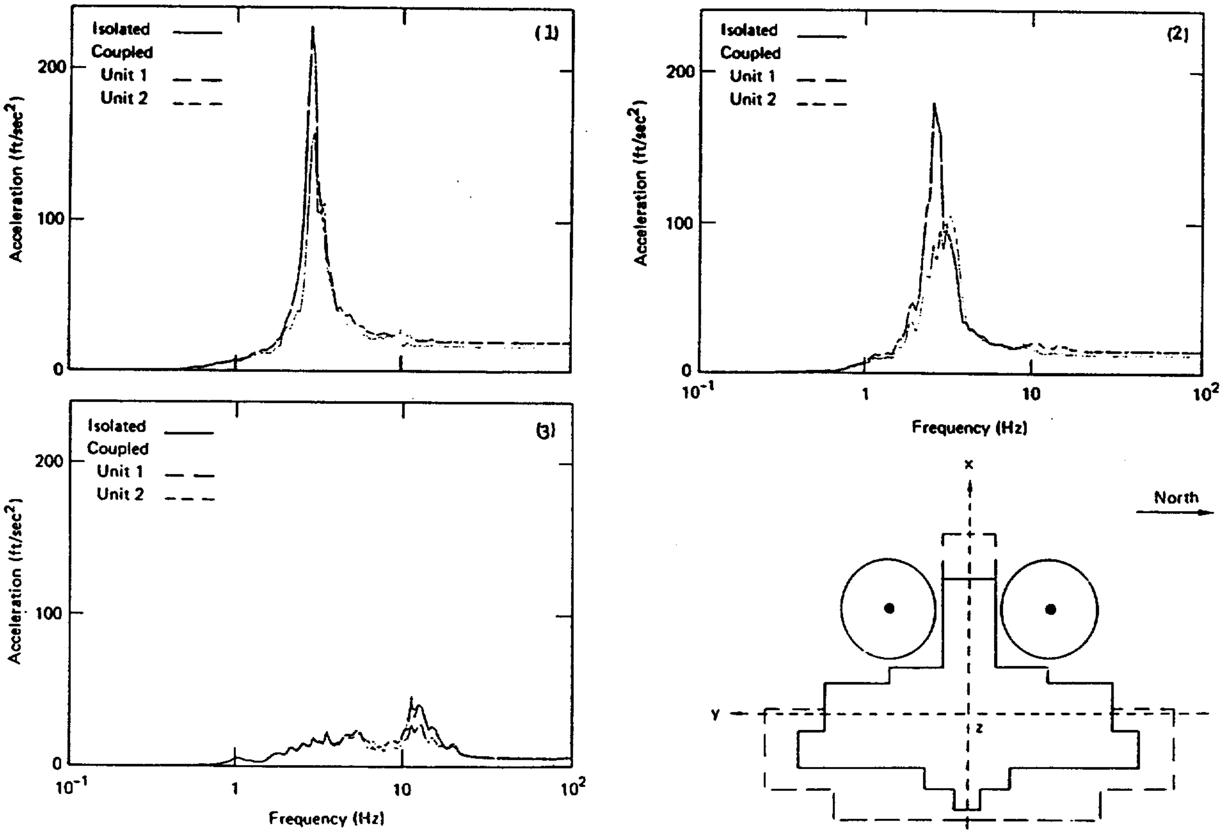

Fig. 7 Comparison of isolated and coupled foundation response at the top of containment shell. Shown are (1) E-W translation, (2) N-S translation, (3) Vertical translation.

