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TWO-DIMENSIONAL HYBRID MODELLING OF SOIL-STRUCTURE INTERACTION

by

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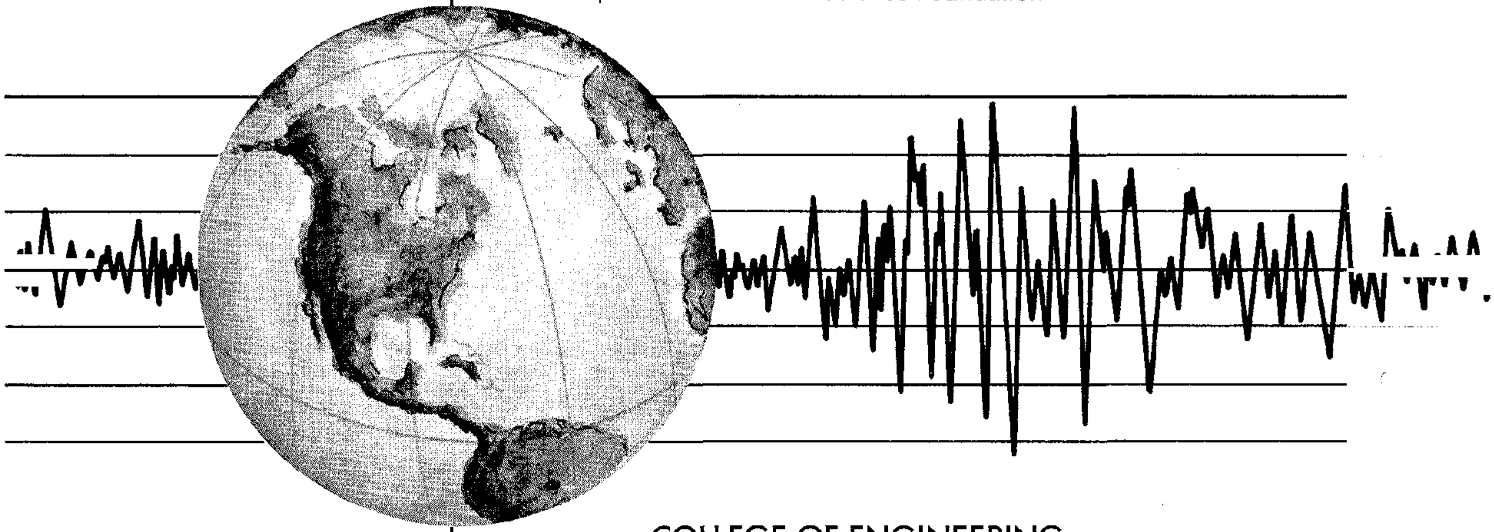
Report to the National Science Foundation



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Sunil Gupta
and
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To determine the two-dimensional frequency dependent impedance functions, a method of system identification is used to insure that the resulting hybrid model reproduces the known compliances of an infinite rigid strip on an elastic halfspace. These impedance functions have been employed to calculate the compliances of the strip for different R/a ratios. Good agreement between the computed and known compliances is shown.

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ABSTRACT

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1. INTRODUCTION

Soil-structure interaction has considerable influence on the dynamic response of deeply embedded or massive structures such as nuclear power plant buildings, offshore gravity towers, and dams. A concerted research effort in recent years, primarily motivated by the concern for safety and reliability of nuclear power plants during earthquakes, has considerably improved the state of the art of soil-structure interaction analysis. However, conceptual and computational difficulties still remain, primarily due to the three-dimensional semi-infinite nature of the soil medium and the complexities caused by the embedment of structures. Non-homogeneity and strain dependency of soil properties, and uncertainties associated with seismic input motions are factors which further complicate the modelling process.

The two basic methods currently in use for the analysis of soil-structure interaction are the finite element method and the substructure or continuum method(1). In the finite element method both the structure and the soil are modelled as a single system using finite elements. This method has been used extensively because of its ability to model embedded structures and the natural layering of the soil deposits. Non-linear soil properties can also be treated in an approximate fashion. However, a major disadvantage of this method is that the soil, essentially semi-infinite in nature, is normally modelled by a two-dimensional, finite-sized system with a rigid lower boundary. Thus, radiation damping which accounts for the loss of energy due to waves traveling away from the foundation can not be modelled accurately, although the use of viscous(2) or transmitting(3) boundaries to simulate the lateral extent of the soil region may somewhat mitigate these errors.

In the substructure method, the foundation is usually idealized by a rigid, massless, circular plate bonded to the surface of a semi-infinite halfspace. Frequency dependent impedance functions for the plate are developed and incorporated into the Fourier transformed equations of motion for the structure by imposing the conditions of compatibility and equilibrium between the structure and the plate. This method accounts for radiation damping in the semi-infinite soil medium and provides a realistic, simple, and economical three-dimensional model for a restricted class of structures satisfying the rigid plate foundation conditions mentioned above. Theoretically, the substructure method is also applicable to structures having more complex foundation conditions; e.g., embedded structures(4). Difficulties arise, however, in using the method due to lack of realistic solutions for the required impedances representing the semi-infinite soil medium.

Although both methods, when used carefully and skillfully, may provide realistic estimates of the soil-structure interaction effects, it is apparent that they have certain inherent limitations. In an earlier investigation(5), noting that generally the advantages of one approach are the disadvantages of the other, a hybrid model was introduced in which the whole system is modelled through a combination of finite elements and impedance functions resulting in a realistic, practical, and economical method for the three-dimensional analysis of soil-structure interaction.

In the present investigation, the previously reported hybrid modelling approach is applied to the analysis of plane problems, e.g., long concrete gravity or earth dams where it is reasonable to assume two-dimensional behavior. Although most of the concepts are the same as presented before, they are repeated here for the sake of completeness.

The hybrid model is developed in Chapter 2 of this report by partitioning the total soil-structure system into a near-field and a far-field. The near-field may be modelled by finite elements. Modelling of the far-field by continuous impedance functions and the determination of these impedance functions by the methods of system identification is explained in Chapter 3. In Chapter 4, numerical results for the identified far-field impedance functions are presented and the responses of some simple systems using these impedance functions are compared with other analytical solutions. Significant conclusions and remarks for further developments are presented in Chapter 5.

2. HYBRID MODELLING APPROACH

2.1 Hybrid Model

The hybrid model is obtained by partitioning the total soil-structure system into two substructures, termed the near-field and the far-field. The approach is, therefore, similar in concept to the general substructure method in that the total system is considered to be composed of two subsystems. However, a major difference is that in the present case the near-field consists not only of the structure but also a portion of the foundation soil within the smooth interface shown in Fig. 2.1. The far-field contains the remaining soil region outside this interface. For three-dimensional problems the interface was appropriately chosen to be hemispherical. For plane problems, with which the present investigation is concerned, this interface is taken to be a semi-cylinder.

Both the structure and the soil in the near-field may be modelled in discrete form using the finite element method, thus taking advantage of its ability to accommodate irregular geometries such as those encountered with embedded foundations. Non-homogeneous and non-linear soil properties in the immediate vicinity of the foundation can also be modelled by assigning appropriate properties to the affected finite elements.

The far-field, which in the present investigation is a uniform elastic half-space with a semi-cylindrical cavity, shares a common interface with the near-field along which the nodal points are common to both. It accounts for the loss of energy due to waves travelling away from the foundation. An accurate representation of this behavior requires the development of a far-field impedance matrix which relates the far-field forces to the far-field displacements corresponding to the interface degrees of freedom. Since rigorous solutions to this problem appear mathematically intractable at present, the far-field is modelled in this investigation by continuous impedance functions distributed over the interface. The far-field impedance matrix may then be obtained by discretizing these impedance functions at the boundary nodes. This matrix when combined with the near-field equations of motion effectively and efficiently simulates the total soil-structure system. The determination of the far-field impedance functions using the method of system identification will be discussed in Chapter 3.

The term "hybrid" adopted herein reflects the fact that by this approach the soil region is modelled by both finite elements and impedance functions allowing realistic modelling of both the near- and far-fields which has been difficult to accomplish in the past by the existing methods for the analysis of soil-structure interaction.

2.2 Equations of Motion

The equation of motion for the isolated near-field subjected to uniform ground motion along the interface can be written as

$$\underline{M\ddot{u}} + \underline{C\dot{u}} + \underline{Ku} = \underline{p}(t) + \underline{f}(t) \tag{2.1}$$

in which $\underline{u}(t)$ is the vector of nodal point displacements in the near-field (including interface nodes) relative to the motion of the boundary, and $\underline{\dot{u}}$ and $\underline{\ddot{u}}$ are the corresponding velocity and acceleration vectors, respectively. Mass matrix $\underline{M}$ is, in general, a full matrix but it can be diagonalized using a lumping procedure that gives sufficient accuracy and saves substantial computer storage. The near-field stiffness matrix $\underline{K}$ is positive semi-definite. Viscous damping matrix $\underline{C}$ accounts for energy dissipation in the near-field due to material damping. Vector $\underline{p}(t)$

contains the components of effective inertia loading on the system due to earthquake ground motion, and vector $\underline{f}(t)$ contains the far-field interaction forces corresponding to the interface degrees of freedom.

For steady state response, Eq. 2.1 can be transformed into frequency domain, giving

$$(-\omega^2\underline{M} + i\omega\underline{C} + \underline{K})\ \underline{U}(\omega) = \underline{P}(\omega) + \underline{F}(\omega) \tag{2.2}$$

or

$$\underline{S}(\omega)\ \underline{U}(\omega) = \underline{P}(\omega) + \underline{F}(\omega) \tag{2.3}$$

where

$$\underline{S}(\omega) = -\omega^2\underline{M} + i\omega\underline{C} + \underline{K}$$

is the frequency dependent impedance matrix which characterizes the mass, damping and stiffness properties of the near field. $\underline{U}(\omega)$, $\underline{P}(\omega)$ and $\underline{F}(\omega)$ are the Fourier transforms of the displacement, loading, and interaction force vectors, respectively, and ω is the excitation frequency.

The vector $\underline{U}$ of nodal point displacements can be partitioned into two parts: $\underline{U}_b$ corresponding to the nodal displacements at the boundary common to the near- and far-fields, and $\underline{U}_s$ corresponding to the remaining nodal displacements of the near-field. Thus, Eq. 2.3 can then be written in the partitioned form

$$\begin{bmatrix} \underline{S}_{ss} & \underline{S}_{sb} \\ \underline{S}_{sb}^{T} & \underline{S}_{bb} \end{bmatrix} \begin{Bmatrix} \underline{U}_s \\ \underline{U}_b \end{Bmatrix} = \begin{Bmatrix} \underline{P}_s \\ \underline{P}_b \end{Bmatrix} + \begin{Bmatrix} \underline{0} \\ \underline{F}_b \end{Bmatrix} \tag{2.4}$$

Because there are no interaction forces in the interior of the near-field, only vector $\underline{F}_b$ corresponding to the interface degrees of freedom exists in vector $\underline{F}(\omega)$.

