IMPEDANCE APPROACH AND FINITE ELEMENT METHOD FOR SEISMIC RESPONSE ANALYSIS OF SOIL-STRUCTURE SYSTEMS

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SYNOPSIS

Vertical seismic soil-structure interaction analyses are performed using the impedance approach and the direct finite element method (FLUSH) for a deeply embedded nuclear power plant. Important parameters affecting seismic soil-structure interaction analysis such as foundation embedment, superstructural modeling, and input motions are investigated. It is found that effects of the details of structural modeling and foundation input motion on the vertical total foundation motion is insignificant. The use of the surface impedance function gives very conservative structural response as compared to that obtained using the embedded impedance function. The impedance approach and the direct finite element method are found to predict slightly different vertical peak accelerations. The peak spectral acceleration at the top of the reactor building obtained by FLUSH is approximately 20% lower than that obtained by the impedance approach. The difference in the spectral amplitude can be attributed to two causes: 1) material damping is not considered in the impedance approach and 2) the two-dimensional characteristics of the FLUSH solution may give spectral response lower than that of a three-dimensional solution. These results suggest that the major contribution to the difference in the vertical FLUSH and the impedance approach analysis may be attributed to the two-dimensional characteristics of the FLUSH analysis.

RESUME

Pour une centrale nucléaire profondément encastrée dans le sol, on a étudié l'interaction sol-structure lors d'un séisme en utilisant la méthode de l'impédance et la méthode des éléments finis (FLUSH). Les facteurs importants ayant une influence sur l'interaction sol-structure, tels que la profondeur de la fondation, la schématisation de la structure et les mouvements du sol, ont été considérés dans l'étude. On a constaté que la schématisation de la structure et les mouvements du sol ont peu d'effets sur le mouvement vertical total des fondations. La méthode de l'impédance et la méthode des éléments finis ont donné des accélérations verticales maximum légèrement différentes. L'accélération spectrale maximum au sommet de l'édifice du réacteur, obtenue avec FLUSH, est inférieure d'environ 20% à celle obtenue par la méthode de l'impédance. Cette différence peut avoir deux causes: 1) l'amortissement des matériaux n'est pas considéré dans la méthode de l'impédance et 2) la solution bi-dimensionnelle de la méthode FLUSH peut donner une réponse spectrale plus faible que celle d'une solution tri-dimensionnelle. Les résultats semblent indiquer que la cause la plus importante de cette différence serait le fait que l'analyse par la méthode FLUSH est bi-dimensionnelle.

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INTRODUCTION

One major aspect of the seismic design of deeply embedded nuclear power plants and many other important civil engineering structures is the effect of the motion of a massive, stiff structure on the soil. The soil-structure interaction effect can initiate rocking and result in different soil motions compared to the free field motions, thus significantly affecting the structural response. Two methods are generally used to solve the seismic soil-structure interaction problems: the direct finite element method (FLUSH, 1) and the substructure or impedance approach (2,3,4,5,6).

In the direct finite element method the earthquake input is defined at the artificial bottom boundary of the finite element mesh. This input is determined by deconvolution of the specified surface motions assuming that they were produced exclusively by vertical propagation of shear waves. Although an attempt is made to simulate approximately the three-dimensional effect, the FLUSH analysis uses basically a two-dimensional model. In the impedance approach, the soil-structure system is analyzed in several stages, each dealing separately with one substructure - soil region or structure. The specified free-field motions are treated directly as the excitation in the three-dimensional impedance approach, thus eliminating the deconvolution calculations required in the direct finite element method. Each method has its advantages and limitations and both methods should give similar results if they are formulated and used correctly to solve the same problem. However, occasional comparisons between these two methods sometimes lead to conflicting results (7,8). This paper presents the results of the vertical seismic soil-structure interaction analysis using the impedance approach and the direct finite element method for a deeply embedded nuclear power plant.

THE IMPEDANCE APPROACH

In this method, the soil-structure interaction problem is separated into three parts: 1) determination of the foundation impedance functions, 2) evaluation of the foundation input motions, and 3) analysis of the superstructure response using the computed foundation motions. The impedance function simulates the process by which forces that are exerted on the foundation by the superstructure radiate seismic energy. The input motion characterizes the process by which incoming seismic waves scattered by the foundation exert forces on the base of the structure. Figure 1 illustrates the procedure of seismic soil-structure interaction analysis using the impedance approach (9, 10).

The impedance approach allows engineers to solve a large class of practical seismic soil-structure interaction problems. Problems which involve horizontally layered viscoelastic media, arbitrarily shaped rigid foundations, multiple foundations and foundation embedment can be considered. However, there are limitations to the method. At present the foundation has to be assumed rigid, but the stiffening effect of the superstructure often justifies such an assumption. Work is underway to allow determining impedance functions at several points along the interface so that flexible foundations can be considered. Presently, material damping is not directly considered in the soil impedance formulations. Some assumptions, such as the type of wave producing the criteria motion, are required to specify the foundation motions but this is less limiting than the deconvolution required in the direct finite element analysis.

THE DIRECT FINITE ELEMENT METHOD

The direct finite element method is an alternative approach to solving seismic soil-structure interaction problems. The general procedure for making a complete finite element soil-strucutre interaction analysis is shown schematically in Figure 2. The advantage of the direct finite element analysis is that the non-linear soil properties and other types of material behavior can be approximately included in the analysis. However, inaccurate solutions and misleading conclusions can result when discretization of the time and space variables, such as the finite extent of the spatial grid and finiteness of the time sample over which a solution can be economically computed, are not carefully considered.

One of the characteristics of the direct finite element method is the finiteness of the model. Resonant conditions at certain particular frequencies result from the use of the box-like model. In order to minimize these box effects, a very large model must be used. Furthermore, to be able to transmit higher frequencies, sufficiently small elements must be used. The combined effect of these two requirements leads to very high cost and requires a very large computer storage memory. Radiation damping is considered only if a large enough soil model is used to represent the energy dissipation into the soil. To incorporate the strain-dependent properties and damping, an approximate procedure called "equivalent linear method" is commonly used in the direct finite element approach. This approximate method of solution does not satisfy compatibility of strain at each instant of time and it tends to overestimate the system damping and underestimate the system stiffness (2).

A recent development of the direct finite element method of analysis allows the use of transmitting boundaries to simulate the effect of radiation damping within the plane. To approximate the three-dimensional effect of a soil-structure systems, viscous boundaries are used along the planar surface of a soil slice in which one or more structures are located. In spite of these significant improvements in the direct finite element method to eliminate its inability to represent an extended earth by a numerical grid of finite extent, no satisfactory conditions have been developed for allowing seismic energy to pass through the bottom boundary of the soil-structure model. The direct finite element method can, however, reproduce the condition in which a softer layer overlays a harder half-space.

There are also difficulties in prescribing the incoming seismic waves for the direct finite element method. The conventional procedure of specifying free-field particle motions along a grid boundary to simulate incoming seismic waves neglects the existence of a scattered wave field which arises from the presence of an embedded structure. The direct finite element method in its present form cannot study the torsional response of a soil-structure system as a result of the non-vertically incident seismic waves, or the lack of symmetry of the structural configuration. It has been shown that non-vertically incident SH waves generate a marked torsional response, and non-vertically incident P waves and SV waves may cause a considerable amount of rocking of the foundation. The non-vertical incident of the seismic waves also causes a notable decrease in the translational response for high frequencies (11, 12). These results suggest that seismic soil-structure interaction studies should not be limited to seismic excitation with vertical incident only.