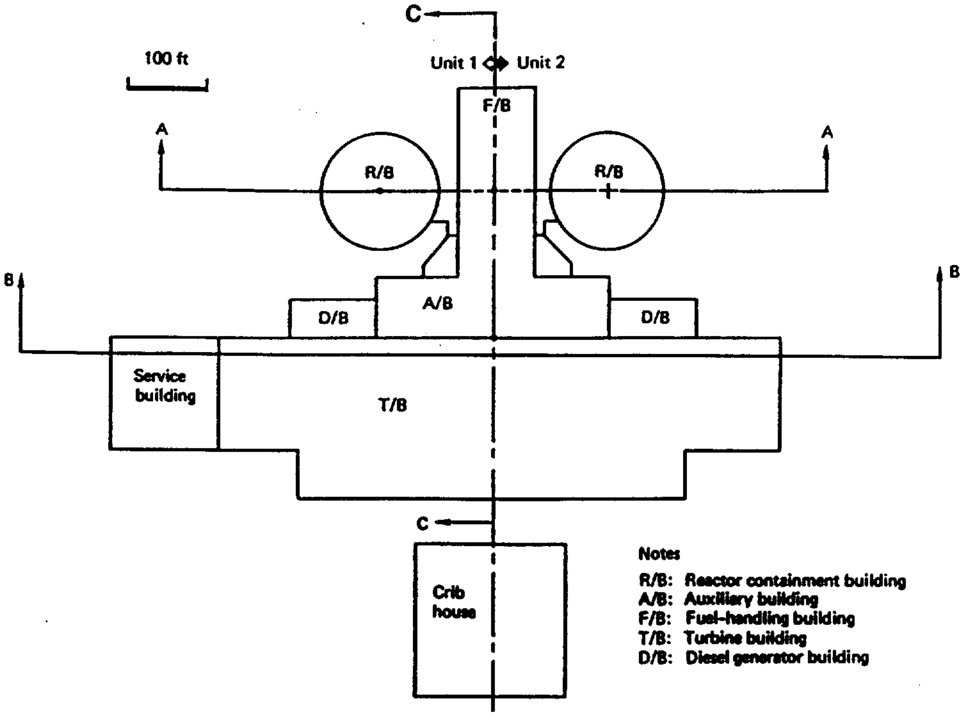

Fig. 8 Plan view of the Zion Nuclear Power Plant showing cross-section selections used for FLUSH analysis.

