EVALUATION OF METHODS FOR EARTHQUAKE ANALYSIS OF STRUCTURE-SOIL INTERACTION

by

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SYNOPSIS

Three methods for analysis of earthquake response of structures including structure-soil interaction are evaluated for their effectiveness and applicability in handling various types of structures and soil conditions encountered in practice. Two of these--a simple substructure method and a direct finite element method--have been employed in analysis of practical problems for sometime, whereas the third, a general substructure method, has been developed only recently.

SIMPLE SUBSTRUCTURE METHOD

In the early research(1), the structure was idealized as a one-dimensional system, the base of the structure as a rigid plate supported on the surface of the soil region idealized as a halfspace. The available results for harmonic vibration of a rigid plate on an elastic halfspace were used. The complex valued stiffness (or impedance) coefficients, which depend on the excitation frequency, relate the harmonic forces applied to the rigid plate and the resulting displacements. By imposing requirements of equilibrium between the interaction forces and of compatibility between displacements at the base plate in the two substructures--the structure and the soil system--these impedance coefficients were incorporated in the governing equations for the structure written in the Fourier-transformed frequency domain. These equations are solved for a range of excitation frequencies and then using Fourier transform methods the response to arbitrary ground motion may be determined.

This analysis procedure is referred to as a substructure method because the system is analyzed in two steps: First the dynamic of a rigid plate on the soil region is analyzed separately from the structure; the resulting foundation impedance coefficients appear in the structural equations, which are then solved to determine the structural response.

The first stage of such analyses, the general problem of dynamic response of rigid footings, has been the subject of considerable research: various footing geometries--circular, rectangular and strip--were considered; the soil was treated as a viscoelastic material thus removing the restriction of linear elasticity; various soil regions--e.g., halfspace, layer, layered halfspace, were considered; embedded footings were analyzed.

This method is especially convenient if the base of the structure, the constitutive properties of the soil, and the geometry of the soil region can be idealized to conform to one of the above-mentioned cases for which foundation impedance coefficients are available. Then, only the second stage of the analysis need be performed.

The computation in the second stage of the analysis can be drastically reduced as follows. The displacements are decomposed into two parts as shown in Fig. 1. The part r_j^s may be interpreted as the quasistatic displacement in the jth degree of freedom due to base translation r_{1b} and

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rotation r_{2b}. The part r_j^d which then represents the dynamic displacements relative to the quasistatic displacements is expressed as the superposition of the natural modes of vibration of the structure on fixed base. Because excellent results can be obtained by including only the first few modes, the number of algebraic equations that need to be solved for each excitation frequency are considerably reduced, thus drastically reducing the computational effort, because the solution of equations has to be repeated for several hundred values of the excitation frequency(2).

The simple substructure method of analysis outlined above has a number of important limitations: The assumption of a rigid base plate is not appropriate in many situations; e.g., buildings with stiff central core combined with flexible frames(3), buildings supported on a number of individual footings, concrete gravity dams, and earth dams. Only approximate solutions are available for foundation impedance coefficients for embedded foundations. Solutions have not been completely developed for foundation impedances required in analysis of two or more adjacent structures involving structure-soil-structure interaction. Arbitrary non-homogeneities in the halfspace cannot be tackled.

In the simple substructure method, the specified free-field earthquake motion at the base of the structure is directly treated as the excitation.

DIRECT FINITE ELEMENT METHOD

The direct method for analysis of structure-soil systems is the result of an obvious application of the finite element method(4,5). The system to be analyzed is defined simply as the structure combined with a portion of the soil. While this method has the obvious advantage in that it can routinely handle non-homogeneous soil properties and embedded structures, it has a number of serious limitations, the more important of which are discussed in what follows.

A boundary is introduced to define the portion of the soil to be included in the system to be analyzed, whether a natural dividing line such as a soil-rock interface exists at the site or not. To overcome this definiency, transmitting boundaries to limit the lateral extent of the soil portion have been developed(6), but the horizontal boundary to define the vertical extent must be assumed as rigid. To evaluate the errors that may be caused by the introduction of such a rigid boundary, the recently developed general substructure method(7) was employed to determine the dynamic response of an example structure supported on a viscoelastic soil with specified properties; two idealizations for the geometry of the soil region: a layer of depth equal to the base width of the structure, as recommended for analysis by the direct method(5), and a halfplane. Numerical results (not presented here but will be reported elsewhere) demonstrated that if essentially similar soils extend to large depths at the site under consideration, the direct finite element analysis would be in error to an unacceptably large degree.

Because essentially all of the information on ground motion during earthquakes is based on records from accelerographs located on the ground surface or at shallow depths--in basements of buildings, the design earthquake is specified at the ground surface. However, in the direct finite element method the earthquake input is defined at the base of the finite element mesh at considerable depth. This input is determined by deconvolution of the surface level motions, assuming that they were produced exclusively by vertically propagating shear waves. This assumption excludes surface waves as well as non-vertically incident body waves. The latter can cause significant torsional response even when the structure is symmetric, whereas a vertically incident body wave would not cause any torsional response in such a structure(8).