POWER PLANT DESCRIPTION AND SOIL PROPERTIES

The nuclear power plant analyzed is deeply embedded in layered soil media and is potentially subject to a high-intensity earthquake. The reactor building is 279 feet square in plan, 249.3 feet high, and 147.6 feet embedded. The design earthquake time history is the first 12 seconds of Taft 1952 EW specified at the surface of the plant free-field. The surface motion is to be so scaled that the design peak accelerations, 0.306 g, is obtained at the base of the free-field soil column.

The plant soil profile used for the seismic analysis is shown in Figure 3. In the free field, a Banjin sand layer exists from the surface (El. 17.38 ft) to El. -2.30 ft. The soft mudstone layer then extends to El. -48.22 ft, after which there is hard mudstone for the remainder of the soil deposit. The reactor building is founded in the hard mudstone. Backfill material is placed in the excavation on the sides of the building down to El. -69.54 ft. Soil properties used for the seismic soil-structure interaction analysis are given in Table 1.

DIRECT FINITE ELEMENT SOIL-STRUCTURE INTERACTION ANALYSIS

Figure 4 illustrates the soil-structure model of the reactor building used in the direct finite element (FLUSH) analysis. The transmitting boundary is used to model the effect of a semi-infinite half-space. Viscous boundaries are used by FLUSH to model the out-of-plane energy dissipation through the soil. The viscous dampers extend up to the ground level, and their damping properties are based on the free-field soil properties. Because of the symmetry, only half of the reactor building model is considered. No horizontal motion is permitted along the centerline of the building. Results of the direct finite element analysis are shown in Table 2.

IMPEDANCE APPROACH SOIL-STRUCTURE INTERACTION ANALYSIS

The dynamic force displacement relationships for a rigid foundation embedded in a layered elastic half-space play an important role in the study of seismic soil-structure interaction. These relationships permit the calculation of the seismic response of a soil-structure system. In this study, the method proposed by Day (13) to obtain the dynamic response of embedded rigid foundations is used. The computed impedance functions and input motions are combined with the structural parameters to obtain the total interaction foundation motions. The interaction foundation motions are then used as superstructure base excitation to obtain the dynamic structural response using the procedure described by Lee and Wesley (14).

VERTICAL IMPEDANCE FUNCTIONS AND INPUT MOTIONS

To find the foundation impedance matrix $[K(\omega)]$, which describes the steady-state response of the foundation, a corresponding transient problem is solved to obtain an impulse response matrix $[\bar{K}(t)]$. The foundation impedance matrix $[K(\omega)]$ is obtained from $[\bar{K}(t)]$ through Fourier transformation. A mixed boundary value problem is solved to determine each column of the foundation impulse response matrix $[\bar{K}(t)]$.

The input motion $\{U^*\}$ associated with a particular seismic disturbance is found by determining the generalized forces $\{F^*\}$ required to hold foundation stationary in the presence of the incident disturbance. Once $\{F^*\}$ is known, $\{U^*\}$ is obtained from $\{F^*\} = [K]\{U^*\}$. To find $\{F^*(\omega)\}$, which corresponds to a steady-state seismic disturbance, a transient problem is solved. A transient generalized force $\{F^*(t)\}$ is found, and a Fourier transformation is used to obtain $\{F^*(\omega)\}$. An explicit time stepping finite element algorithm based on one described by Frazier and Petersen (15) is used to obtain an approximate solution of these mixed boundary value problems.

Impedance Function

The soil-foundation model used to evaluate the vertical impedance function and input motion is shown in Fig. 5. The model assumes axisymmetry and only half of the soil foundation system is considered. Since the method presently does not take into account nonlinear strain-dependent soil properties, the iterated soil properties used in the vertical FLUSH analysis are employed in the present investigation.

The complex vertical impedance function, K_{VV} which describes the vertical force-displacement relationship between the foundation and soil medium can be expressed as:

$$K_{VV} = Ga(k_{VV} + ia_O c_{VV}) \qquad (1)$$

where: k_{VV} = the vertical stiffness coefficient

c_{VV} = the vertical radiation damping coefficient

a_O = the dimensionless frequency, $\omega \cdot a/V_S$

a = equivalent radius of the axisymmetric reactor building model

G = shear modulus of reference

V_s = shear wave velocity of reference

For normalization purposes, the rigidity G and the shear wave velocity V_s of reference are taken equal to the corresponding values for the soil under the base of the foundation.

Figure 6 shows the computed vertical stiffness and radiation damping coefficients for the embedded reactor building foundation. These values are normalized by use of a reference shear modulus and a reference shear wave velocity. The stiffness and radiation damping coefficients show a strong dependency on frequency. This strong frequency-dependence is associated with the soil layering and the presence of Rayleigh or surface waves. A detailed discussion of this aspect may be found in Reference 16.

The method developed by Luco (19) has been used to investigate the effect of foundation embedment on the impedance function of a rigid foundation. As indicated in Figure 6, the surface foundation has comparable vertical stiffness coefficients and lower radiation damping coefficients as compared to those of an embedded foundation.

Vertical Input Motion

The vertical input motion for the embedded reactor building foundation for the case of vertically incident P waves is obtained. The P waves excite only vertical motion of the embedded foundation, so that the foundation input motion can be written as:

$$\{U^*\} = (0,0,\Delta V,0,0,0)^T \qquad (2)$$

where ΔV represents the vertical translation of the foundation. The vertical free-field displacement (displacement in the absence of waves generated by the embedded rigid foundation) for the P waves is assumed to have an amplitude U_V at grade level.

Figure 7 shows the numerical values obtained for $\Delta V/U_V$ as functions of the dimensionless frequency a_o. For a surface foundation, the vertical input motion would simply be equal to the vertical free-field amplitude U_V at all frequencies. However, Figure 7 indicates that the amplitude of ΔV for an embedded foundation is slightly reduced, especially at high frequencies, as a result of the foundation embedment. On the average, the magnitude of ΔV is reduced to approximately $0.85U_V$. Also, the effect of soil layering introduces a marked frequency dependence.

FACTORS AFFECTING FOUNDATION RESPONSE

Effect of Superstructure Model

The following three fixed base lumped mass building models are used to investigate the effect of details of structural modeling on the vertical foundation motion.

a. Model A uses the vertical lumped mass reactor building stick model without the building internals.

b. Model B is the same as the stick Model A except that the stiffnesses of the members below grade are increased 100 times to simulate structural rigidity as assumed for the building in computing the foundation impedances.

c. Model C is the same as the Model A but uses additional masses to represent the building internals.

Figure 8 shows the comparison of the response spectra of the computed vertical foundation motions. There is good agreement in maximum spectral acceleration and frequency for maximum spectral acceleration for the vertical foundation motion. This suggests that the reactor building itself is very stiff. The frequency for maximum spectral acceleration is not sensitive to any further stiffness increases. In general, similar vertical foundation motion is obtained independent of the rigidity assumptions below the ground surface. Also, the inclusion of building internals does not affect the vertical foundation motion in this case.