For the isolated far-field, the interface dynamic force-deflection relationship is

$$\underline{S}_f(\omega)\ \underline{U}_f(\omega) = \underline{F}_f(\omega) \tag{2.5}$$

where $\underline{S}_f(\omega)$ is the far-field impedance matrix which has to be determined by a separate analysis. In rigorous form, it is a full matrix the elements of which characterize the mass, radiation damping, and stiffness characteristics of the far-field. It is complex valued and frequency dependent.

The equations of motion for the far-field are incorporated into the frequency domain near-field equations by invoking the conditions of compatibility and equilibrium at the interface, i.e.,

$$\underline{U}_f = \underline{U}_b \tag{2.6}$$

and

$$\underline{F}_f + \underline{F}_b = 0 \tag{2.7}$$

Substitution of Eqs. 2.5, 2.6 and 2.7 into Eq. 2.4, leads to the following equations of motion for the hybrid model of the entire soil-structure system in the frequency domain:

$$\begin{bmatrix} \underline{S}_{ss} & \underline{S}_{sb} \\ \underline{S}_{sb}^T & \underline{S}_{bb}+\underline{S}_f \end{bmatrix} \begin{Bmatrix} \underline{U}_s \\ \underline{U}_b \end{Bmatrix} = \begin{Bmatrix} \underline{P}_s \\ \underline{P}_b \end{Bmatrix} \tag{2.8}$$

or,

$$\hat{\underline{S}}(\omega)\ \underline{U}(\omega) = \underline{P}(\omega) \tag{2.9}$$

where $\hat{\underline{S}}(\omega)$ is the impedance matrix of the total hybrid system including near- and far-fields.

2.3 Dynamic Response

For a prescribed earthquake input motion, the Fourier amplitude, $\underline{P}(\omega)$, of the resulting load vector, $\underline{p}(t)$, can be obtained from

$$\underline{P}(\omega) = \int_0^{T_d} \underline{p}(t)\, e^{-i\omega t} dt \tag{2.10}$$

where T_d is the time duration of excitation. The solution $\underline{U}(\omega)$ of Eq. 2.9 for discrete values of the excitation frequency completely characterizes the response in the frequency domain. The time histories of response can then be obtained by the inverse Fourier transformation of the complex frequency response into the time domain using

$$\underline{u}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \underline{U}(\omega)\, e^{i\omega t}\, d\omega \tag{2.11}$$

The transform pairs of Eqs. 2.10 and 2.11 can be evaluated in a very efficient and economical way by using Fast Fourier Transform (FFT) techniques.

The definition of a realistic input motion to the soil-structure systems is still a debatable issue. The seismic energy arriving at a particular site depends upon so many factors, such as fault rupture mechanism, travel path of the seismic waves, and local soil conditions, that a complete characterization of the earthquake ground motion unique to a particular site appears impossible and impractical within the present state of the art. Analytical studies to predict the motion on the surface of a layered halfspace(6) or along cavities of various shapes(7,8,9) in a uniform halfspace due to a system of travelling waves provide an insight into this complex phenomonen, but have limited use because of lack of knowledge about the angle of incidence of incoming seismic waves and their composition which vary from earthquake to earthquake. Therefore, at the present time it seems reasonable and prudent to specify a site-dependent response spectrum from which time histories of motion can be generated to be used as input to the soil-structure system.

The equations of motion in this report have been developed for uniform earthquake excitation at the interface. Spatially varying ground motions along the interface, if known, can be incorporated by solving a modified set of dynamic equilibrium equations and combining the resulting nodal displacements with the corresponding quasi-static displacements produced by the prescribed interface displacements(10).

3. FAR-FIELD IMPEDANCE FUNCTIONS

3.1 Mathematical Model

An accurate representation of the far-field which accounts for radiation damping in the semi-infinite soil medium is central to the concept of hybrid modelling. The development of a far-field impedance matrix, $\underline{S}_f(\omega)$, as needed by the hybrid model, requires the solution of a set of partial differential equations with prescribed boundary conditions at the interface. Since such analytical solutions are difficult to obtain except for very simple systems(5), a semi-analytical approach is adopted here in which, physically, the far-field may be thought of as being composed of infinitesimally thin soil elements, extending to infinity in the direction normal to the semi-cylindrical cavity, and which act independently of each other. This is a realistic assumption if the deformations are smooth and slowly varying functions over the interface. This can be assured by placing the interface at a reasonable distance from the structure since the influence of foundation irregularities on stresses and displacements along the semi-cylindrical boundary diminish with distance from the foundation.

The dynamic load-deflection relationship of each of these infinitesimal soil elements can be characterized by impedance elements, the real part representing stiffness and the imaginary part representing radiation damping. Since there is an innumerable number of such closely spaced infinitesimal soil elements, the far-field, in the limit, may be replaced by continuous impedance functions placed in the two coordinate directions on the interface between the near- and far-fields. Conceptually, this is the dynamic equivalent of the Winkler assumption made for the case of static loading of beams on an elastic foundation.

In general, the far-field impedances can be expressed in terms of a Fourier series involving the angle ϕ. Since for uniform or horizontally layered halfspaces the far-field possesses material and geometric symmetry about the vertical axis, the impedance functions must be symmetric in ϕ; thus giving

$$\begin{aligned} S_R(R,\phi,b_o) &= \sum_{n=0}^{\infty} S_{Rn}(R,b_o)\cos n\phi \\ S_\phi(R,\phi,b_o) &= \sum_{n=0}^{\infty} S_{\phi n}(R,b_o)\cos n\phi \end{aligned} \tag{3.1}$$

in which S_R and S_ϕ are the complex valued far-field impedances per unit area in the normal and tangential directions to the semi-cylindrical interface as shown in Fig. 3.1.a. Coefficients S_{Rn} and $S_{\phi n}$ are functions of the interface radius R, the shear modulus G, and the non-dimensional frequency parameter b_o defined by $b_o = \omega R/C_S$ where ω is the excitation frequency, $C_S = \sqrt{G/\rho}$ is the shear wave velocity, and ρ is the mass density of the far-field material.

The number of terms required in Eq. 3.1 to properly represent the far-field depends upon the complexity of layering. In the present investigation the far-field is considered to be a homogeneous, isotropic, and elastic halfspace for which the infinitesimal soil elements around the interface will have the same properties. This gives rise to uniformly distributed impedance functions. Therefore, only the constant terms in Eq. 3.1 need be retained, giving

$$\begin{aligned} S_R(R,\phi,b_o) &= S_{Ro}(R,b_o) = \eta_R + i\xi_R \\ S_\phi(R,\phi,b_o) &= S_{\phi o}(R,b_o) = \eta_\phi + i\xi_\phi \end{aligned} \tag{3.2}$$

where the η's and ξ's are the real and imaginary parts, respectively, of the unknown far-field impedance functions.

These continuous far-field impedance functions can be discretized at the boundary nodes to obtain the far-field impedance matrix. This can be achieved by using the principle of virtual work expressed as

$$\delta W = \int \delta \underline{u}^T \underline{p} \, ds \tag{3.3}$$

where $\delta \underline{u}$ is the 2-component vector of kinematically admissible virtual displacements on the interface, and $\underline{p}$ is the corresponding 2-component vector of real interface forces in equilibrium, and s is distance along the interface.

From the assumed model of the far-field, the interface forces and displacements are related by

$$\begin{Bmatrix} p_r \\ p_\phi \end{Bmatrix} = \begin{bmatrix} S_R & 0 \\ 0 & S_\phi \end{bmatrix} \begin{Bmatrix} u_r \\ u_\phi \end{Bmatrix} \tag{3.4}$$

where S_R and S_ϕ are the continuous far-field impedance functions defined earlier.

In addition, the far-field displacements expressed in the cylindrical coordinate system will be transformed into the Cartesian coordinate system used for the near-field finite element model by the relation

$$\begin{Bmatrix} u_r \\ u_\phi \end{Bmatrix} = \begin{bmatrix} \sin\phi & \cos\phi \\ \cos\phi & -\sin\phi \end{bmatrix} \begin{Bmatrix} u_x \\ u_z \end{Bmatrix} \tag{3.5}$$

Substitution of Eqs. 3.4 and 3.5 into 3.3 gives

$$\delta W = \int \delta\langle u_x \; u_z\rangle \begin{bmatrix} S_R\sin^2\phi+S_\phi\cos^2\phi & (S_R-S_\phi)\sin\phi\cos\phi \\ (S_R-S_\phi)\sin\phi\cos\phi & S_R\cos^2\phi+S_\phi\sin^2\phi \end{bmatrix} \begin{Bmatrix} u_x \\ u_z \end{Bmatrix} ds \tag{3.6}$$

Now, the displacements on the interface may be expressed in terms of the same interpolation functions as used for the near-field finite element discretization to ensure compatibility of displacements along the interface. Thus, for a quadratic element 'p' on the interface

$$\begin{Bmatrix} u_x \\ u_z \end{Bmatrix} = \begin{bmatrix} N_1 & N_2 & N_3 & & & \\ & & & N_1 & N_2 & N_3 \end{bmatrix} \begin{Bmatrix} u_{x1} \\ u_{x2} \\ u_{x3} \\ u_{z1} \\ u_{z2} \\ u_{z3} \end{Bmatrix}_p = \begin{bmatrix} \underline{N} & \\ & \underline{N} \end{bmatrix} \begin{Bmatrix} \underline{u}_x \\ \underline{u}_z \end{Bmatrix}_p \tag{3.7}$$

where u_{x1}, u_{z1}, etc. are the nodal point displacements at the interface, and N_1, N_2, N_3 are the interpolation functions given by

$$N_1 = \frac{t}{2}(t-1)$$
$$N_2 = 1-t^2 \qquad -1 \leq t \leq 1$$
$$N_3 = \frac{t}{2}(t+1)$$

Therefore, the contribution of element 'p' to the total virtual work can be obtained by substituting Eq. 3.7 into Eq. 3.6, giving

$$\delta W^p = \delta\langle \underline{u}_x^T \; \underline{u}_z^T\rangle_p \; \underline{S}_f^p \begin{Bmatrix} \underline{u}_x \\ \underline{u}_z \end{Bmatrix}_p \tag{3.8}$$

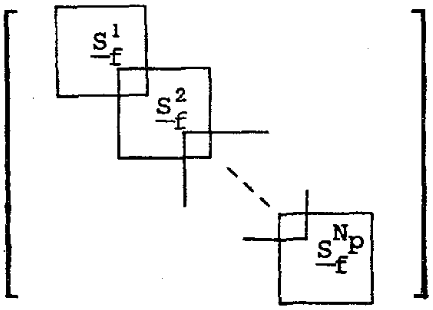
in which,

$$\underline{S}_f^p = \int_p \begin{bmatrix} (S_R\sin^2\phi+S_\phi\cos^2\phi)\,\underline{N}^T\underline{N} & (S_R-S_\phi)\sin\phi\cos\phi\,\underline{N}^T\underline{N} \\ (S_R-S_\phi)\sin\phi\cos\phi\,\underline{N}^T\underline{N} & (S_R\cos^2\phi+S_\phi\sin^2\phi)\,\underline{N}^T\underline{N} \end{bmatrix} ds \tag{3.9}$$

is the 6 x 6, consistent far-field impedance matrix in Cartesian coordinates for an element p on the interface. Because of the complexity of the terms in Eq. 3.9, six Gaussian quadrature points along an element interface are needed to avoid incomplete integration.