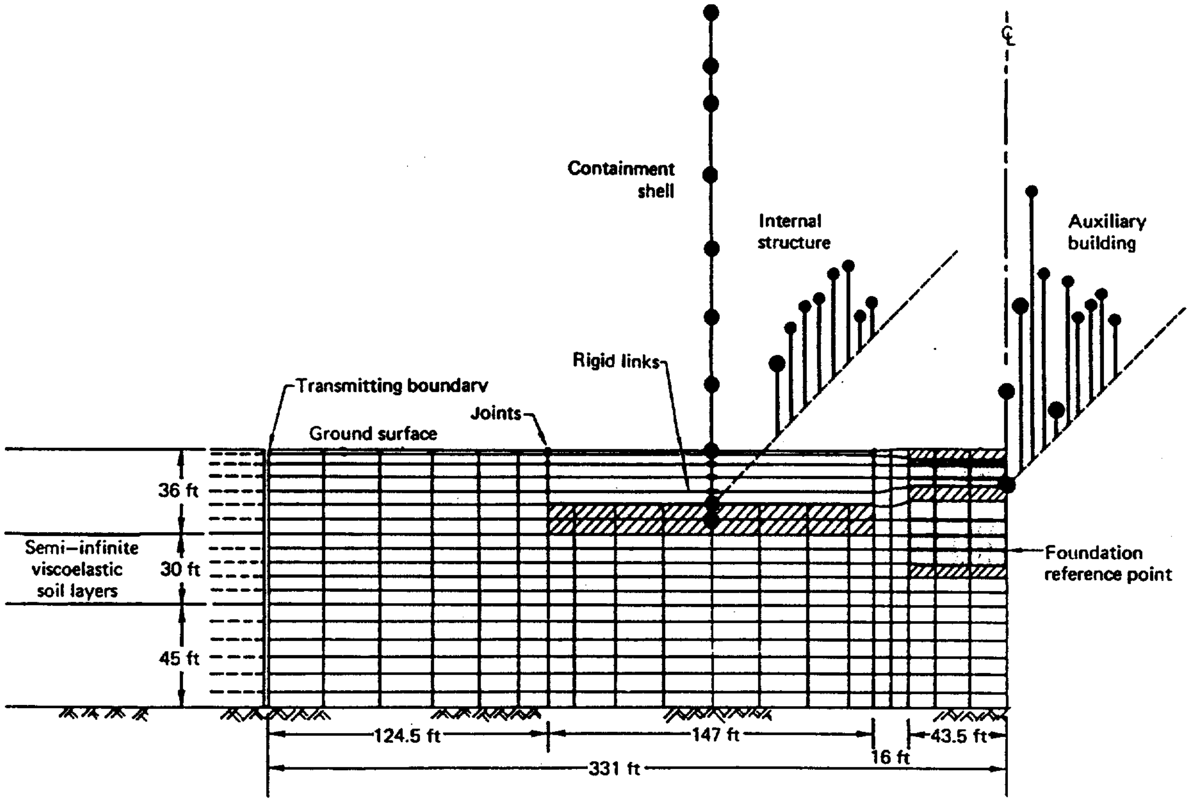

Fig. 9 Finite Element model for FLUSH analyses - Cross Section A-A.

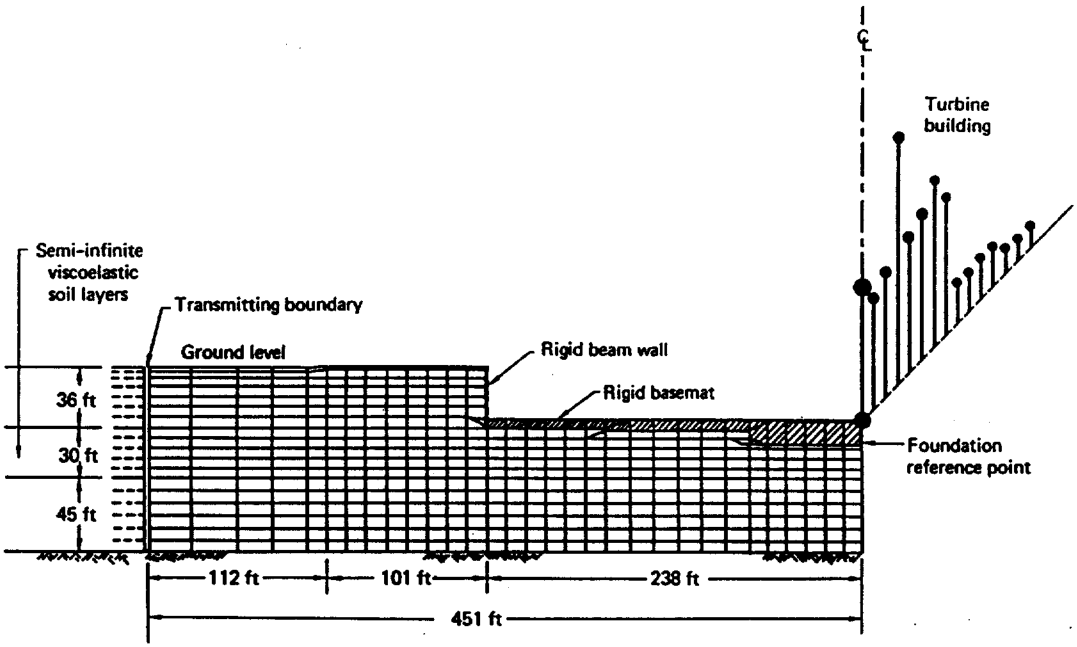

Fig. 10 Finite Element model for FLUSH analyses - Cross Section B-B.

