NONLINEAR SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS OF NUCLEAR POWER PLANT STRUCTURES

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SUMMARY

The heterogeneous and nonlinear soil medium and the detailed three-dimensional structure are synthesized to determine the seismic response to soil-structure systems. The approach is particularly attractive in a design office environment since it:

a) leads to detailed structural response without the additional step of exciting the structure by interactive motion at the soil-structure interface;
b) uses existing public domain programs such as SAPIV, LUSH and FLUSH with marginal modifications; and
c) meets current regulatory requirements for soil-structure interaction analysis.

Past methods differ from each other depending on the approach adopted for soil and structure representations and procedures for solving the governing differential equations. Advantages and limitations of these methods are reviewed.

In the current approach, the three-dimensional structure is represented by the dynamic characteristics of its fixed base condition. This representation is ideal when structures are designed to be within elastic range. An important criterion is the design of the nuclear power plant structures. Model damping coefficients are varied to reflect the damping properties of different structural component materials. The detailed structural model is systematically reduced to reflect important dynamic behavior with simultaneous storing of intermediate information for retrieval of detailed structural response.

The approach uses current concepts in the finite element idealization of the soil medium as developed by Lysmer et al. and as incorporated in the LUSH and FLUSH programs. Unlike other approaches that extract soil modes or predetermine soil impedence functions, the present approach retains the physical configuration of the soil medium throughout the analysis.

Structural representation is put in the form of "eigen elements" having complex material properties. These "eigen elements" are coupled with physical finite element representation of the soil. The approach thus facilitates automated iterative usage of the frequency domain integration to provide a practical solution of a truly nonlinear problem. The resulting structural responses, which are of primary concern to designers, correctly account for the inertial, rigid body translational and rocking effect. It has been demonstrated that neglecting the rocking effect in computing structural response produces erroneous results. Simple dynamic models of adjacent buildings used with the modal representation of the main building account for the effect of inter-building interaction.

Governing equations of motion and flow charts for procedural implementation are presented. The approach documented in an earlier report is the first step in consolidating structural response programs with current soil-structure interaction programs for obtaining seismic response of structural systems.

Validity of the approach has been established with simple numerical experiments. A numerical example of the soil-structure interaction analysis of a reactor building is presented to show the efficiency and effectiveness of the new approach.

1.0 INTRODUCTION

A method is developed for the seismic analysis of nuclear power plant structures including soil-structure interaction. This method synthesizes the finite-element representation of the heterogeneous and nonlinear soil medium and the modal representation of the three-dimensional structure.

The conventional approaches for seismic analyses including soil-structure interaction, have been to represent the structure with its inherent complex arrangement of load-carrying components, and the soil medium, by plane-strain finite elements. The material nonlinearity of the soil medium is accounted for by solving the nonlinear eouations of motion in an iterative fashion [1, 2]. This approach requires gross approximations in arriving at a reasonable number of elements to represent all the important structural components. Generally the number of elements is limited by modeling the structure very crudely with a few finite elements.

In the conventional approach a soil-structure plane-strain model is first analyzed to establish the interactive motion at the base of the structure. A second analysis is then performed wherein the computed interactive translatory motion is applied to the base of the more detailed structural model to obtain the response of the structural components. Since the translatory base motions alone produce erroneous structural response both the translatory and rocking interactive motions of the base of the strucure must be used [3].

The method described in this paper offers an improvement over the conventional approaches as the investigator is now capable of analyzing directly an elaborate three-dimensional structural model combined with a finite element model of the soil. The three-dimensional structure is represented by the predominant dynamic characteristics of its fixed base condition. This representation is particularly suited for nuclear power plant structures which are designed elastically.

The detailed structural model is first systematically reduced to its modal representation form so as to reflect important dynamic behavior. The modal representation is then coupled with physical finite elements representing the soil. The approach thus facilitates automation by minor modifications of the program LUSH [1]. This modified program integrates equation of motions in the frequency domain to provide a practical solution of a nonlinear problem. The resulting structural response correctly accounts for the rigid body translation and rocking motions of the foundation mat.