Effect of Impedance Function and Input Motion

Two types of vertical impedance function as shown in Figure 6 and two types of vertical input motion as shown in Figure 7 are used in conjunction with the vertical lumped mass stick Model A to investigate the effects of impedance functions and input motions on the total vertical foundation motion. The effect of the use of embedded vertical impedance function or flat vertical impedance function on the vertical foundation motion is quite significant as can be seen from the vertical response spectra shown in Figure 9. The use of embedded vertical input motion and free-field input motion has insignificant effect on the vertical foundation motion. As indicated in Figure 10, the use of free-field input motion gives a slightly conservative vertical foundation motion as compared to that obtained using embedded vertical input.

COMPARISON OF RESULTS

Vertical seismic soil-structure interaction analysis results obtained using both the direct finite element method (FLUSH) and the impedance approach are compared. These results are compared in terms of peak acceleration and 5% floor response spectra.

The distribution of the peak acceleration for different floor levels of the reactor building is shown in Table 2. For the present case FLUSH and impedance approach predict slightly different vertical peak accelerations at both the foundation base and different floor levels of the structure. The FLUSH predicts a vertical peak acceleration of .46 g for the foundation base and peak acceleration of .61 g for the top of the reactor building. The predicted vertical peak accelerations for the foundation base and the top of the building obtained from the impedance approach analyses are .54 g and .70 g respectively. In the building at the level of the ground surface, the peak vertical response obtained from FLUSH and impedance approach are .57 g and .68 g, while it is .57 g in the free-field. This suggests that the building provides about the same amplification as the comparable portion of the free-field soil column. The ratio of peak vertical accelerations at the top and the foundation base of the reactor building are practically the same for both the FLUSH and impedance approach results.

The peak vertical acceleration, peak spectral acceleration and the corresponding frequency are summarized in Table 2 . Both FLUSH and the impedance approach predict the same frequencies for spectral spikes at 3.0 and 4.5 cps which appear to be the characteristics of the base motion. However, at the top of the reactor building the FLUSH analysis predicts a maximum spectral acceleration 20% lower than that predicted by the impedance approach (Figure 11). The response spectra obtained from both the FLUSH and the impedance approach analyses do not change significantly with height in the building. This is typical of vertical seismic soil-structure interaction analyses where the building is more rigid than the soil medium.

The differences in the vertical peak accelerations and the spectral amplitude can be attributed to two causes:

1. Material damping is not considered in the impedance approach analysis.

2. The two-dimensional characteristics of the FLUSH solution may give spectral response lower than that of a three-dimensional solution (17).

In the 2-D model the waves usually get trapped within the slice and energy attenuation is mainly due to material damping. In the 3-D case, the waves will attenuate essentially as the inverse of the distance even if no material damping is present. Comparison study by Berger et. al. (18) on 2-D and 3-D vertical seismic soil-structure interaction analyses indicates that the vertical response spectra are very similar in shape. However, the 3-D analysis gives spectral amplitudes which are consistently slightly larger than those of the 2-D analysis. At the top of structure, the difference in response between these two types of analyses becomes more pronounced. The 3-D solution may result in response values up to 30% higher than that obtained from the 2-D solution. This suggests that the major contribution to the difference in the vertical FLUSH and the impedance approach analyses may be attributed to the two-dimensional characteristics of the FLUSH analysis.

SUMMARY AND CONCLUSIONS

1. FLUSH and the impedance approach predict slightly different vertical peak accelerations. The peak spectral acceleration at the top of the reactor building obtained by FLUSH is approximately 20% lower than that obtained by the impedance approach.

2. The foundation embedment slightly increases the vertical stiffness and significantly increases the vertical radiation damping.

3. The amplitude of the vertical input motion at the foundation base is slightly reduced (about 85%) due to the presence of the rigid foundation.

4. The details of structural modeling on the vertical foundation motion obtained using the impedance approach is negligible for this study.

5. The use of the surface impedance gives very conservative foundation motion and superstructure responses as compared to those obtained using the vertical embedded impedance function.

6. The difference between the response obtained by use of the embedded input motion and that based on the free-field input motion is insignificant for this analysis.

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Table 1
Soil Properties
For Seismic Analysis

Property	Banjin Sand	Soft Mudstone	Hard Mudstone
Unit Weight (KCF)	.125	.120	.107
Poisson's Ratio	.48	.33	.43
Shear Wave Velocity (FPS)	984.	197.-547.	1771.-2198.
Shear Modulus (KSF)	3757.	145.-1117.	10470.-16140.

Table 2

Flush and Impedance Approach

Response Spectra Summary (5% Damping)

Elevation (Ft)	Peak Acceleration (g)		Maximum Spectra Acceleration S_a (g)		Frequency For S_a (cps)	
	Flush	Classi	Flush	Classi	Flush	Classi
118.1 (36.0 m)	.711	.715	2.23/ 2.19	3.2/ 2.9	8.0/ 2.4	6.0/ 3.0
59.0 (18.0 m)	.62	.48	1.9	2.35	2.4/ 2.2	3.0/ 2.4
17.4 (5.3 m)	.46	.49	1.67	1.98/ 1.90	2.4	2.4/ 3.0
-8.9 (-2.7 m)	.48	.47	1.48	1.80	2.4	2.4
-52.8 (-16.1 m)	.41	.43	1.19	1.50	2.4	2.4
-106.6 -32.5 m) Translation	.37	.37	.86	1.15/ 1.03	2.2	2.4/ 7.0
-106.6 -32.5 m) Rocking	.17*	.17*	.73	.90	3.0	3.0