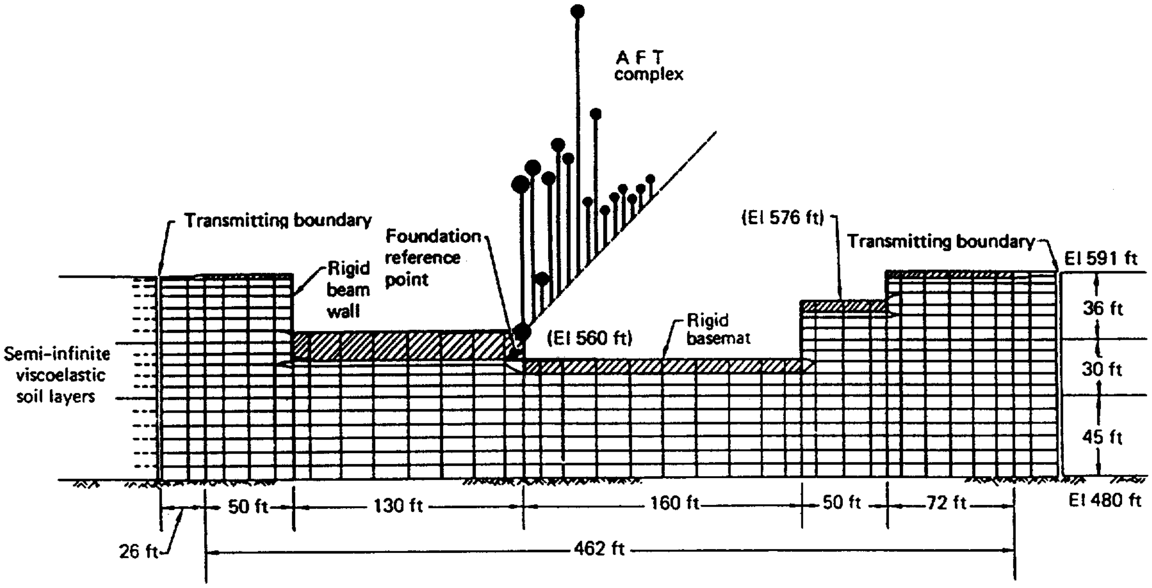

Fig. 11 Finite Element model for FLUSH analyses - Cross Section C-C.

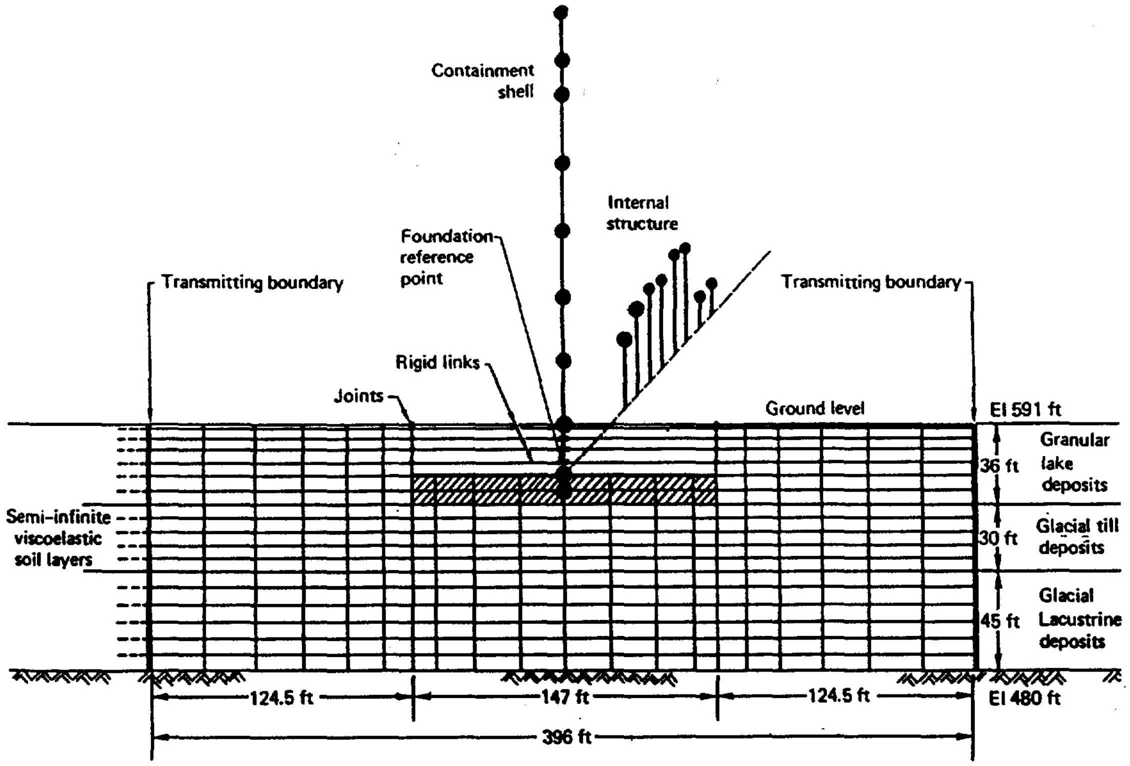

Fig. 12 Finite Element model for FLUSH analyses - isolated reactor building through cross section A-A.