The representation of the structure by the predominant modes reduces the number of simultaneous equations and consequently the problem size.

Unlike other approaches that extract soil modes [4] or predetermine soil impedence functions [5], the method described in this paper retains the physical configuration of the soil throughout the analysis. Therefore, simple models of adjacent buildings may easily be used in conjunction with the modal representation of the main building, to account for the effects of inter-building interaction.

The equations of motion for a soil-structure interaction system are developed in the next section. The third section presents the procedures to solve the equations and describes the computer programs developed for the analyses. An application of the procedure to predict the soil-structure interaction of a nuclear containment is described in Section 4.

2.0 EQUATIONS OF MOTION

The equations of motion for a soil-structure model subjected to base (bedrock) motion are presented and are then modified to represent the structure by its predominant modes. These equations are put in a form so that the program LUSH/FLUSH, with minor modifications, could be used to solve them [1,6].

A typical finite-element model of a soil-structure system consisting of a structure, mat, and soil foundation is shown in Figure 1. The three-dimensional structure is represented by a combination of beam and plate elements whereas the mat and soil foundation are idealized by two-dimensional plane strain finite elements. In order to introduce dimensional compatibility between the two-dimensional soil elements and three-dimensional structural elements, the structural properties (such as Young's modulus, etc. of the structural elements) are appropriately scaled down [3].

If the components of the absolute displacements of the joints of the structure, foundation mat, and soil medium are designated as X_{st}, X_m and X_s respectively, and if their corresponding displacements relative to the base of the soil foundation are denoted as q_{st}, q_m and q_s, then the equations of motion for the total system may be written as:

$$[M]\ \{\ddot{X}\} + [C]\ \{\dot{q}\} + [K]\ \{q\} = 0 \qquad (1)$$

or

$$[M]\ \{\ddot{q}\} + [C]\ \{\dot{q}\} + [K]\ \{q\} = -\ [M]\ [N]\ \{\ddot{X}_o\} \qquad (2)$$

where,

$$\{X\} = \begin{Bmatrix} X_{st} \\ X_m \\ X_s \end{Bmatrix}, \quad \{q\} = \begin{Bmatrix} q_{st} \\ q_m \\ q_s \end{Bmatrix}, \quad \{N\} = \begin{Bmatrix} N_{st} \\ N_m \\ N_s \end{Bmatrix}$$

$$[M] = \begin{bmatrix} M_{st} & o & o \\ o & M_m & M_{ms} \\ o & M^T_{ms} & M_s \end{bmatrix}, \quad [C] = \begin{bmatrix} C_{st} & o & o \\ o & C_m & C_{ms} \\ o & C^T_{ms} & C_s \end{bmatrix}, \quad [K] = \begin{bmatrix} K_{st} & K_{stm} & o \\ K^T_{stm} & K_m & K_{ms} \\ o & K^T_{ms} & K_s \end{bmatrix}$$

M_{st}, M_m and M_s are square matrices representing the mass of the structure, the mat and the soil foundation respectively. M_{ms} is the dynamic cross-coupling matrix between the masses of the mat and the soil foundation. In case of the lumped mass approach, this matrix becomes a null matrix. The damping matrices C's and the stiffness matrices K's are similarly defined. N_{st}, N_m and N_s relate the rigid body motions of the structure, the mat and the soil medium to the base motion X_o.

Equation (2) will now be modified to incorporate the modal representation of the elastic structure.

The relative displacements q_{st} of the structure can be expressed in terms of the mode shapes of the structure with fixed base and displacements of a fixed reference point by

$$\{q_{st}\} = [\phi]\ \{\xi\} + [B]\ [\lambda]\ \{q_R\} \tag{3}$$

where ϕ is the matrix of the predominant modes of the structure, ξ's are the modal amplitudes, B is a matrix relating the rigid body motion of the three-dimensional structure to the motion of the reference joint, and λ is coordinate transformation matrix relating the three-dimensional coordinate system of the structure to the two dimensional coordinate system of the soil medium. The column vector q_R consists of two translations and a rotation of the reference joint in the plane of the soil elements.