* $a\ddot{\phi}/g$, a = 42.5 meters

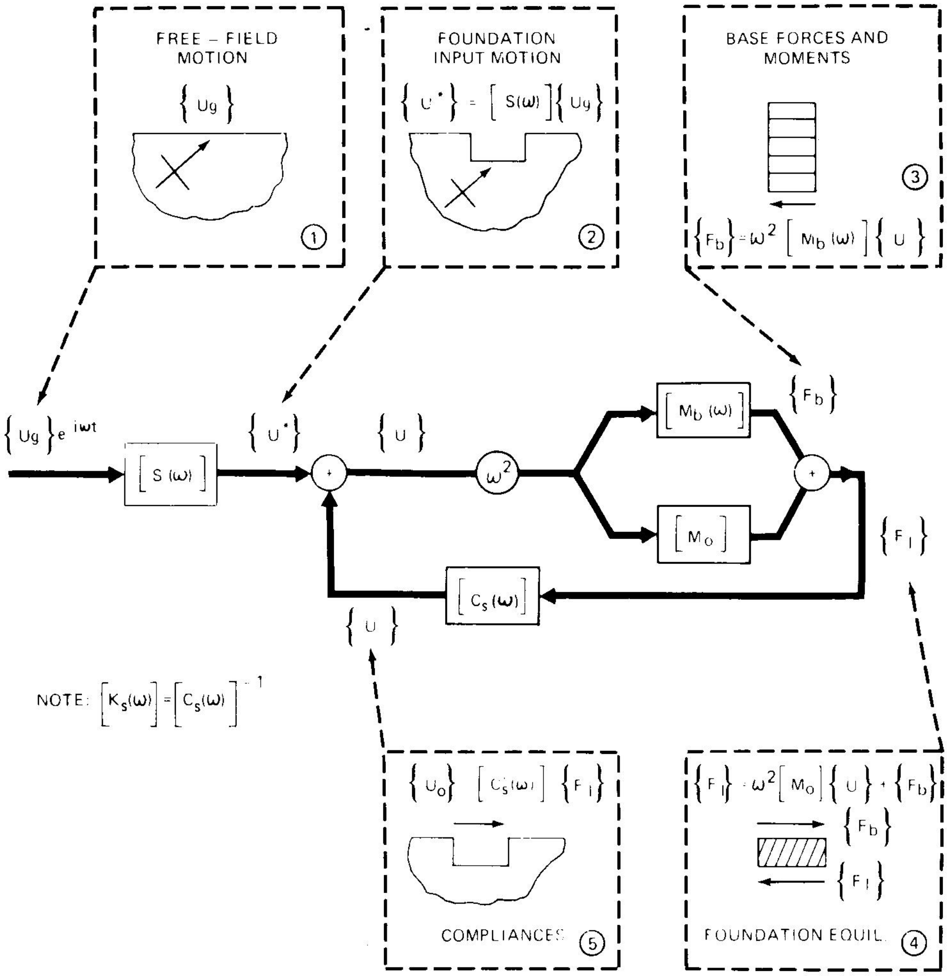
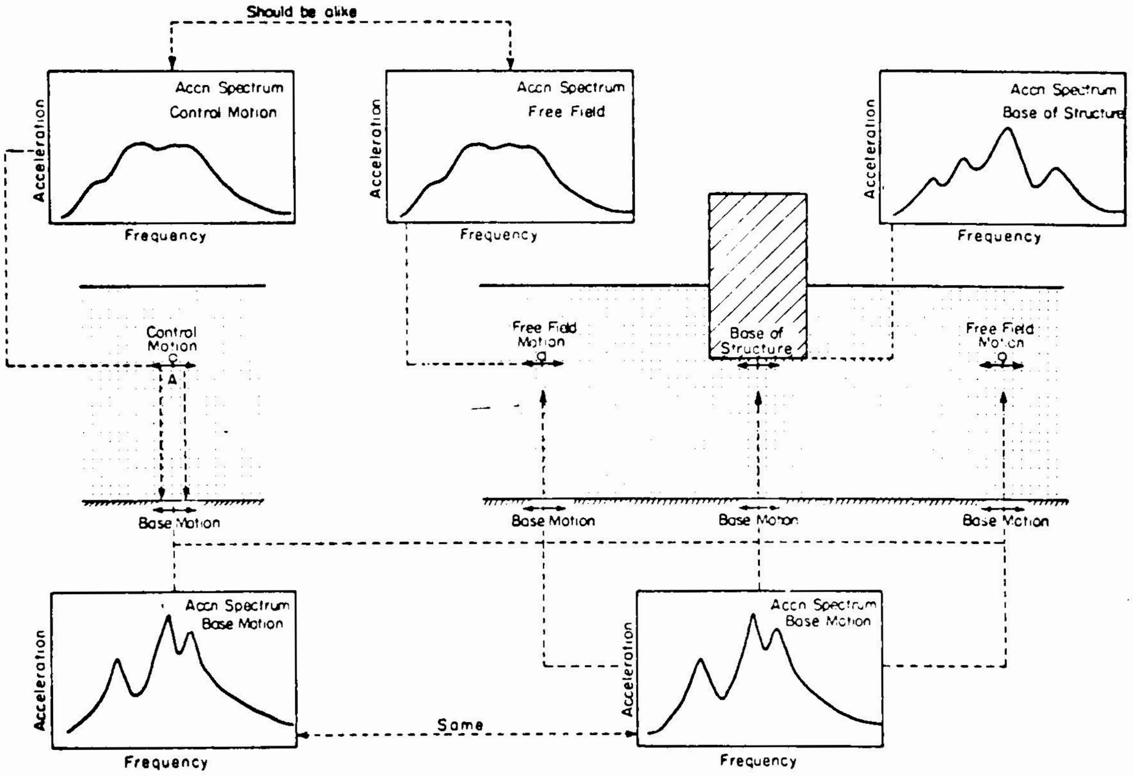