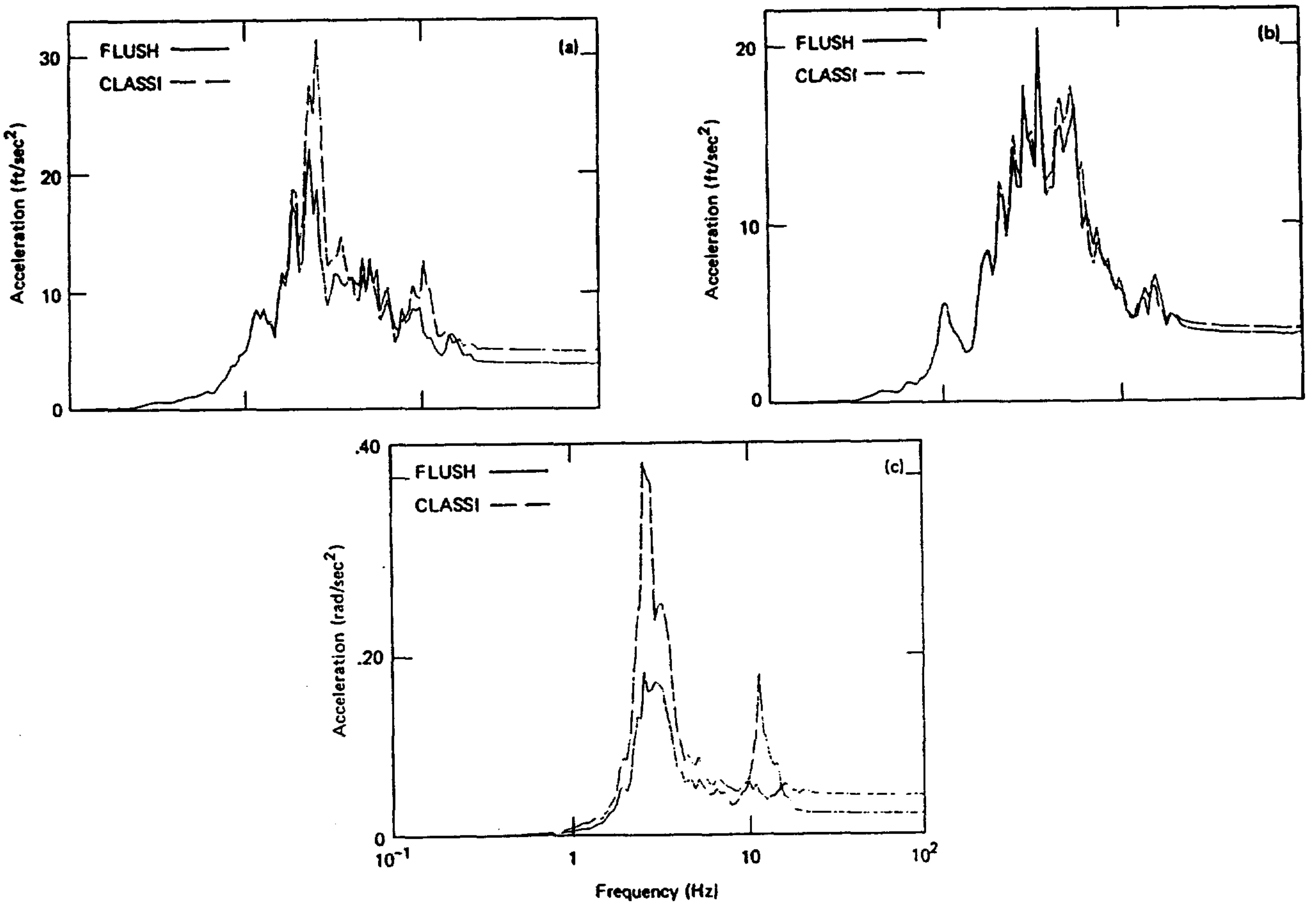

Fig. 13 Comparison of the containment building foundation reponse spectra for CLASSI and FLUSH analysis, including structure-to-structure interaction, shown are (a) N-S translation, (b) vertical translation, (c) N-S rocking.