The far-field impedance matrix for the entire interface may be obtained by standard assembly procedure giving

$$\underline{S}_f =$$



(3.10)

in which, the element impedance matrix given by Eq. 3.9 is used for assembly.

The overall far-field impedance matrix so obtained may be employed in the hybrid system as represented by Eq. 2.8 to solve two dimensional problems.

3.2 Parameter Identification

The unknown far-field impedance functions S_R and S_ϕ are determined by the method of system identification. System identification is an iterative process in which the unknown parameters of the postulated analytical model are determined by systematically adjusting them in such a way that the resulting model provides a best fit to the actual observed behavior of the system. In the present investigation, which is concerned with two-dimensional problems, the "observed behavior" is taken as that given by the theoretical solutions for the dynamic response of an infinitely long, rigid, massless strip footing on a uniform elastic halfspace in the vertical and coupled translation-rocking modes of vibration. These solutions have been determined by Oien(11) and Luco and Westmann(12) and can be defined by the following matrix equation.

$$\begin{Bmatrix} \Delta_V \\ \Delta_H \\ \Delta_M \end{Bmatrix} = \begin{bmatrix} C_{VV} & & \\ & C_{HH} & C_{HM} \\ & C_{MH} & C_{MM} \end{bmatrix} \begin{Bmatrix} V \\ H \\ M \end{Bmatrix} \tag{3.11}$$

In the above equation, the coupling compliance C_{HM} equals C_{MH} owing to the reciprocity condition. Since the solutions obtained by Luco and Westmann for Poisson's ratio other than 1/2 are valid only for non-dimensional frequency a_o below 1.5 due to the numerical difficulties involved, the compliances used here are those generated by Oien. The corresponding hybrid model of the rigid strip, with the near-field modeled by finite elements and far-field by impedance functions, must reproduce these known solutions within some prescribed tolerance level.

For a prescribed value of the excitation frequency and for assumed values of far-field impedance functions, the equation of motion for the hybrid system, Eq. 2.9, can be solved to yield the complex displacement amplitudes (compliances) of the rigid massless strip footing. These compliances depend upon the assumed far-field impedance and will, in general, be in error with the known compliances. To systematically minimize these errors using the methods of system identification, an error function containing the sum of squared errors of all the strip compliances is formed giving,

$$\begin{aligned} J(\underline{\beta},\omega) &= \sum_{i=1}^{NC} \left| \left[U_i(\underline{\beta},\omega)-C_i\right] \right|^2 \\ &= \sum_{i=1}^{NC} \{[\mathrm{Re}(U_i)-\mathrm{Re}(C_i)]^2 + [\mathrm{Im}(U_i)-\mathrm{Im}(C_i)]^2\} \end{aligned} \tag{3.12}$$

in which, $\underline{\beta}$ is an n-dimensional vector containing all of the far-field impedance coefficients (in the present case $\underline{\beta}^T = < \eta_R\ \xi_R\ \eta_\phi\ \xi_\phi >$ as given by Eq. 3.2), $U_i = U_i(\underline{\beta},\omega)$ are the strip compliances from the hybrid model, $C_i = C_i(\omega)$ are the known strip compliances, ω is the excitation frequency, and NC is the total number of strip compliances considered in the solution.

The error function $J(\underline{\beta},\omega)$ which can be visualized as an n-dimensional space surface corresponding to the n parameters in the far-field impedance vector $\underline{\beta}$ is minimized for discrete values of ω to give the corresponding $\underline{\beta}$ over the desired range of frequencies. Methods of system identification are used to systematically adjust the originally assumed values of the far-field impedance coefficients. Most of these methods use the so-called gradient techniques in which new values for the components in vector $\underline{\beta}$ are obtained by following in the direction of the negative gradient of the error function in the n-dimensional parameter spaces. However, the convergence by employing the gradient techniques is always slow. To overcome this difficulty the modified Gauss-Newton method which makes use of the information on second derivatives has been selected for the present study, thus resulting in an improved convergence rate$^{(13)}$. The procedure is to expand the error function $J(\underline{\beta},\omega)$ into a Taylor's series, neglecting the terms of order higher than two, and then equating the gradient to zero which leads to the equation

$$\underline{g}(\underline{\beta}_{i-1},\omega) + \underline{h}(\underline{\beta}_{i-1},\omega)(\underline{\beta}_i-\underline{\beta}_{i-1}) = \underline{0} \qquad (3.13)$$

where $\underline{\beta}_{i-1}$ and $\underline{\beta}_i$ are the parameter vectors at iterative steps i-1 and i, respectively,

$$\underline{g}^T(\underline{\beta},\omega) = < \frac{\partial J}{\partial \beta_1} \; \frac{\partial J}{\partial \beta_2} \text{----} \frac{\partial J}{\partial \beta_n} > \tag{3.14}$$

is the gradient vector, and

$$\underline{h}(\underline{\beta},\omega) = \begin{bmatrix} \frac{\partial^2 J}{\partial \beta_1^2} & \text{-------} & \frac{\partial^2 J}{\partial \beta_1 \partial \beta_n} \\ | & & | \\ | & & | \\ \frac{\partial^2 J}{\partial \beta_n \partial \beta_1} & \text{--------} & \frac{\partial^2 J}{\partial \beta_n^2} \end{bmatrix} \tag{3.15}$$

is the n x n Hessian matrix.

If the Hessian matrix is inversible, $\underline{\beta}_i$ can be expressed as

$$\underline{\beta}_i = \underline{\beta}_{i-1} - \lambda \, \underline{h}^{-1}(\underline{\beta}_{i-1},\omega) \; \underline{g} \; (\underline{\beta}_{i-1},\omega) \tag{3.16}$$

The equation in which the inverse Hessian matrix modifies both the magnitude and the direction of the steepest descent given by the negative gradient defines the Gauss-Newton method. Scalar λ is a positive parameter selected to ensure a decrease in error within each iteration cycle. Eq. 3.16 may also be written as

$$\underline{\beta}_i = \underline{\beta}_{i-1} - \lambda \, \underline{d}_{i-1} \tag{3.17}$$

where

$$\underline{d}_{i-1} = \underline{h}^{-1} \; (\underline{\beta}_{i-1},\omega) \; \underline{g} \; (\underline{\beta}_{i-1},\omega)$$

is the search direction vector as defined by the modified Gauss-Newton method.

The components of the gradient vector in Eq. 3.14 are obtained by taking the partial derivatives of the error function at $\underline{\beta}_{i-1}$, i.e.,

$$\frac{\partial J}{\partial \beta_j} = 2 \sum_{i=1}^{NC} [\mathrm{Re}(U_i)-\mathrm{Re}(C_i)] \frac{\partial \mathrm{Re}(U_i)}{\partial \beta_j} + 2 \sum_{i=1}^{NC} [\mathrm{Im}(U_i)-\mathrm{Im}(C_i)] \frac{\partial \mathrm{Im}(U_i)}{\partial \beta_j} \tag{3.18}$$

Similarly, the coefficients of the Hessian matrix are

$$\frac{\partial^2 J}{\partial \beta_j \partial \beta_k} = 2 \sum_{i=1}^{NC} \left\{ \frac{\partial \mathrm{Re}(U_i)}{\partial \beta_j} \frac{\partial \mathrm{Re}(U_i)}{\partial \beta_k} + [\mathrm{Re}(U_i)-\mathrm{Re}(C_i)] \frac{\partial^2 \mathrm{Re}(U_i)}{\partial \beta_j \partial \beta_k} \right\} + 2 \sum_{i=1}^{NC} \left\{ \frac{\partial \mathrm{Im}(U_i)}{\partial \beta_j} \frac{\partial \mathrm{Im}(U_i)}{\partial \beta_k} + [\mathrm{Im}(U_i)-\mathrm{Im}(C_i)] \frac{\partial^2 \mathrm{Im}(U_i)}{\partial \beta_j \partial \beta_k} \right\} \tag{3.19}$$

Since the effort required to calculate the second derivatives in Eq. 3.19 is prohibitive, the modified Gauss-Newton method approximates the coefficients of the Hessian matrix by

$$\frac{\partial^2 J}{\partial \beta_j \partial \beta_k} = 2 \sum_{i=1}^{NC} \left[\frac{\partial \mathrm{Re}(U_i)}{\partial \beta_j} \frac{\partial \mathrm{Re}(U_i)}{\partial \beta_k} + \frac{\partial \mathrm{Im}(U_i)}{\partial \beta_j} \frac{\partial \mathrm{Im}(U_i)}{\partial \beta_k} \right] \tag{3.20}$$

A justification for neglecting the two higher order terms in Eq. 3.19 is that near the minimum these terms are small compared to the first order terms. The approximation given by Eq.3.20 makes the Hessian matrix positive semi-definite, a property that the original matrix based on Eq. 3.19 does not posses. To ensure that the inverse of the Hessian matrix in Eq. 3.16, does exist, it is necessary only to add a small positive constant to the diagonal elements. The added term can be considered as an approximation to the higher order terms ignored in Eq. 3.20, and it improves the search direction. Although, this modification usually damps the rate of convergence(16), its use is advantageous when approaching the minimum where convergence is not always stable. Also, since the response quantity $U_i(\underline{\beta},\omega)$ is not an explicit function of $\underline{\beta}$, but is obtained through a numerical process involving the solution of Eq. 2.9, the partial derivatives $\frac{\partial U_i}{\partial \beta_j}$ in Eqs. 3.18 and 3.20 are replaced by finite differences $\frac{\Delta U_i}{\Delta \beta_j}$.