FIGURE 1

PROCEDURE FOR COMPLETE SOIL-STRUCTURE INTERACTION ANALYSIS USING IMPEDANCE APPROACH



(a) Free-Field Model (b) Model of Soil-Structure System

FIGURE 2

SCHEMATIC REPRESENTATION OF SOIL-STRUCTURE INTERACTION ANALYSIS USING FINITE ELEMENT MODEL

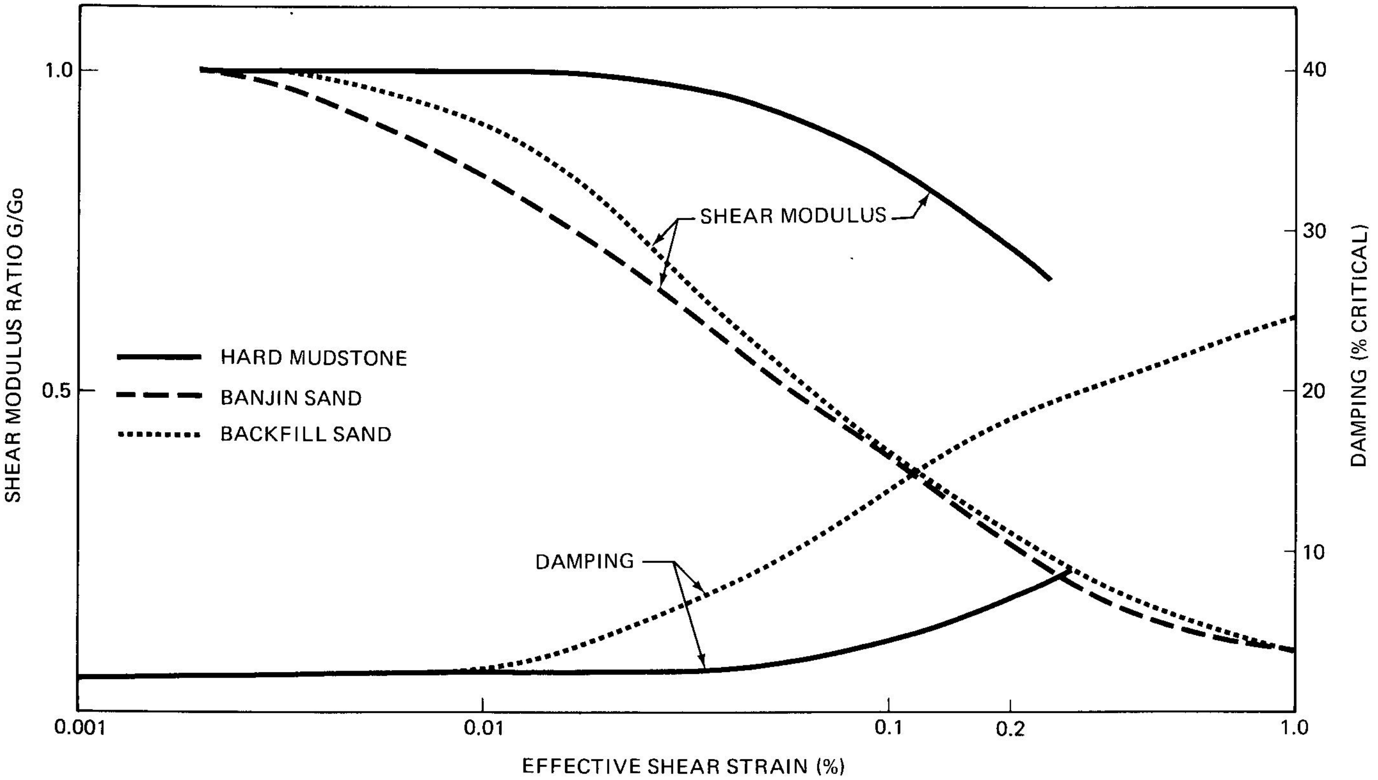


FIGURE 3

STRAIN DEPENDENT PROPERTIES FOR SOILS