Enormous computational effort is required in direct analysis of structure soil systems because finite element idealizations that are typically used for such analyses have several hundred to a few thousand degrees of freedom. Furthermore, modal analysis cannot be used with advantage to reduce the number of unknowns because the natural modes of vibration of the complete structure-soil system are generally inefficient in representing the deformations of the structure.

In its commonly used form(5), the direct method is limited to two-dimensional finite element systems, leading to significant errors in analysis of even an isolated structure and requiring unrealistic simplifications in modelling of a complex of structures encountered in analysis of nuclear power plants(10).

GENERAL SUBSTRUCTURE METHOD

To overcome the limitations of the direct finite element method, a substructure method which is a generalization of the simpler version discussed first has been developed(7). This method can analyze structure-soil systems with the structure idealized as a finite element system and the soil region as either a continuum, for example as a viscoelastic halfspace, or as a finite element system. The free-field earthquake motion, including spatial variations if any, at the structure-soil surface is treated directly as the excitation, thus eliminating the deconvolution calculations and the related assumptions required in the direct method.

The concept of the foundation impedance coefficients is generalized as shown in Fig. 2 to avoid the restrictions of a rigid base plate in the simple substructure method. Methods have been developed to determine the foundation impedance matrix considering a deformable structure-soil interface for soil regions idealized as a finite element system(7) or as a viscoelastic half plane(11).

Theoretically, for structure-soil systems idealized as an assemblage of finite elements, the general substructure method will lead to results identical to those from the direct method, provided the free-field motion prescribed at the structure-soil interface in the substructure method is consistent with--i.e., represents the free field response of the soil region to--the motion prescribed at the base of the finite element mesh in the direct method(7). Computationally, however, the substructure method is more efficient(7).

The substructure method is computationally efficient because it works with two smaller systems--the structure and the soil region--and more important, it takes advantage of an extension of the modal analysis concepts discussed earlier in context of the simple substructure method. By separating the structural displacements into two parts, the quasistatic displacements associated with the interaction displacements at the structure-soil interface and the remaining dynamic displacements, and expressing the latter as superposition of the first few modes of vibration of the structure on fixed base, a drastic reduction in the computational effort is achieved. Accurate solutions are obtained by including only those modes with natural frequencies within--or slightly beyond--the frequency range of interest.

For example, accurate solutions over the frequency range 0-10 cps were obtained for a structure with 96 degrees of freedom by considering only the first four vibration modes on fixed base(7).

The substructure method is applicable to complex structural idealizations, with the soil region idealized as a viscoelastic halfspace or as a finite element system, whichever is appropriate for the particular site. For finite element idealization of the soil region, the substructure method provides, for the reasons discussed above, a better alternative to the direct method. For sites where essentially similar soils extend to large depths and there is no obvious rigid boundary such as a soil-rock interface, numerical results (not presented here to keep this presentation within limits) have demonstrated that the direct method would generally result in unacceptable errors and the general substructure approach provides the only reliable analysis technique.

Combining the attractive features of the two commonly used methods--simple substructure method and direct finite element method--the general substructure method provides an effective approach to earthquake analysis of structure-soil systems, capable of analyzing any system that the commonly used methods can, and more.

ACKNOWLDEGMENT

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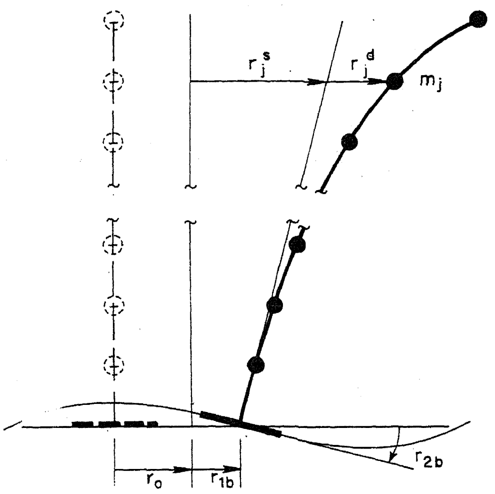

FIG. 1 SEPARATION OF DISPLACEMENTS INTO QUASI-STATIC AND DYNAMIC DISPLACEMENTS

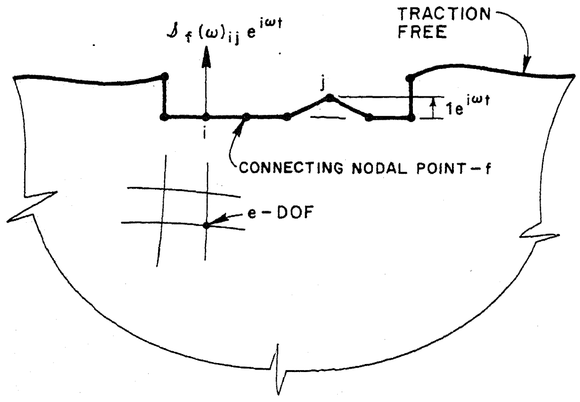

FIG. 2 PHYSICAL INTERPRETATION OF THE FREQUENCY DEPENDENT FOUNDATION STIFFNESS MATRIX $\underline{\mathcal{S}}_f(\omega)$