The error function $J(\underline{\beta},\omega)$ defines an n-dimensional surface which in two dimensions is easy to visualize as shown in Fig. 3.2. The modified Gauss-Newton method is an iterative process in which the error is minimized by obtaining successively better estimates of the far-field impedance vector $\underline{\beta}$ until a point $\underline{\beta}^*$ is located where the slope of the error surface approaches zero. The slope of the error profile at a point $\underline{\beta}_i$ along the search direction $\underline{d}_{i-1}$ is obtained by differentiating the error function with respect to the step size λ, giving

$$\alpha_{i-1}(\underline{\beta}_i) = - \underline{g}^T(\underline{\beta}_i,\omega)\ \underline{d}_{i-1} \tag{3.21}$$

At any step i-1, a typical iteration cycle proceeds as follows -- The far-field impedance matrices corresponding to the parameter vector $\underline{\beta}_{i-1}$ are formed as explained earlier and then they are combined with the near-field finite element equations to give the equations of motion, Eq. 2.9, for the hybrid model. These equations are solved to obtain the response U_i of the rigid strip and the error is evaluated according to Eq. 3.12. The slope of the error surface, $\alpha_{i-1}(\underline{\beta}_{i-1})$ is obtained by substituting $\underline{\beta}_{i-1}$ for $\underline{\beta}_i$ in Eq. 3.21 which is then compared against a specified tolerance on slope taken sufficiently close to zero. If the slope is less than the specified tolerance, the error surface is considered flat (or nearly flat) and the error J is assumed to be minimized. The parameter vector $\underline{\beta}_{i-1}$ in that case is the desired far-field impedance vector $\underline{\beta}^*$. If the slope is greater than the specified tolerance, a line search along the direction $\underline{d}_{i-1}$ is made as shown in

Fig. 3.2. According to Eq. 3.17 each value of the step size parameter λ defines a different point $\underline{\beta}_i$ along this direction. Within a line search, the step size λ is systematically adjusted in such a way that a point $\underline{\beta}_i$ is obtained where the slope of the error profile is sufficiently small and the error is minimized in that direction. The parameter vector $\underline{\beta}_i$ so obtained is then used as the next point in the iteration process. The tolerance on slope within a line search affects the number of steps required to determine the step size for which the error profile reaches a minimum in the search direction. If a crude "line stopping" tolerance is specified the process may take fewer steps within each line search but may require a large number of iterations to reach the true minimum indicated by the dashed lines in Fig. 3.2. It has, therefore, been recommended that a moderate amount of effort be spent in the step length determination. How accurately the true minimum is determined depends upon the specified criteria for overall convergence. If a strict tolerance on slope is specified, the process may take longer to converge, but the minimum will be determined more accurately.

To start the iterative process one must have an initial estimate $\underline{\beta}_o$ of the far-field impedance function. The success of the method depends upon the accuracy of this estimate. If the starting vector $\underline{\beta}_o$ is far from the true minimum, the convergence may be very slow. It is possible that, although the iterative process converges to a minimum, the error at that point is still large. This implies one of two possibilities -- either it is a local minimum, or it is a global minimum but the model chosen for the far-field impedances is not adequate. In the first eventuality, one may start from a different set of starting values $\underline{\beta}_o$ until the true minimum is achieved. In the second case, one may try including additional terms in the Fourier expansion of Eq. 3.1.

If that does not work either, then it implies that the chosen model is not realistic. If, however, at the minimum the error approaches zero, it signifies that the chosen mathematical model for the far-field impedances is adequate and that the iterative process has converged to the true minimum.

4. NUMERICAL RESULTS

4.1 Near-Field Finite Element Model

Discretization of the near-field by finite elements causes a filtering effect on waves in the high frequency range. The ability of the finite element near-field to transmit waves will depend upon the assumed displacement field within and the size of each element. It is, therefore, important that having selected the type of finite element to be used, the finite element mesh is fine enough to ensure transmission of waves over the entire frequency range of interest.

The element selected in this study is a quadratic 9-node planar element. The accuracy and stability characteristics of this element have been studied previously(14) where it was noted that the addition of the ninth node to the center of the more conventional 8-node isoparametric element increases its reliability under geometric distortion. The effectiveness of this element in transmitting waves was studied by analyzing the problem of one-dimensional wave propagation through a semi-infinite rod constrained to undergo motion only in the longitudinal direction(5). It was observed that the analytical solutions to this problem are reproduced with an excellent degree of accuracy if the size of these 9-node elements is 1/4th of the wave length. Although this observation pertains to one-dimensional wave propagation, it serves as a useful guideline in selecting the size of the finite element for two- and three-dimensional problems also.

The near-field finite element mesh used in the present investigation to model the rigid strip footing on a uniform elastic halfspace is shown in Fig. 4.1. Since any arbitrary loading on the strip can be decomposed into symmetrical and antisymmetrical components, only one-half of the total region need to be considered and appropriate boundary conditions imposed on the nodes lying on the vertical axis. The radius of the far-field, R, has been initially chosen to be three times the half-width, a, of the rigid strip to ensure slowly varying displacements and stresses at the interface. The largest dimension of the elements anywhere in the mesh is approximately 1/4th of the wave length corresponding to a non-dimensional frequency $b_o = \frac{\omega R}{C_s}$ of 9.0. It is anticipated that the errors in the displacement field, for frequencies below this value, will be on the order of 5%. Such a refined mesh was deemed necessary to ensure that the far-field impedances, identified using this mesh, will not be unduly influenced by the near-field discretization.

4.2 Computational Details

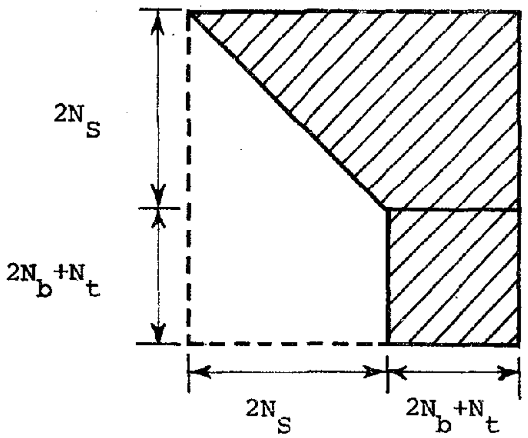
The stiffness and lumped mass matrices of the near-field are obtained using a specifically developed FORTRAN Computer program. The stiffness matrix is stored using an active column scheme to minimize the computer storage. Since no material damping has been used in generating the compliance functions for the infinite rigid strip, the near-field damping matrix is set equal to zero for purposes of generating the far-field impedance functions.

The modified Gauss-Newton algorithum for parameter adjustment is an iterative process requiring repeated solutions of the equations of motion, Eq. 2.9, of the hybrid system. In order to minimize the computational effort the degrees of freedom of the rigid strip are numbered last in the overall equations which can then be partitioned as shown below

$$\begin{array}{cccc} 2N_s & \left[\begin{matrix} \underline{S}_{ss} \\ \underline{S}_{sb}^{T} \\ \underline{S}_{st}^{T} \end{matrix}\right. & \begin{matrix} \underline{S}_{sb} \\ \underline{S}_{bb}+\underline{S}_{f}(\underline{\beta},\omega) \\ \underline{S}_{bt}^{T} \end{matrix} & \left.\begin{matrix} \underline{S}_{st} \\ \underline{S}_{bt} \\ \underline{S}_{tt} \end{matrix}\right] \\ 2N_b & & & \\ N_t & & & \\ & 2N_s & 2N_b & N_t \end{array} \begin{Bmatrix} \underline{U}_s \\ \underline{U}_b \\ \underline{U}_t \end{Bmatrix} = \begin{Bmatrix} \underline{P}_s \\ \underline{P}_b \\ \underline{P}_t \end{Bmatrix} \qquad (4.1)$$

where, $\underline{U}_s$ now represents the interior nodes, $\underline{U}_b$ the boundary nodes, and $\underline{U}_t$ the rigid strip degrees of freedom.

Since within any interaction only the elements of the far-field impedance matrix, $\underline{S}_f(\underline{\beta},\omega)$, are modified, it is not necessary to reduce the entire set of equations every time the far-field impedance vector $\underline{\beta}$ is changed. Instead, the overall impedance matrix in Eq. 4.1 is forwardly reduced only up to the first $2N_s$ equations, at which stage the coefficient matrix appears as shown below.



The $(2N_b + N_t)$ x $(2N_b + N_t)$ submatrix is kept in lower speed storage and read in as new estimates of the parameter vector $\underline{\beta}$ are introduced during the iterations. The advantage of numbering the rigid strip degrees of freedom at the end is that within each iteration the solution procedure requires the repeated forward reduction of the $(2N_b + N_t)$ x $(2N_b + N_t)$ submatrix, but only the last N_t equations need to be back-substituted to obtain the response of the rigid strip. Therefore, since the number of nodes on the interface, N_b, is significantly smaller than the number of interior nodes, N_s, and the number of degrees of freedom of the rigid strip, N_t, is not greater than 2, a great saving in computational effort is achieved.

4.3 Numerical Results

The parameter vector $\underline{\beta}$ includes the coefficients $< \eta_R, \xi_R, \eta_\phi, \xi_\phi >$ corresponding to the far-field impedance functions $\eta_R + i\xi_R$ in the normal direction and $\eta_\phi + i\xi_\phi$ in the tangential direction as discussed in Chapter 3. These impedance functions are determined by minimizing the error function which is formed by considering the response of the strip in the vertical and the coupled translation-rocking modes of vibration.

The identified far-field impedance functions have been plotted in a non-dimensional form in Figures 4.2 and 4.3 as a function of the non-dimensional frequency b_o. These impedances have been generated for a R/a ratio of 3.0 and a Poisson's ratio of 1/3 which is a fairly representative value for soils. For any particular frequency, these uniformly distributed far-field impedance functions are directly proportional to the shear modulus G, and inversely proportional to the interface radius R. Therefore, knowing these two sets of curves, the far-field impedances for any size of far-field, with any shear modulus and mass density can be readily obtained.

The compliances of the rigid strip footing using these far-field impedances are compared with the analytical solutions in Fig. 4.4. In these figures, the abscissa is a non-dimensional frequency defined by $a_o = \omega a/C_S$. For non-dimensional frequencies, a_o, between 0.4 and 2.0 the agreement between the calculated and the exact values is excellent. For high frequencies, $a_o > 2.0$, the agreement is not as good. This may be due to the relatively small values of the real parts of the vertical and horizontal compliances. Also, for very small frequencies, $a_o < 0.4$, because of the singularities in the analytical solutions, the agreement between the analytical and calculated results is less satisfactory, but is still in the acceptable range. Although slight errors are observed in these figures, the proposed hybrid model, in general, is quite effective in reproducing the theoretical solutions over the entire frequency range considered.

In Fig. 4.4, there are some discrepancies observed in the solutions for the coupling compliance, C_{HM}. These may be due to the sensitivity of coupling compliances to the approximate nature of the proposed far-field model. However, these discrepancies can be ignored because the coupling compliance is small compared to the direct compliances. In the analytical solutions(11), a singularity in the stresses exists at the edges of the strip. To incorporate this singularity, a finer mesh in the vicinity of the strip edges was used. However, no significant improvement in the solutions was observed. Therefore, the singularity of stresses under the rigid strip has little effect on the far-field impedance functions.

To investigate the range of applicability of this model, the impedances have been employed to calculate the compliances of the rigid strip for three other R/a ratios of 4.0, 2.4, 1.935 as shown in Figs. 4.5, 4.6 and 4.7. The agreement in solutions for R/a ratios of 4.0 and 2.4 is still very good. Even though a somewhat larger error appears in the real part of the rocking compliance, it does not exceed 5%. Solutions for R/a ratio of 1.935 also look reasonable. The largest error in this case is only 10% in the real part of the rocking compliance. For all the results presented the errors in the imaginary parts are generally much smaller than in the real parts.