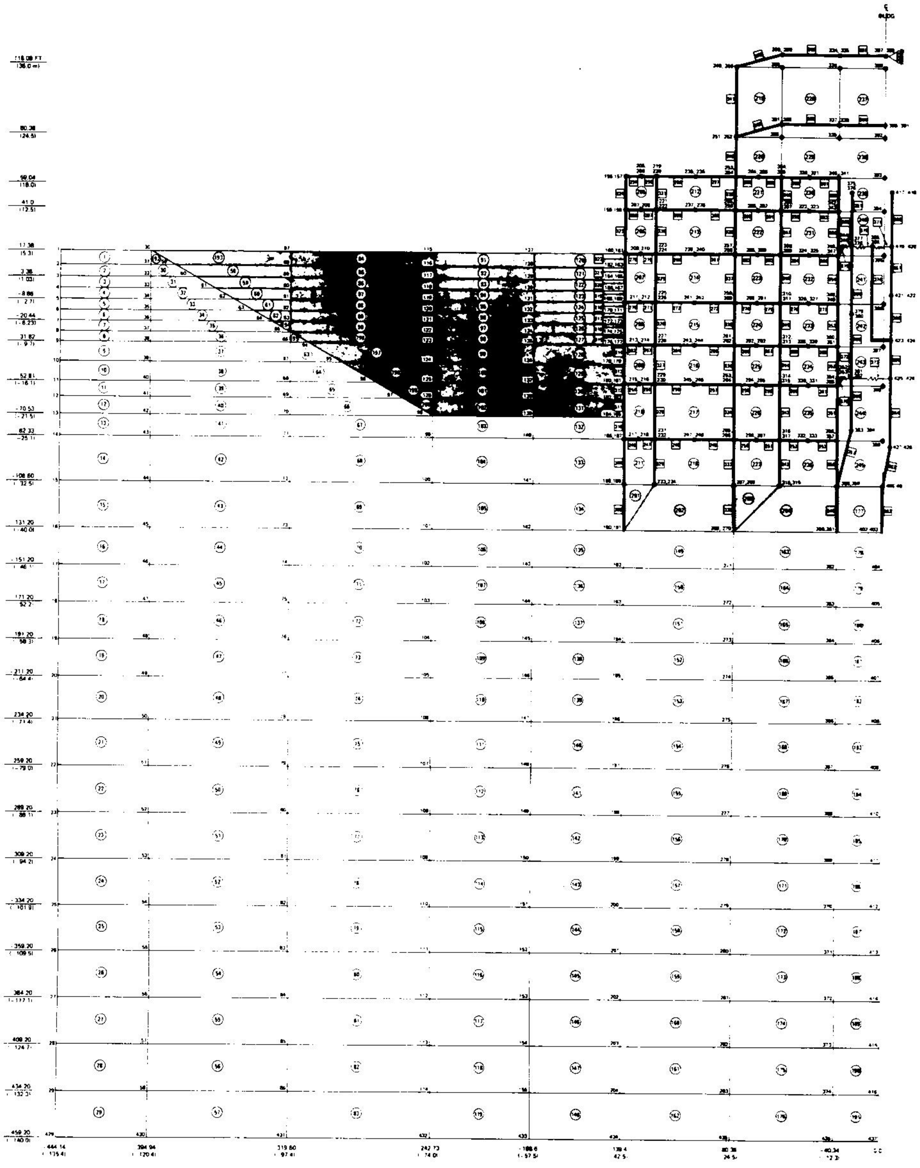


FIGURE 4

VERTICAL FLUSH SOIL-STRUCTURE MODEL

REACTOR BUILDING

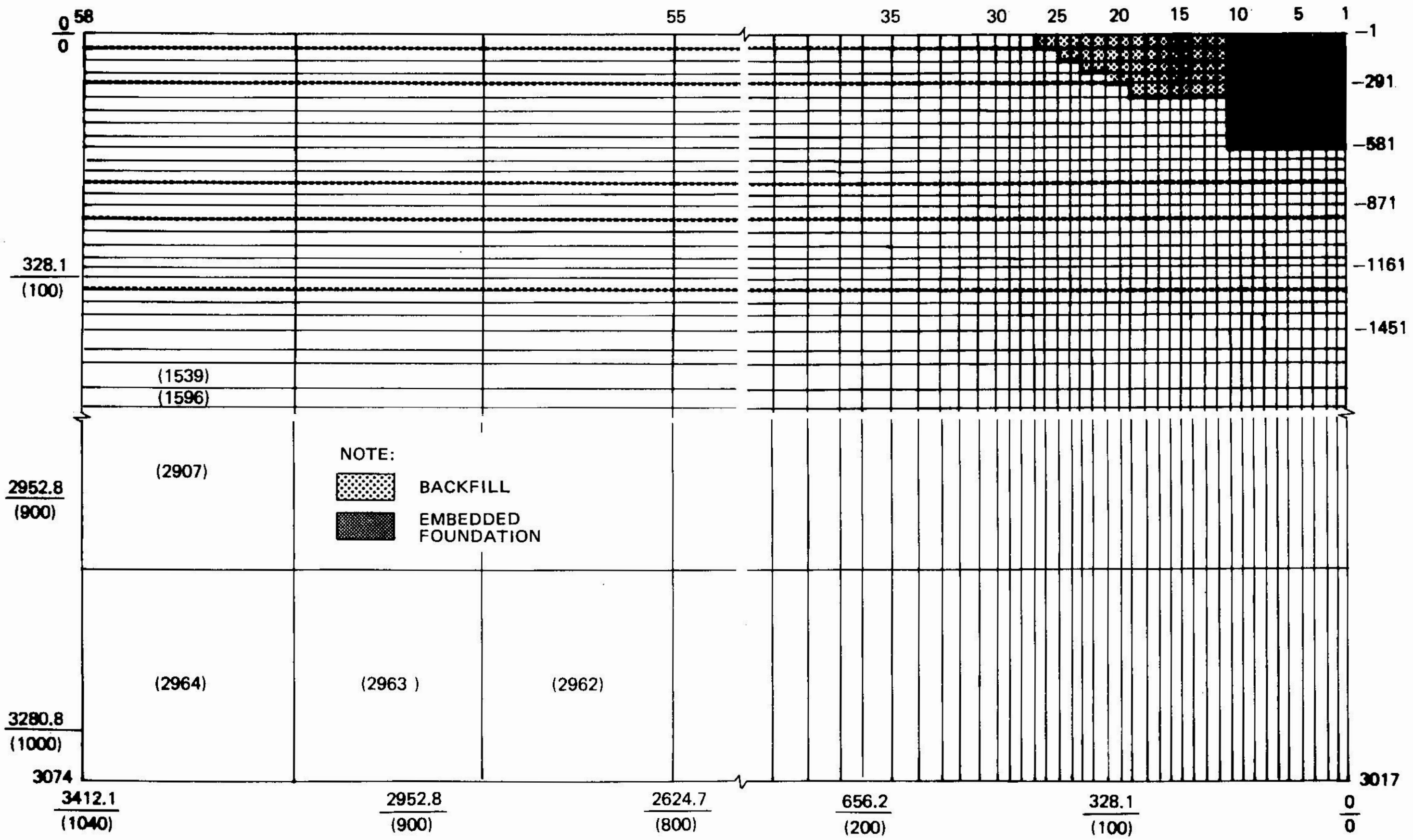


FIGURE 5
SOIL-STRUCTURAL MODEL FOR IMPEDANCE APPROACH ANALYSIS

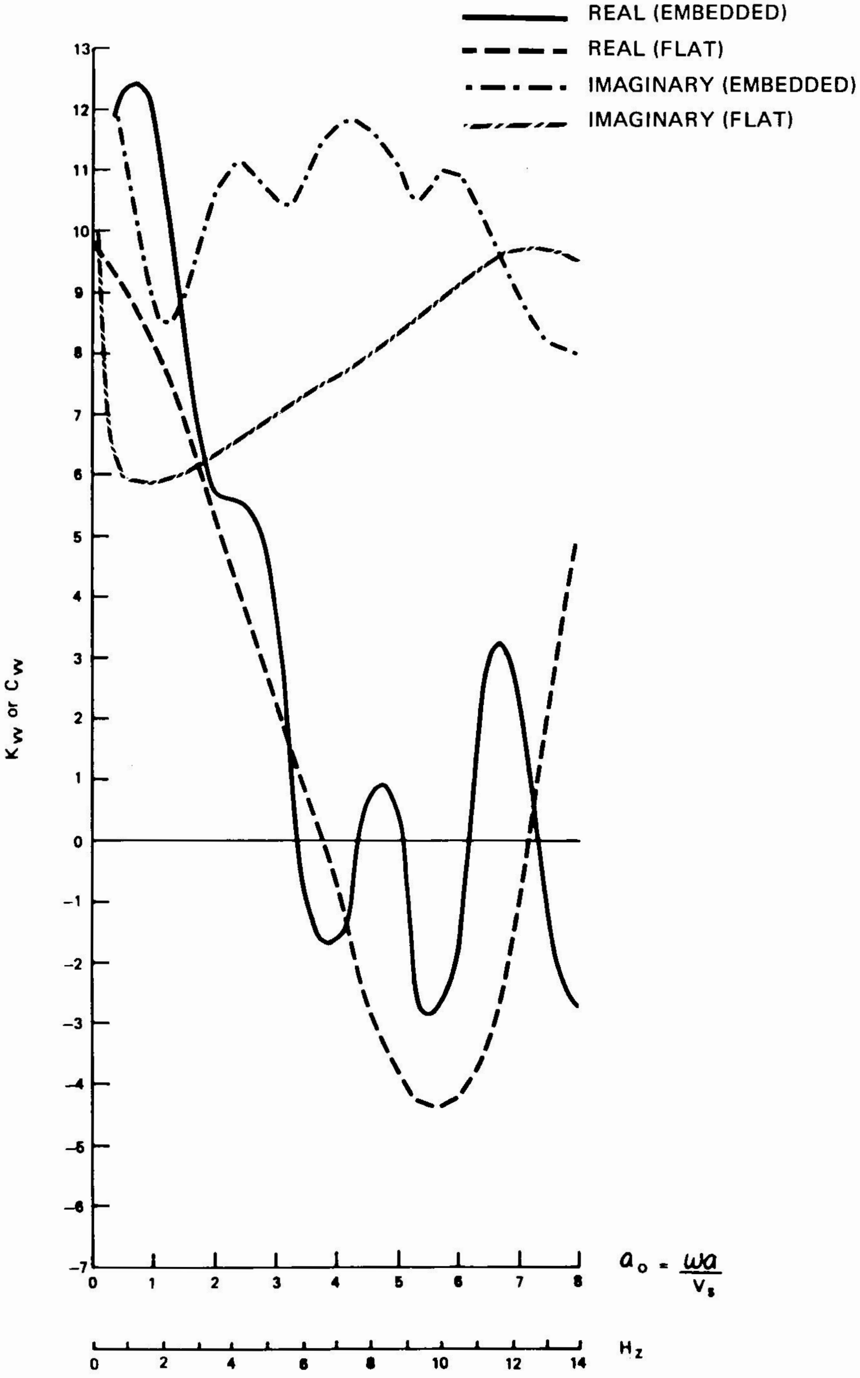


FIGURE 6

REAL AND IMAGINARY PART OF VERTICAL IMPEDANCE FUNCTION

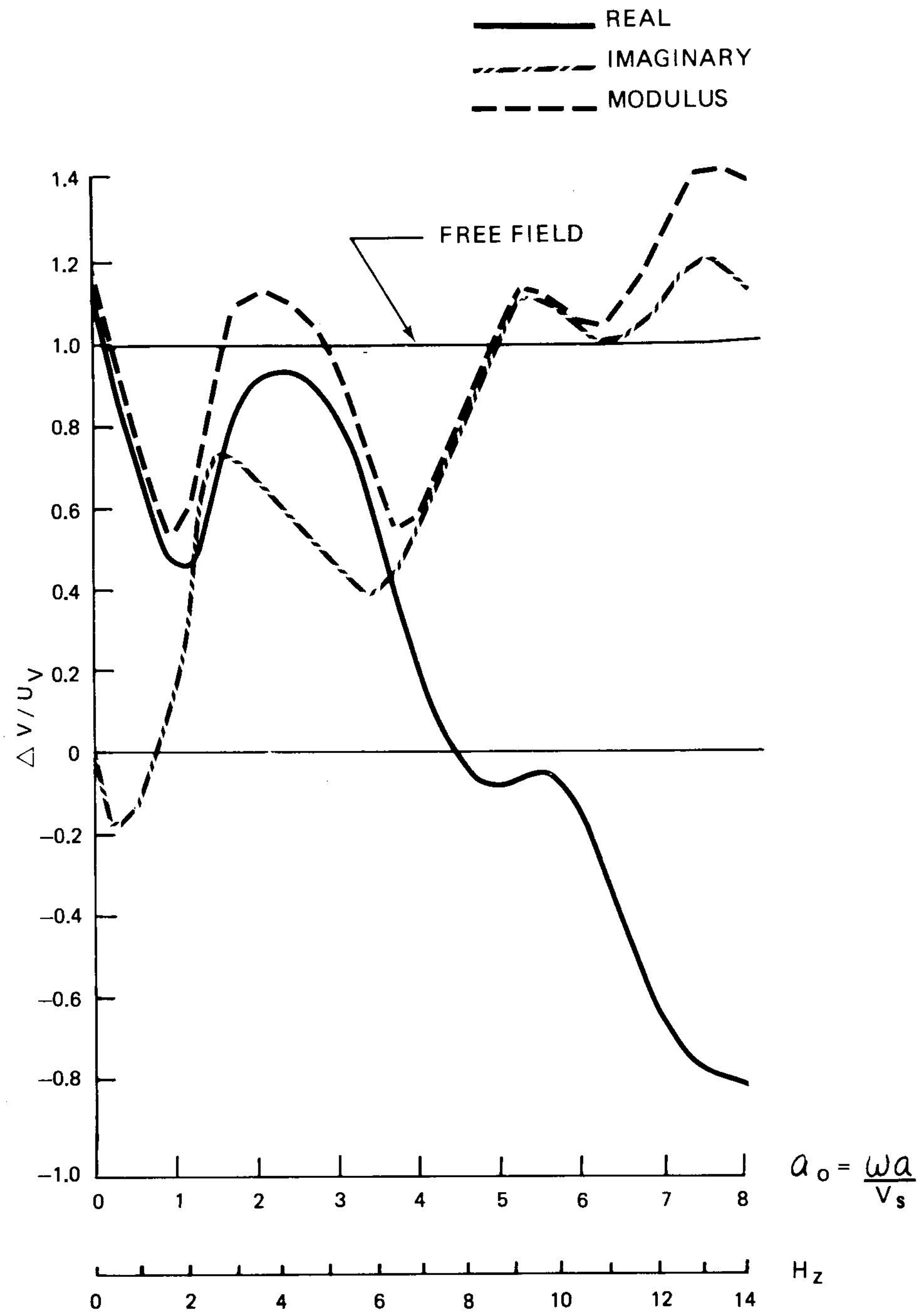