The translation and rotation of the reference joint are related to a set of selected mat joints at the interface of the structure by

$$\{q_R\} = [\bar{B}]\ \{q_m\} \tag{4}$$

where elements of matrix $\bar{B}$ are defined by the coordinates of the selected mat joints and the reference joint, and are derived by a least square fit. Equation (4) implies that the selected mat joints are rigidly connected. For a relatively rigid mat of a typical power plant, average translations and rotation $\{q_R\}$ correctly describe the motion of the mat. The response of the structure away from the mat is not expected to be affected by the assumption of rigid connections between the selected mat joints.

Substitution of equation (4) into equation (2) yields

$$\{q_{st}\} = [\phi]\ \{\xi\} + [N_{st}]\ \{q_m\} \tag{5}$$

where, $[N_{st}] = [B][\lambda][\bar{B}]$

Substitution of equation (5) into equation (2), and combination of the stiffness and damping matrices by the method of complex moduli [7], yields equation (6) which relates the motion of the soil structure system in terms of both the modal amplitudes of the structure and the translations of the plane-strain soil elements. In the derivation of equation (6) the orthogonality relationships of the modes are used.

$$\begin{bmatrix} I & \phi^T M_{st}\bar{N}_{st} & 0 \\ \bar{N}^T_{st} M_{st}\phi & \bar{N}_{st}M_{st}\bar{N}_{st} + M_m & M_{ms} \\ 0 & M^T_{ms} & M_s \end{bmatrix} \begin{Bmatrix} \ddot{\xi} \\ \ddot{q}_m \\ \ddot{q}_s \end{Bmatrix} + \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \underline{K}^*_m & \underline{K}_{ms} \\ 0 & \underline{K}^T_{ms} & \underline{K}_s \end{bmatrix} \begin{Bmatrix} \xi \\ q_m \\ q_s \end{Bmatrix}$$

$$= - \begin{bmatrix} \phi^T M_{st}\bar{N}_{st} & 0 \\ \bar{N}^T_{st} M_{st}\bar{N}_{st} + M_m & M_{ms} \\ M^T_{ms} & M_s \end{bmatrix} \begin{bmatrix} N_m \\ N_s \end{bmatrix} \{\ddot{X}_0\} \tag{6}$$

The matrices $\underline{K}$'s in equation (6) are obtained by the method of complex moduli. Matrix $\underline{K}^*_m$ represents the complex stiffness of the mat and the soil foundation without any contribution from the structure; and matrix $\propto$ represents a diagonal matrix which combines the generalized (modal) stiffness and damping of the structure. The jth diagonal element of matrix $\propto$ is given by

$$\propto_j = \omega_j^2 \, [1 - 2\beta_j^2 + 2i\beta_j \sqrt{1-\beta_j^2}] \tag{7}$$

where ω_j and β_j denote the frequency and modal damping coefficient respectively for the jth mode of the structure fixed at its base.

The modal representation of the structure in equation (6) reflects the true three-dimensional character of the structure with the added advantage of reducing the total number of degrees of freedom for the soil-structure system. The influence of neighboring buildings on the main structure is easily considered by modeling the adjacent buildings with plane-strain finite elements.

The response for the degrees of freedom of the structure is obtained by the following equations:

$$\{X_{st}\} = [\phi] \{\xi\} + [\bar{N}_{st}] \{q_m\} \tag{8}$$

and

$$\{X_{st}\} = [\phi] \{\ddot{\xi}\} + [\bar{N}_{st}] \{\ddot{q}_m\} + [N_m] \{\ddot{X}_o\} \tag{9}$$

The stresses in the structural elements are computed by combining the modal stresses by probabilistic methods such as the square root of the sum of the squares method or the double sum methods [8].