5. CONCLUSIONS

A hybrid model for the analysis of soil-structure interaction has been presented in which the near-field is modelled by finite elements and far-field by continuously distributed impedance functions which have been determined by system identification methods. The validity of this model has been demonstrated by comparing the theoretical and numerical compliances of a rigid strip for several R/a ratios. For three-dimensional problems, the effectiveness of the hybrid modelling technique for surface(5) and embedded foundations(15) has been demonstrated earlier. The hybrid modelling approach, therefore, offers an efficient, simple, and flexible method for the analysis of complex soil-structure interaction problems for which the direct finite element and continuum methods have been found to be deficient.

Further developments are required to extend the method to situations involving layered foundations for which it may be necessary to include more than the first term in the Fourier series expansion of the impedance functions (Eq. 3.1), or it may be more appropriate to choose a cylindrical interface. Efforts are currently underway in this direction.

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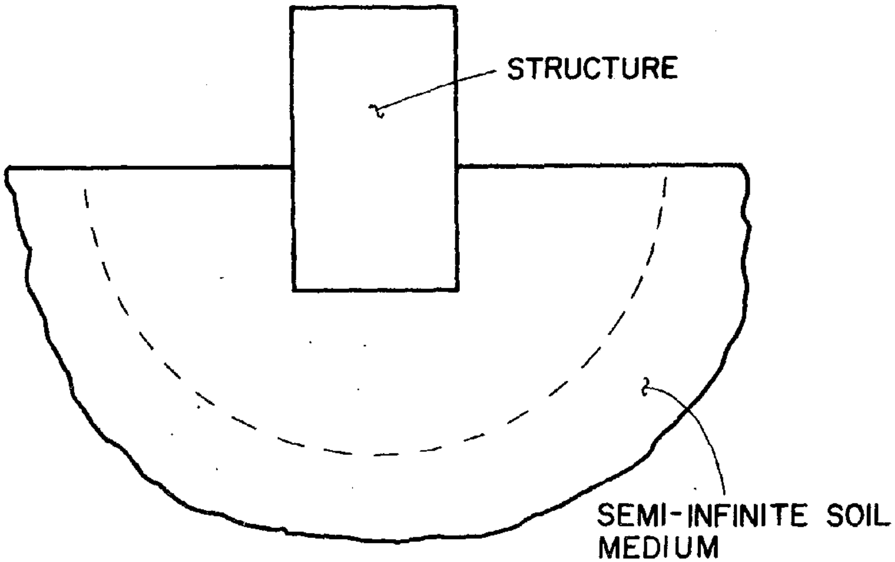
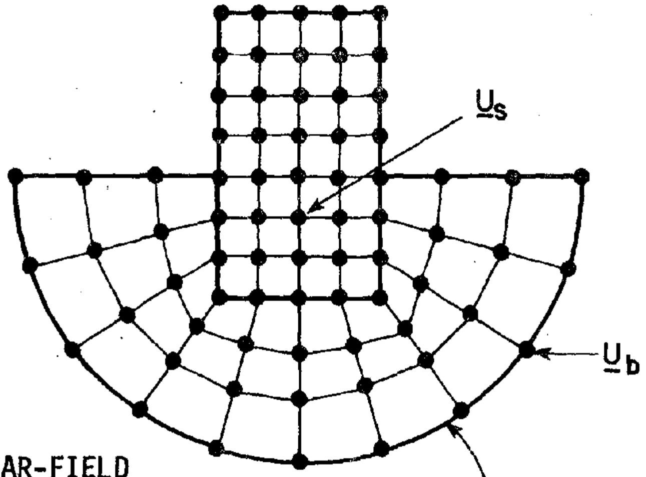
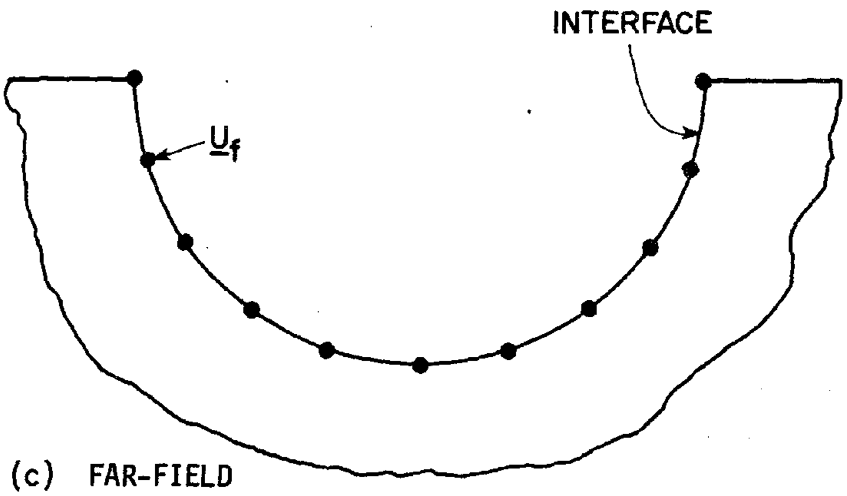