FIGURE 7

VERTICAL INPUT MOTION

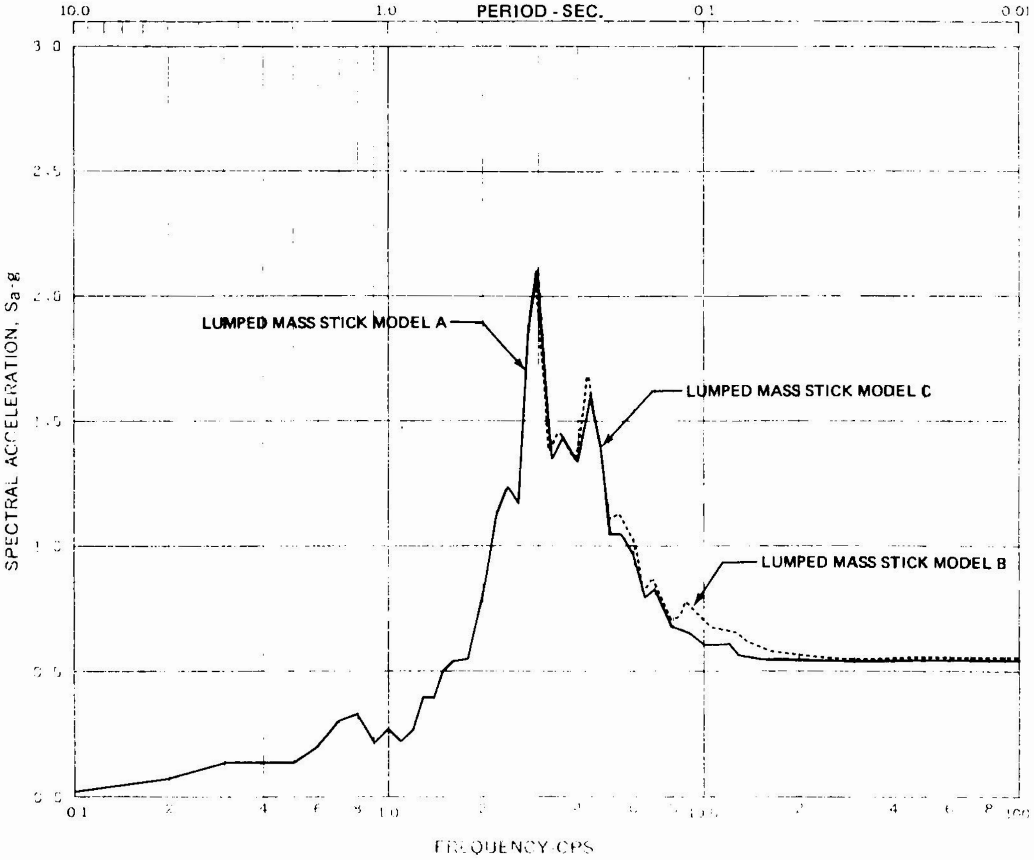


FIGURE 8

EFFECT OF DETAILS OF STRUCTURAL MODELING
ON VERTICAL FOUNDATION MOTION (EL. -131.2 FT.)

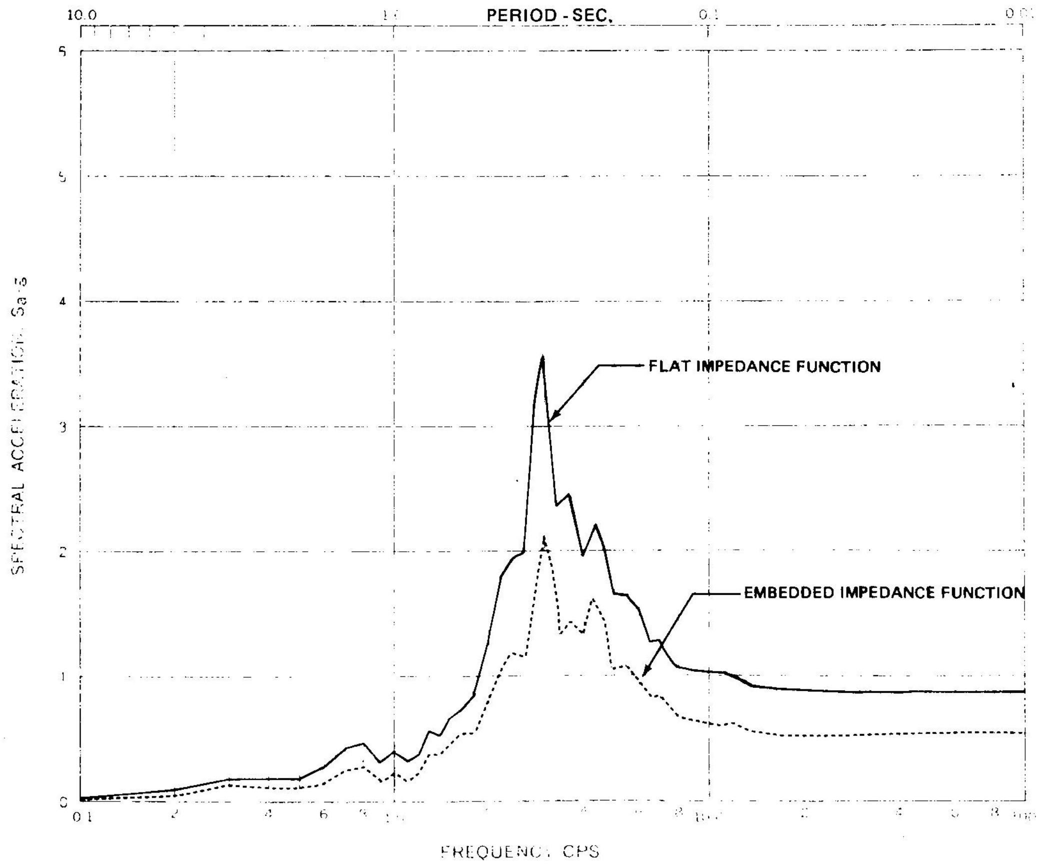


FIGURE 9

EFFECT OF EMBEDDED IMPEDANCE FUNCTION AND FLAT IMPEDANCE FUNCTION ON VERTICAL FOUNDATION MOTION (EL. -131.2 FT)