The structural responses obtained by equations (8) and (9) account for complete soil-structure interaction involving both the translation and the rocking of the foundation mat.

3.0 SOLUTION OF EQUATIONS OF MOTION

A hypothetical element called the "eigen element" is introduced to assemble the generalized mass matrices and the stiffness matrices of the structure's mode shapes to the corresponding matrices of the soil elements. The incidences of an eigen element are the complete set of the selected mat joints at the structure-mat interface and a hypothetical joint called an "eigen joint". The degrees of freedom of the eigen joint are the amplitudes, ξ's, of the two successive modes of the structure. Thus, the total number of eigen joints and similarly the total number of eigen elements equal one-half the number of modes used for the structural representation.

The generalized mass matrix M_j^e and stiffness matrix $\propto_j^e$ of the jth eigen element are defined by equations (10) and (11) respectively.

$$[M_j^e] = \begin{bmatrix} I & [\phi_{2j-1} \; \phi_{2j}]^T [M_{st}][\bar{N}_{st}] \\ \text{sym.} & 0 \end{bmatrix} \tag{10}$$

$$[\alpha_j^e] = \begin{bmatrix} \alpha_{2j-1} & 0 \\ 0 & \alpha_{2j} \end{bmatrix} \qquad (11)$$

where the diagonal elements α_{2j-1} and α_{2j} are defined by equation (7).

A computer program is written to generate the submatrix $[\phi^T M_{st} \bar{N}_{st}]$. The input to the program consists of the mode shapes, frequencies of vibrations, coordinates and masses of structural joints and the incidences of the eigen elements (10).

The transfer mass matrix $[\bar{N}_{st}^T M_{st} \bar{N}_{st}]$ of equation (6), which represents the influence of the structural mass on the mat-joints, is also generated by the program.

Program LUSH is modified to incorporate eigen elements and transfer mass matrix with its plane-strain soil elements. The modified program FPILUSH, sets up and solves equation (6) and iterates on the strain-dependent soil properties. The converged solutions yield the motions of the physical degrees of freedom of the soil and the mat foundation, and the modal degrees of freedom of the structure. (A new program FLUSH [2], which has energy absorbing boundaries, could be used instead of the program lush to set up and solve equation 6).

A post processor [10] for the modified program LUSH generates the displacements and accelerations of the physical degrees of freedom of the structure. The program also computes the stresses in the various structural members by combining modal stresses through the use of probabilistic methods.

The solution procedure is shown in Figure 2 in the form of a block diagram.

A separate post processor program is also written to generate the acceleration spectra at the structural joints [9].

4.0 APPLICATION OF THE METHOD

The method is validated [6] through simple plane-strain models by comparing the results of the new method with those obtained directly by program LUSH. The problems for validation consisted of both symmetrical and asymetrical systems. The results were in good agreement. The small deviations in the results are attributed to the following assumptions in the method or approximations in the structural representation.

a. The flexibility of the structure-soil interface is approximately accounted for in the response of the structure through a least square fit.
b. The use of complex moduli for the "eigen element" representation of the structure.
c. Small number of modes considered for the structure.

The differences in the results are much smaller than the uncertainties associated with the soil properties.

The method is applied to an idealized representation of an isolated reactor building founded on a 100 foot (31.5m) deep soil medium, as shown in Figure 3; and the building is subjected to horizontal base motion. The reactor building was previously studied [3], by using the plane-strain representation of the structure and program LUSH. The structural model with 170 degrees of freedom is replaced in the present method by 10 dynamic degrees of freedom representing the first ten modes of the structure (Figure 4). This represents a reduction of 20 percent in the total degrees of freedom for the soil-structure system. The eigen elements shown in Figure 4 are connected to the joints at the horizontal interface. This introduces incompatibility of displacements at the vertical interface.

The shear stress variations along sections AA and BB of the soil foundation (Figure 3) are compared in Figures 5 and 6 respectively. The shear stresses differ by 15% near the level of the mat foundation (Figure 6). However, the differences diminish with the distance from the mat foundation. The variations in the shear stresses are attributed to the absence of the restraining effect of the embedment soil, and the difference in the distribution of the structural mass through the soil medium.