(a) SOIL-STRUCTURE SYSTEM

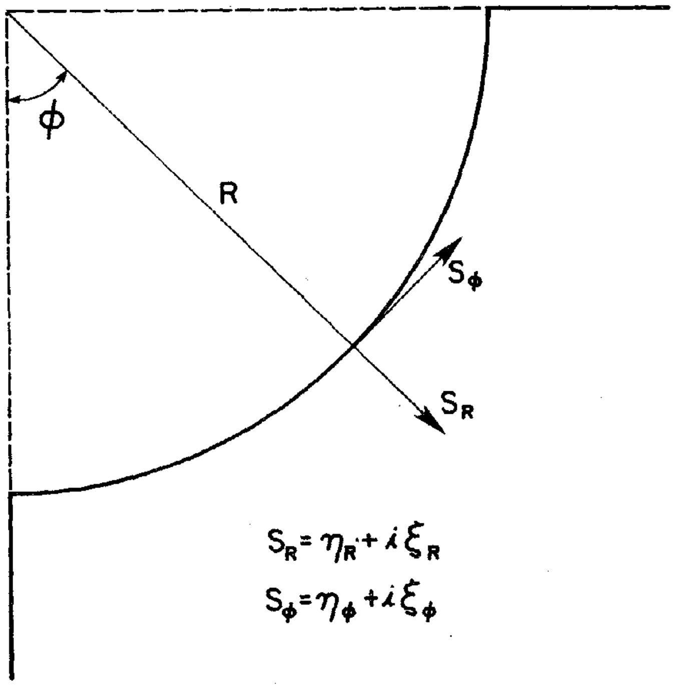


(b) NEAR-FIELD

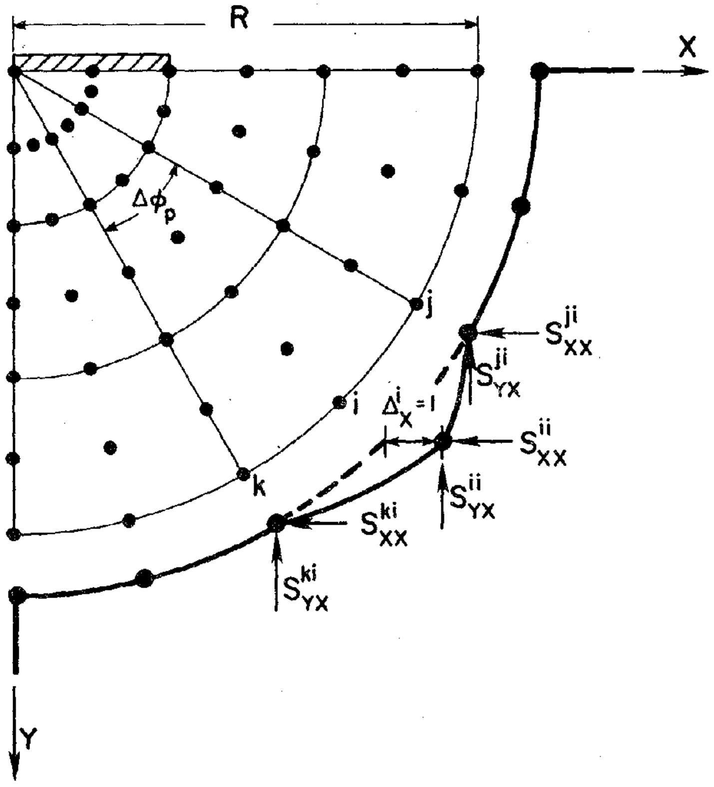


(c) FAR-FIELD

FIG. 2.1 HYBRID MODELLING OF SOIL-STRUCTURE INTERACTION



(a) CONTINUOUS FAR-FIELD IMPEDANCES



(b) FINITE-ELEMENT CONSISTENT IMPEDANCES

FIG. 3.1 FAR-FIELD MODELLING BY IMPEDANCE FUNCTIONS

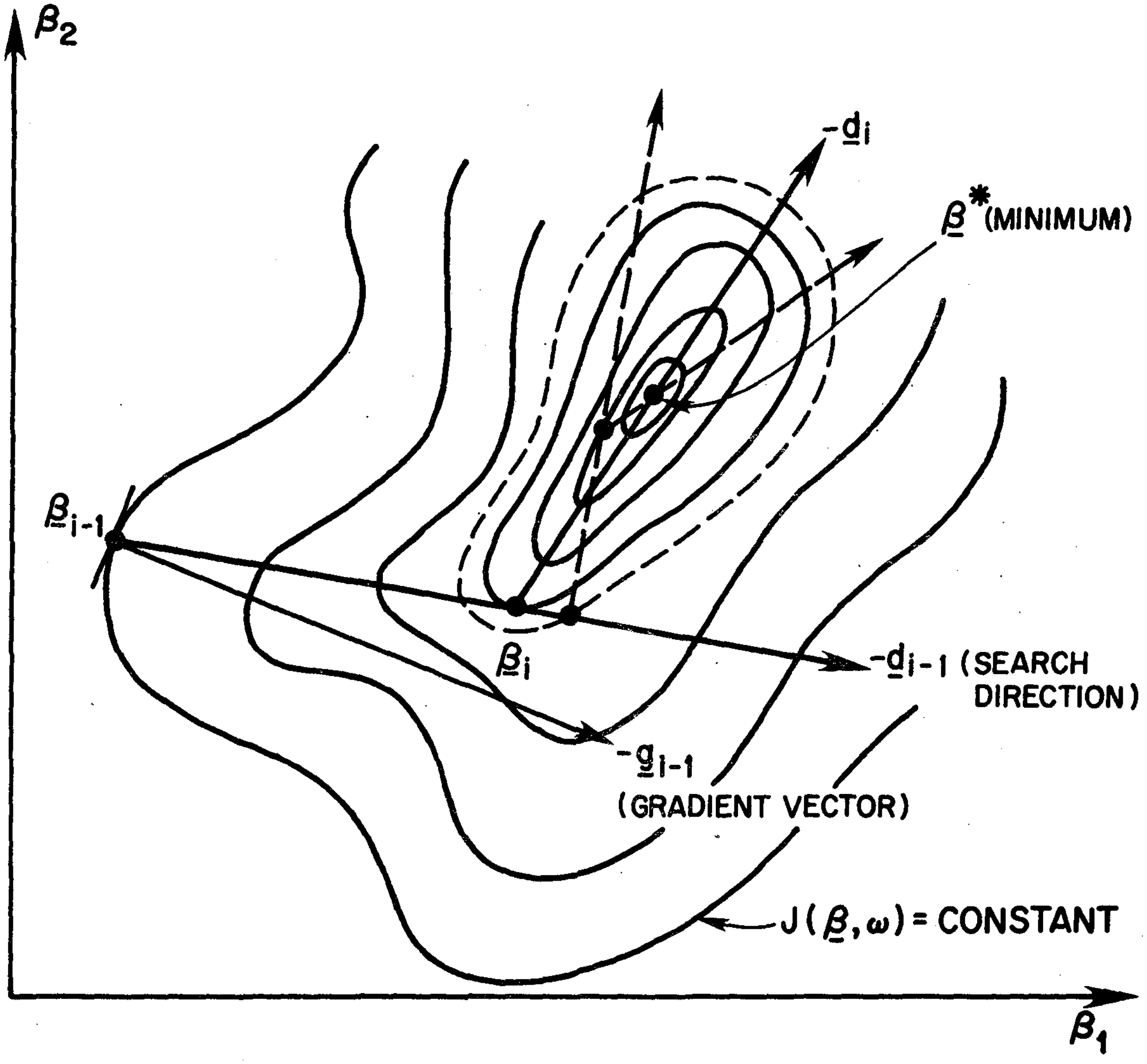