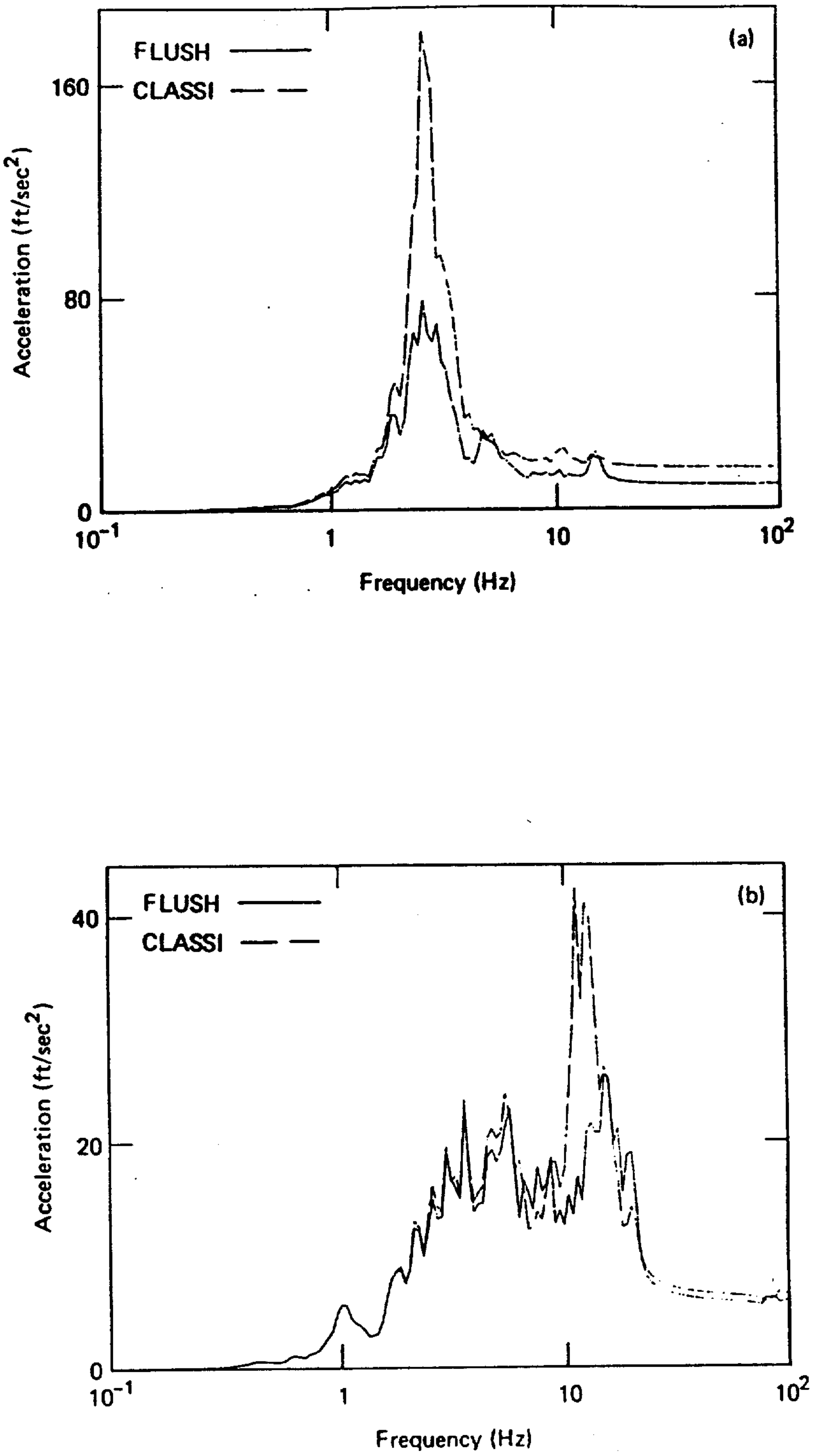

Fig. 14 Comparison of in-structure reponse spectra at the top of the containment shell for CLASSI and FLUSH analysis, including structure-to-structure interaction, shown are (a) N-S translation, (b) vertical translation.