The spectra at the joint C of the structure for 1% of critical damping show good agreement as shown in Figure 7. The spectral accelerations obtained exhibit a faster drop from the peak values than do the accelerations calculated by the conventional method. These variations are attributed to the use of only 10 modes out of 170 possible modes to represent the structure. However, they are minimized in the design spectra which are developed by broadening the amplitudes of the peak accelerations to account for the differences in the soil and structural parameters.

5.0 SUMMARY AND CONCLUSIONS

A method for synthesis of a three-dimensional structure with a plane-strain finite element model of the hetrogeneous and nonlinear soil medium is described. The results of soil-structure interaction analysis of a typical reactor building on a soil medium obtained by the new method and by the conventional plane-strain finite element method are shown to be in good agreement.

The method is particularly attractive in a design office environment because it directly utilizes current public domain programs such as SAP and LUSH with marginal modifications.

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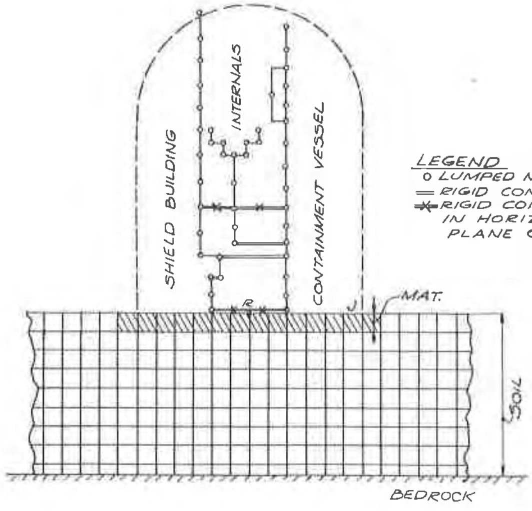