FIG. 3.2 ERROR SURFACE FOR TWO PARAMETERS

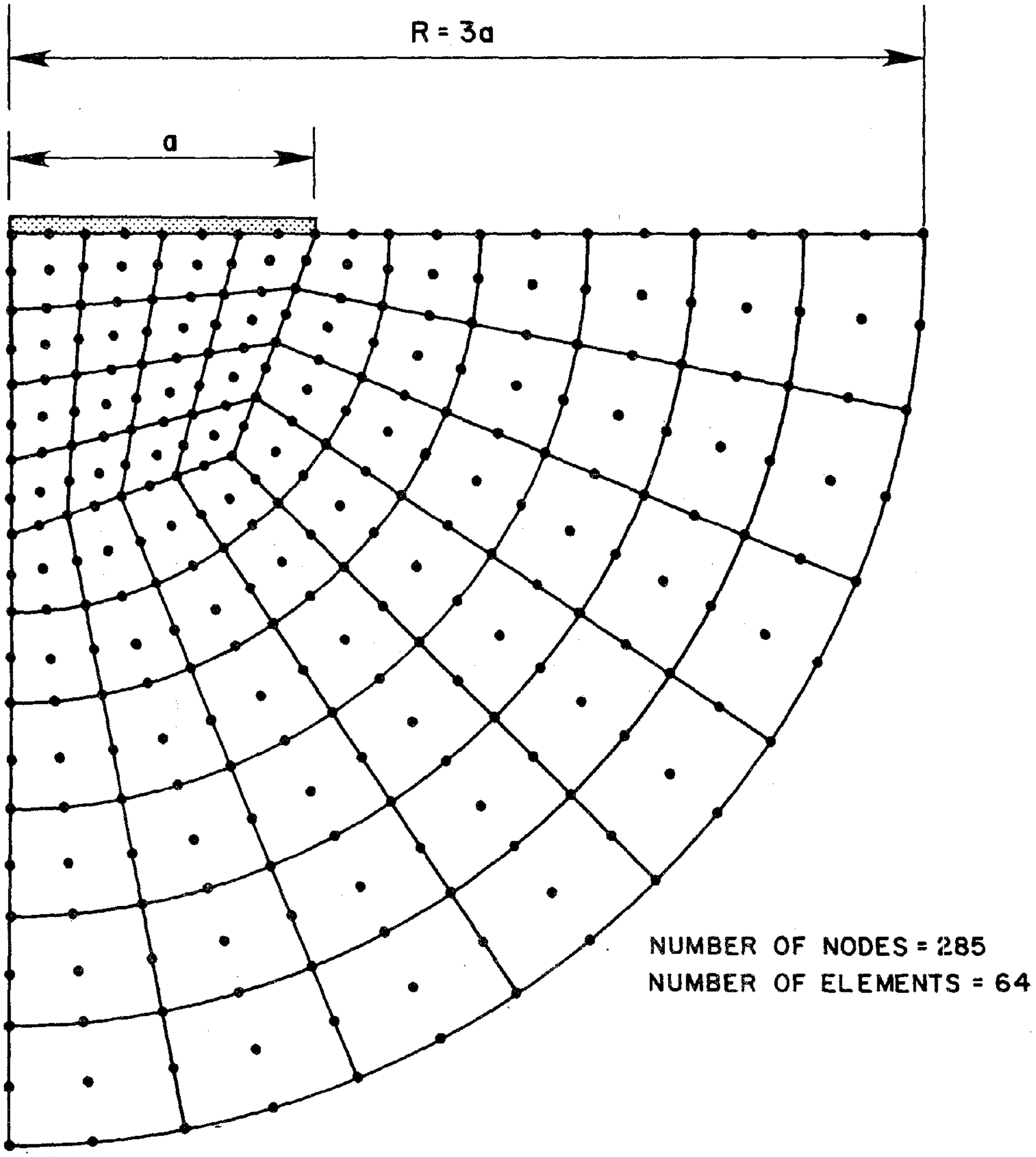


FIG. 4.1 NEAR-FIELD FINITE ELEMENT MESH FOR INFINITE RIGID STRIP

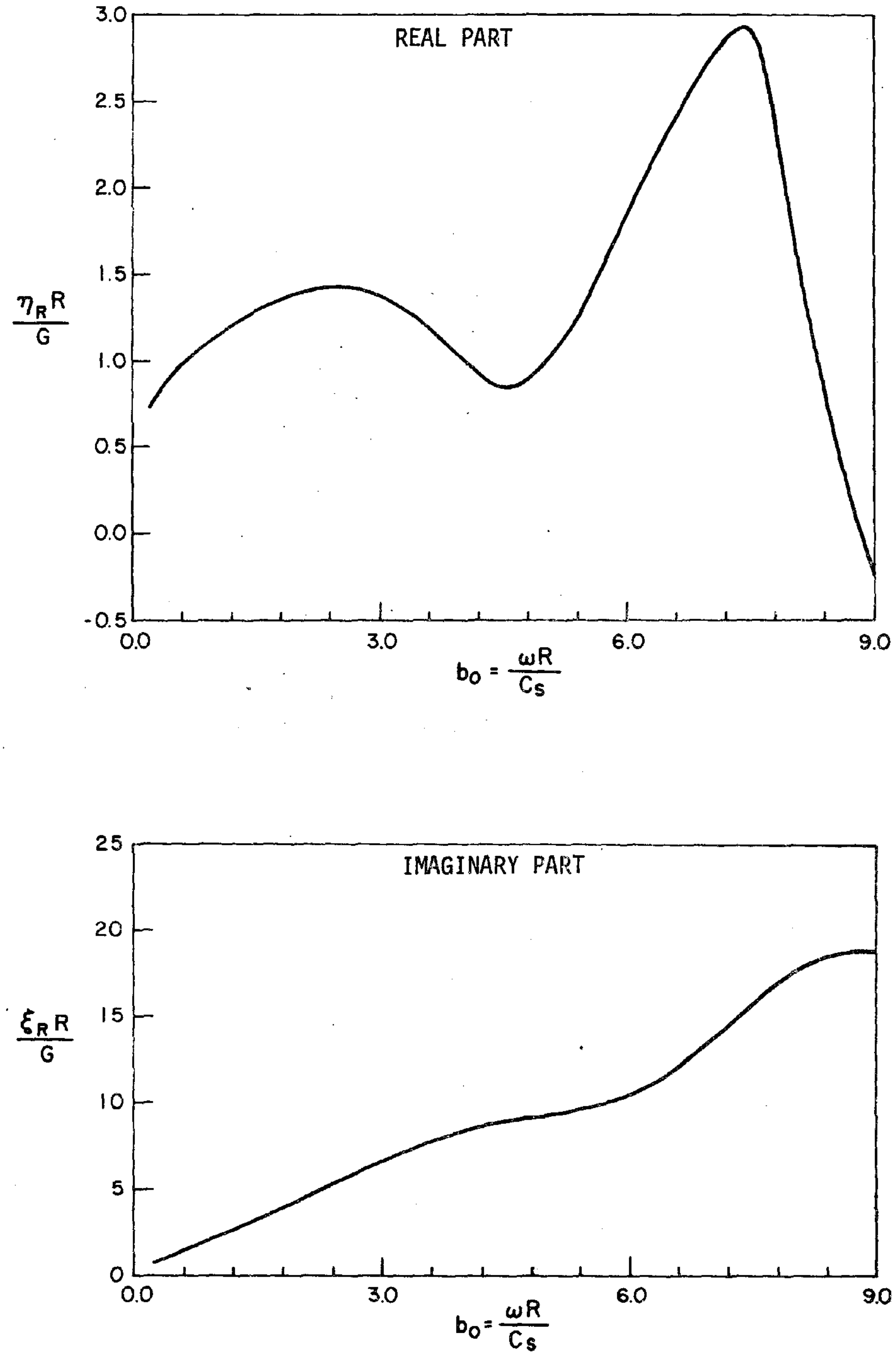


FIG. 4.2 FAR-FIELD IMPEDANCE FUNCTIONS -- RADIAL COMPONENT

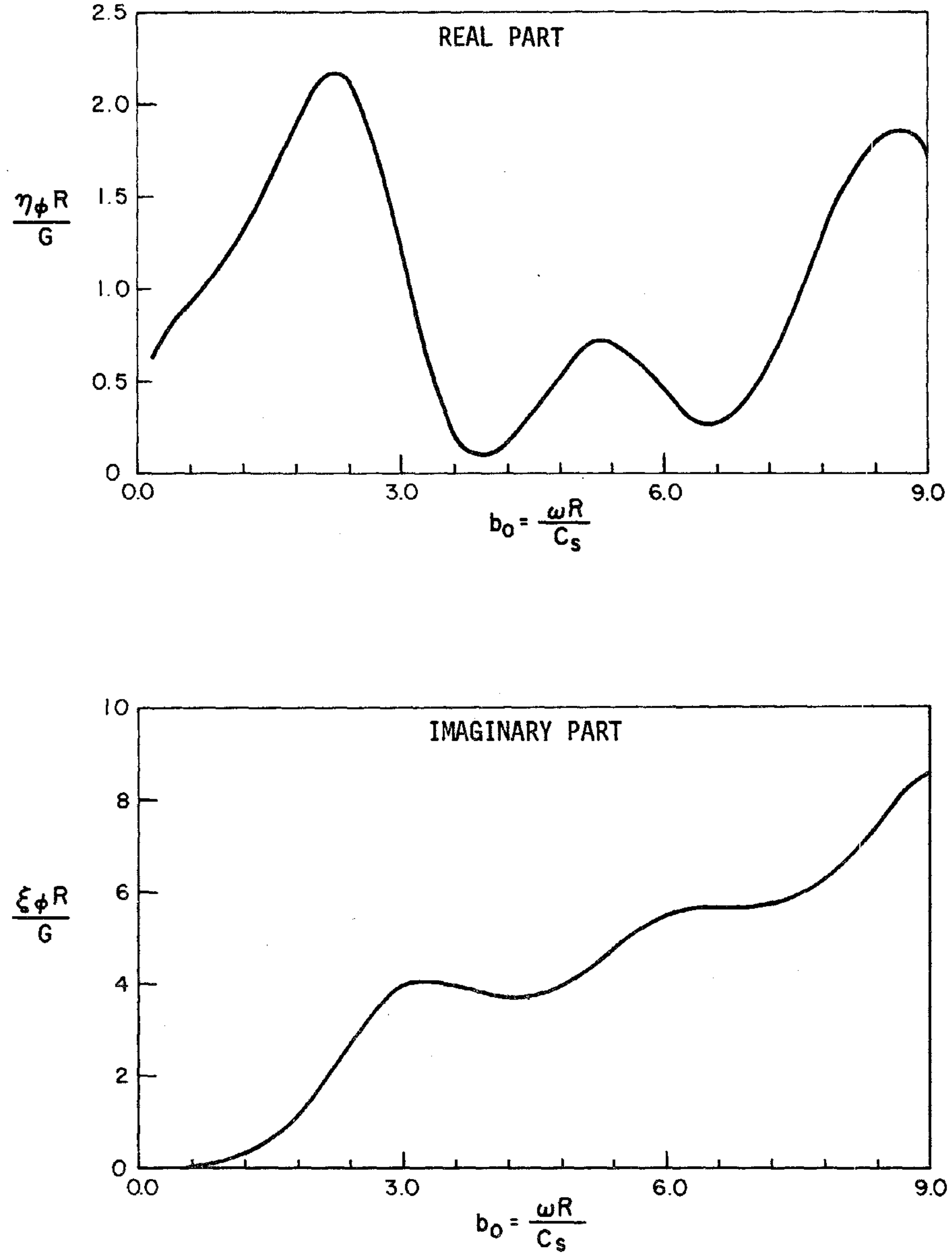
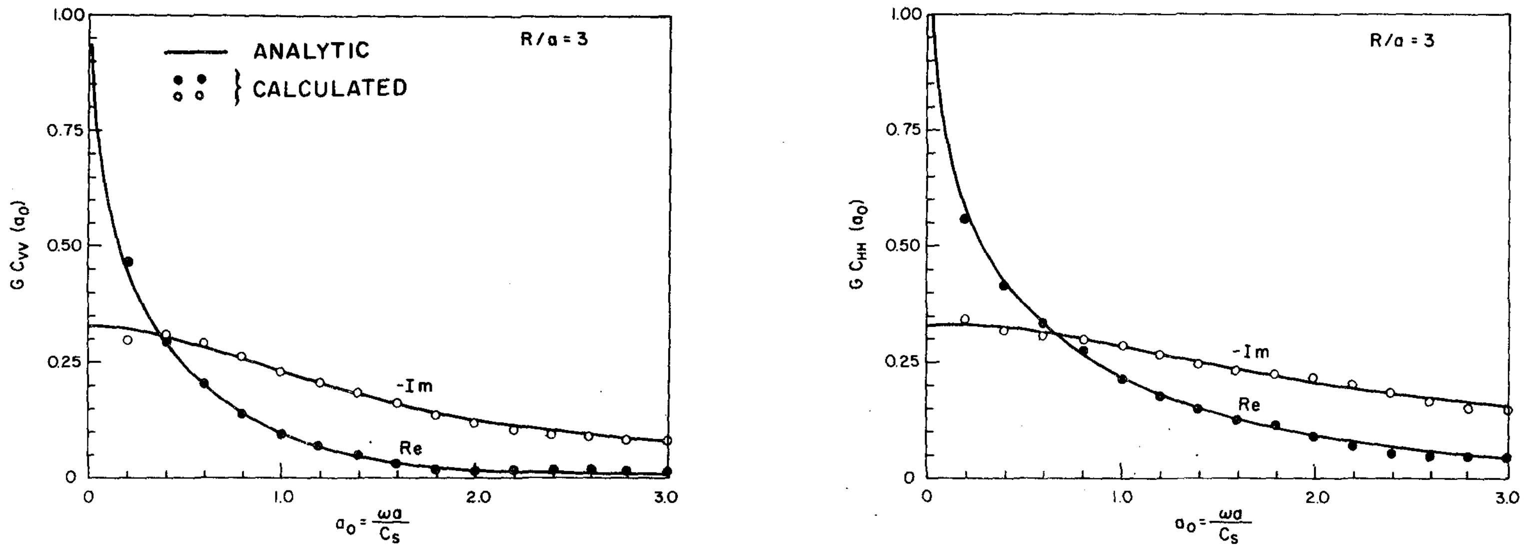
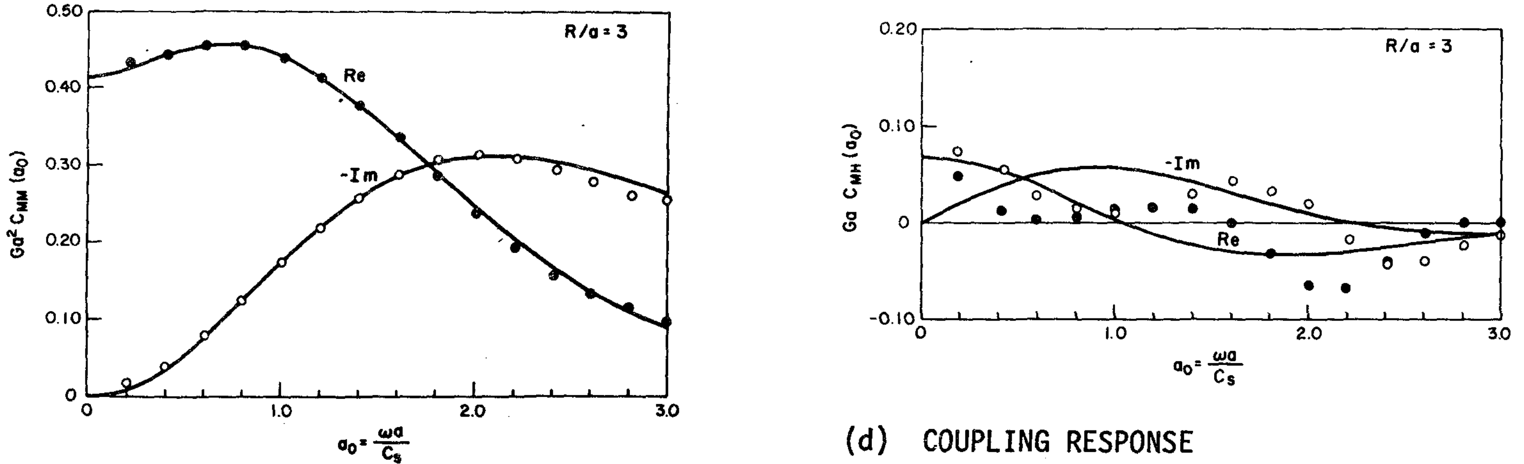