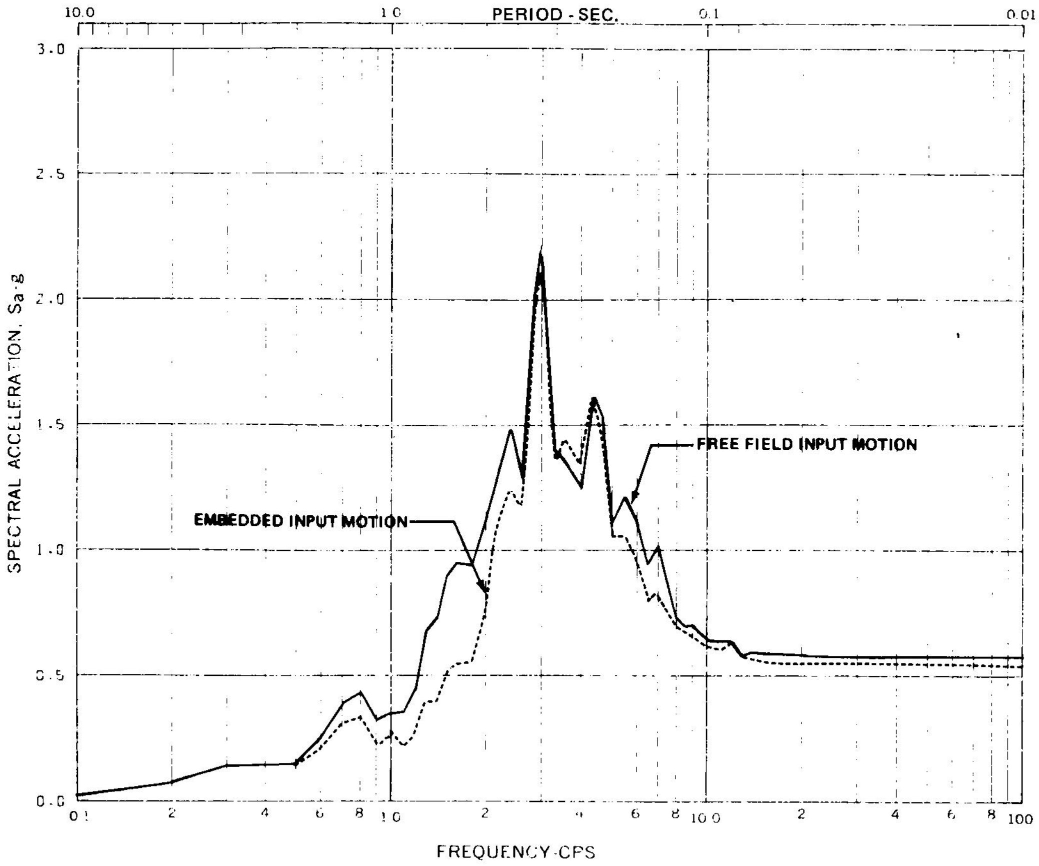


FIGURE 10

EFFECT OF EMBEDDED INPUT MOTION AND FREE FIELD.
INPUT MOTION ON VERTICAL FOUNDATION MOTION (EL. -131.2 FT)

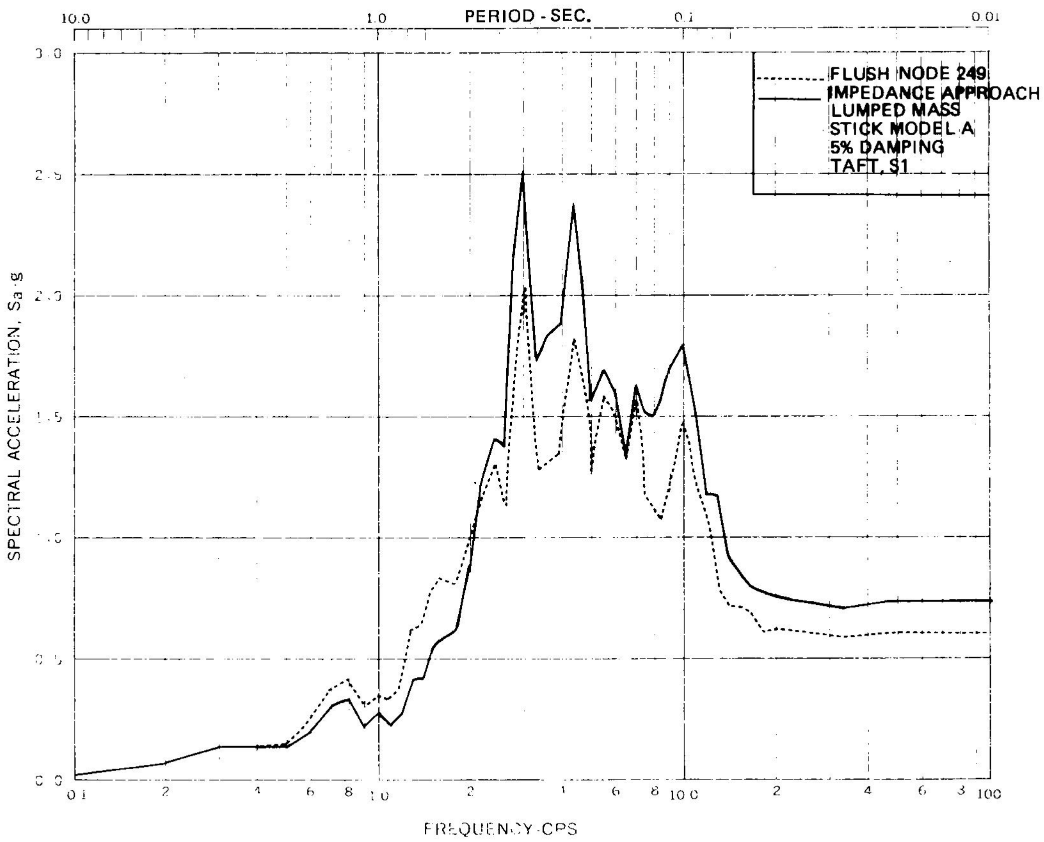


FIGURE 11
RESPONSE SPECTRA, S1, VERTICAL,
REACTOR BUILDING,
TOP (EL. 118.08')