Fig. 1 Typical Finite Element Model of Soil-Structure System

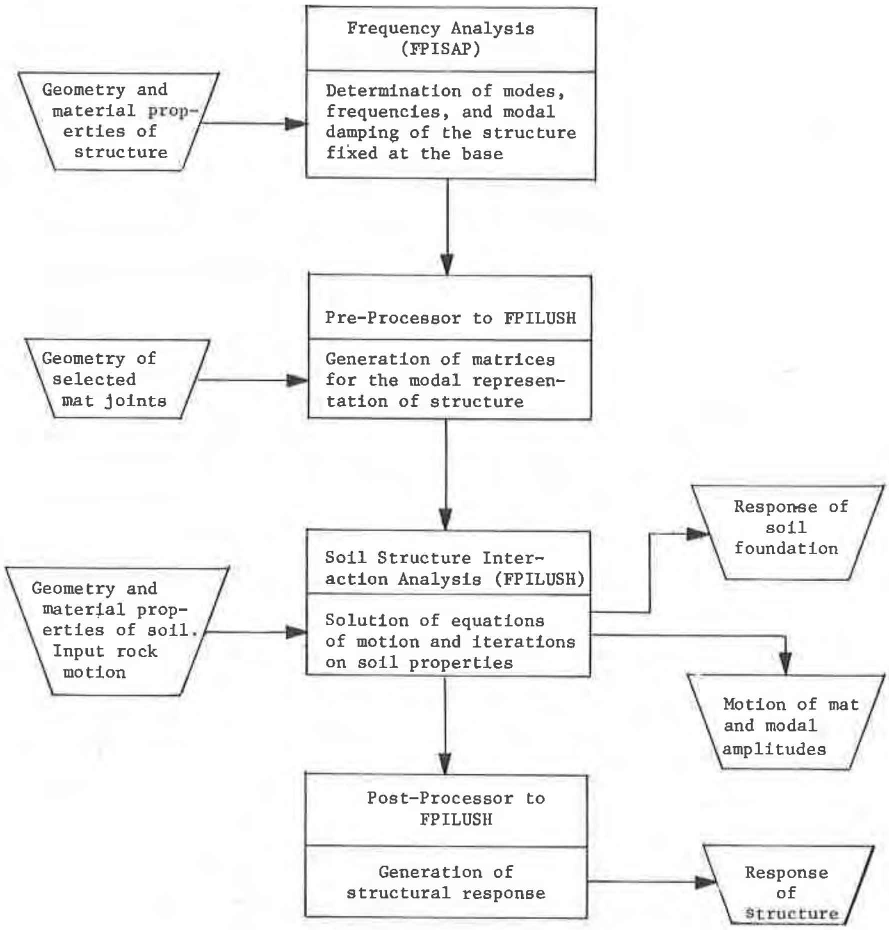

Fig. 2 Solution Procedure

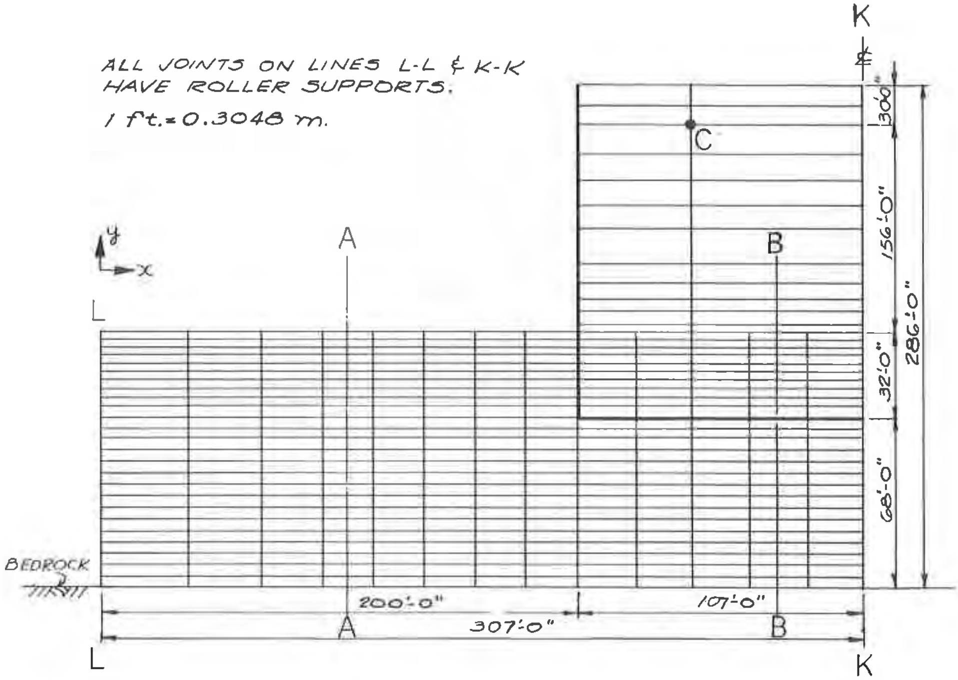

Fig. 3 Idealized Soil-Structure System for a Reactor Building on 100 ft. soil

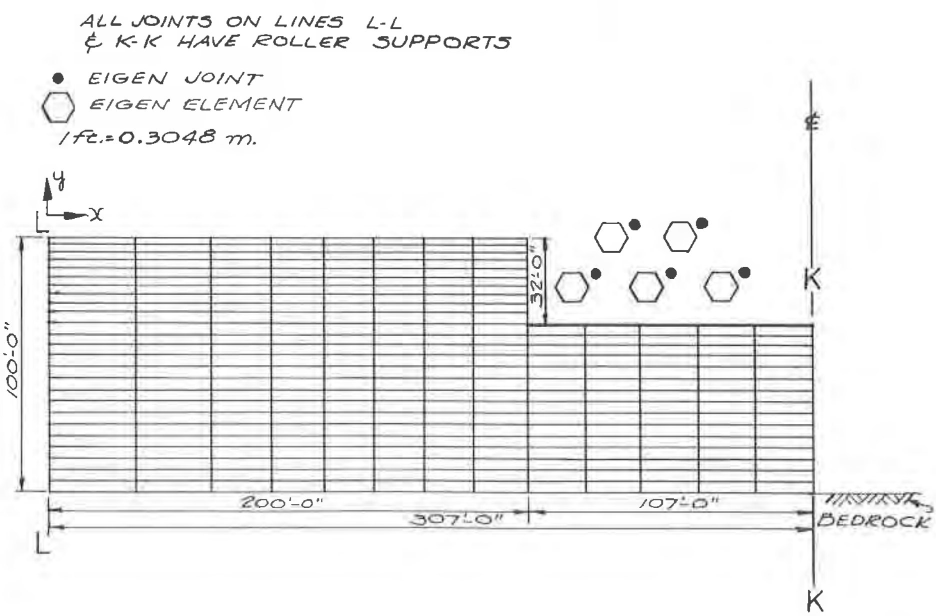