FIG. 4.3 FAR-FIELD IMPEDANCE FUNCTIONS -- TANGENTIAL COMPONENT



(a) VERTICAL RESPONSE

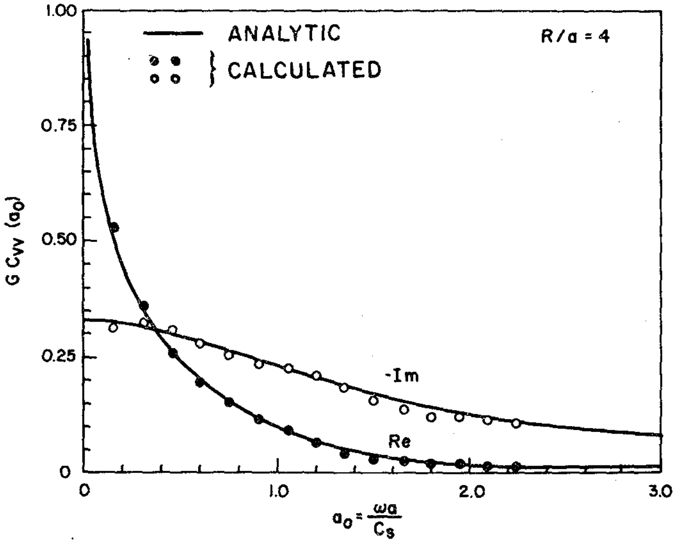
(b) TRANSLATIONAL RESPONSE



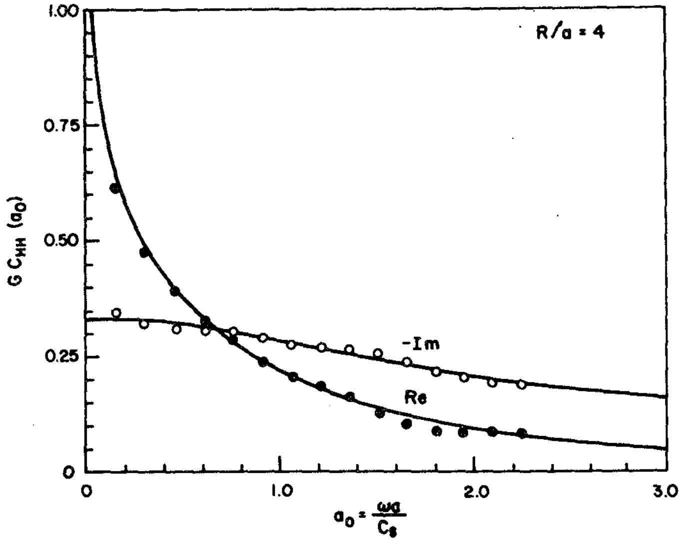
(c) ROCKING RESPONSE

(d) COUPLING RESPONSE

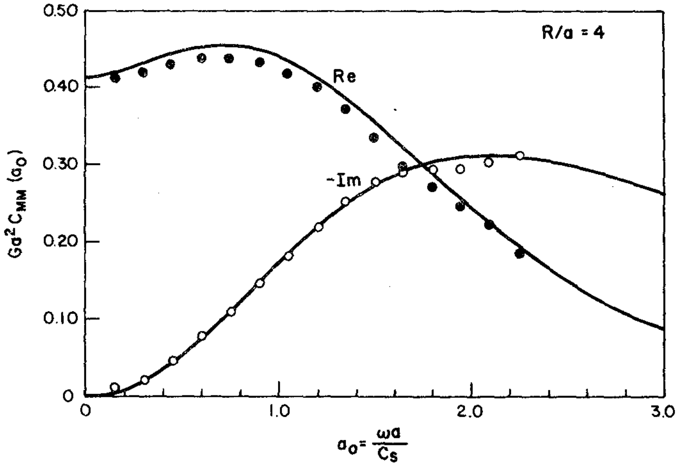
FIG. 4.4 COMPARISON OF STRIP COMPLIANCES USING IDENTIFIED IMPEDANCE FUNCTIONS



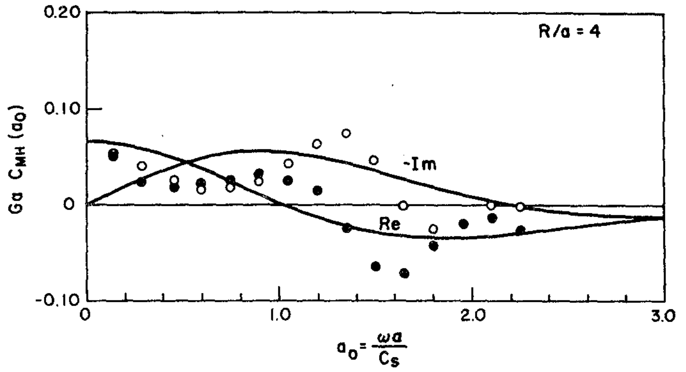
(a) VERTICAL RESPONSE



(b) TRANSLATIONAL RESPONSE

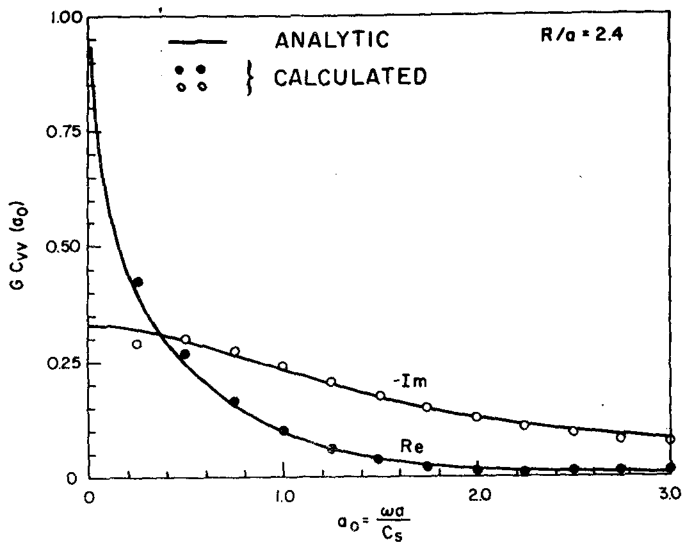


(c) ROCKING RESPONSE

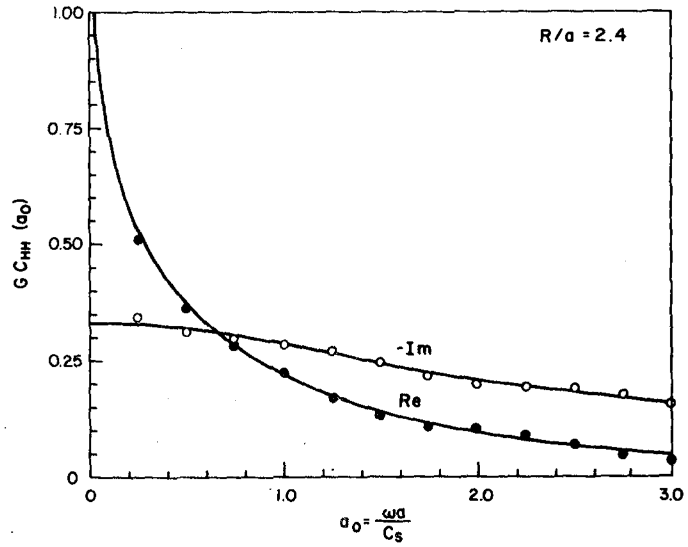


(d) COUPLING RESPONSE

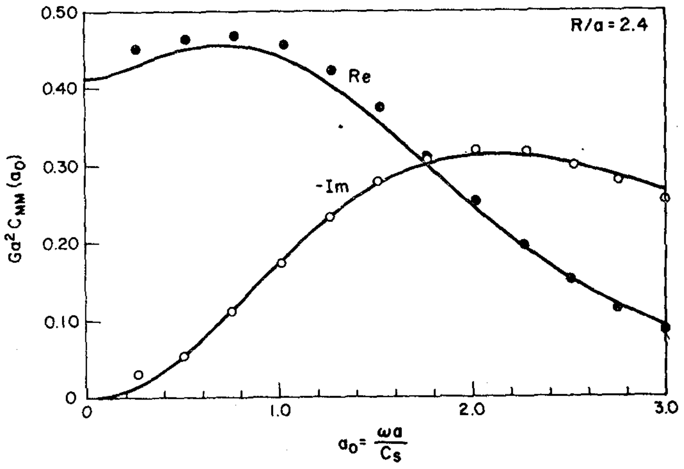
FIG. 4.5 COMPARISON OF STRIP COMPLIANCES USING IDENTIFIED IMPEDANCE FUNCTIONS



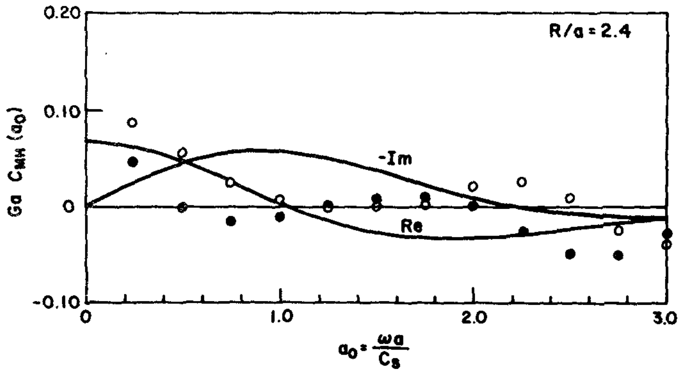
(a) VERTICAL RESPONSE



(b) TRANSLATIONAL RESPONSE

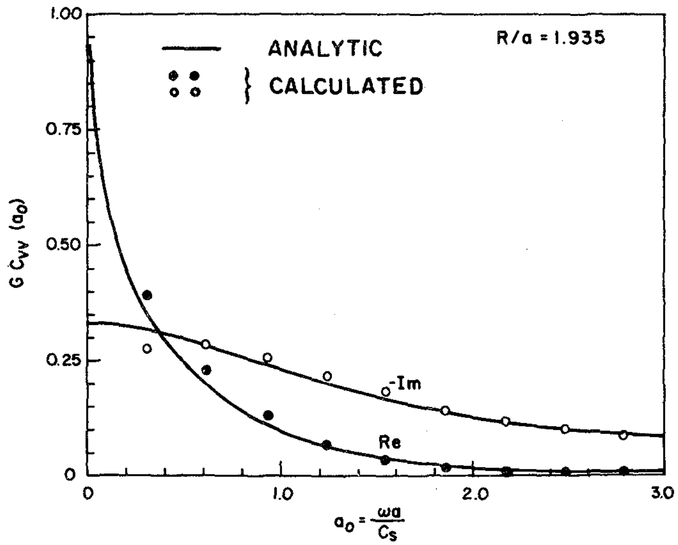


(c) ROCKING RESPONSE

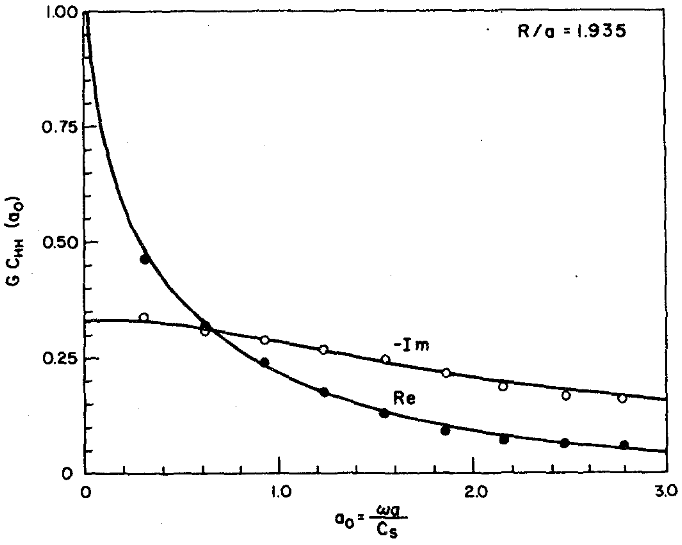


(d) COUPLING RESPONSE

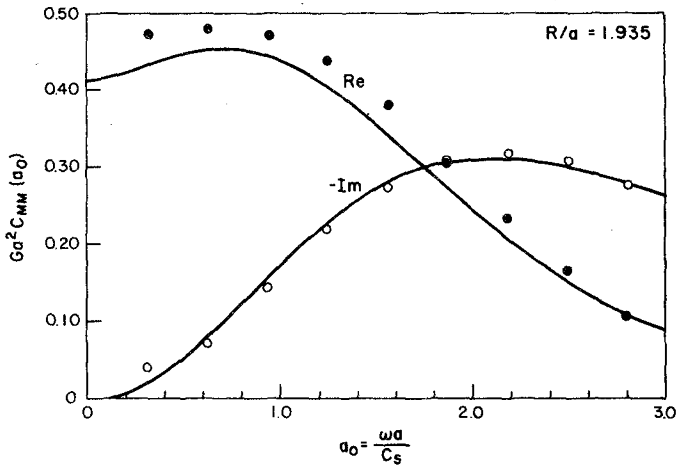
FIG. 4.6 COMPARISON OF STRIP COMPLIANCES USING IDENTIFIED IMPEDANCE FUNCTIONS



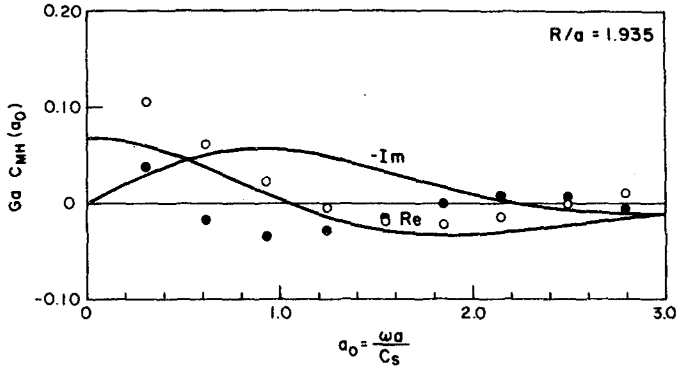
(a) VERTICAL RESPONSE



(b) TRANSLATIONAL RESPONSE



(c) ROCKING RESPONSE



(d) COUPLING RESPONSE

FIG. 4.7 COMPARISON OF STRIP COMPLIANCES USING IDENTIFIED IMPEDANCE FUNCTIONS

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