Fig. 4 Plane Strain Finite Element Model of Soil Foundation and Modal Form of Reactor Building

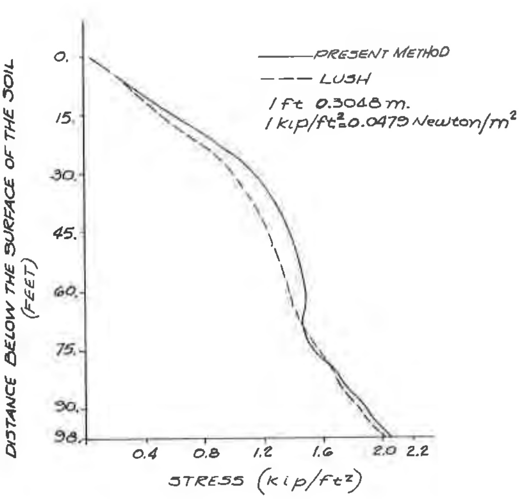

Fig. 5 Shear Stresses Along Section AA (Fig. 3)

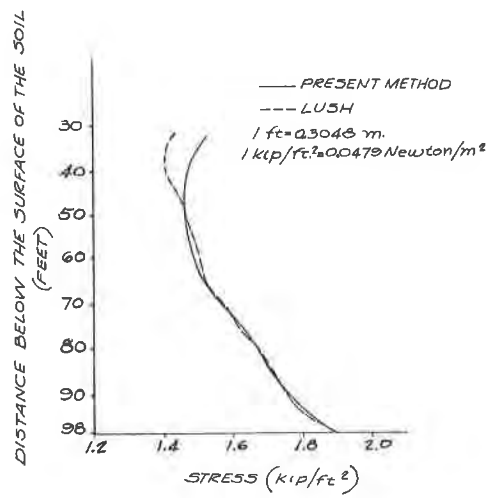

Fig. 6 Shear Stresses Along Section BB (Fig. 3)

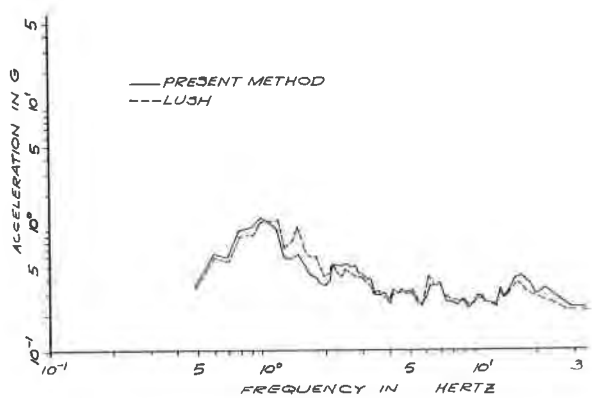

Fig. 7 Acceleration Spectra at Elevation 167' (1% Damping)