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SOIL-STRUCTURE INTERACTION OF RIGID STRUCTURES CONSIDERING THROUGH-SOIL COUPLING BETWEEN ADJACENT STRUCTURES

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SUMMARY

The objective of this study is to develop a theory for the dynamic response of a group of rigid structures with arbitrarily shaped bases attached to the surface of an elastic half space under the effects of the seismic excitation. One of the two methods developed in this paper is the application of a computationally efficient boundary element method (BEM). The other is a simplified method and is for obtaining a first order approximation. Numerical results for two cylindrical masses are presented when they are excited by vertically incident plane waves, and the effects of through-the-soil coupling are evaluated.

INTRODUCTION

The objective of this study is to develop a theory for the dynamic response of a group of rigid structures (Ref.1) with arbitrarily shaped bases attached to the surface of an elastic half space under the effects of the seismic excitation.

Two methods are developed for the calculation of the dynamic response of a number M of rigid structures. One is the application of a computationally efficient boundary element method (BEM). The other is a much simpler method than the first one, and it is for obtaining a first order approximation. For this method only the response of a single structure and the Green's functions for the elastic half-space are needed.

Following the proposed two methods described above, numerical results for two cylindrical masses (Fig.1) are presented when they are excited by vertically incident plane waves, and the three-dimensional through-the-soil coupling effects are evaluated. The variation of such effects is then shown as functions of the frequency of the incident wave and the separation distance between the foundations.

METHODS OF ANALYSIS

Boundary element method This method is the application of a computationally efficient boundary element method (BEM). This procedure is based upon subdividing the contact area into a number N of smaller triangular subregions, and the contact tractions and the Green's functions are assumed to be linearly

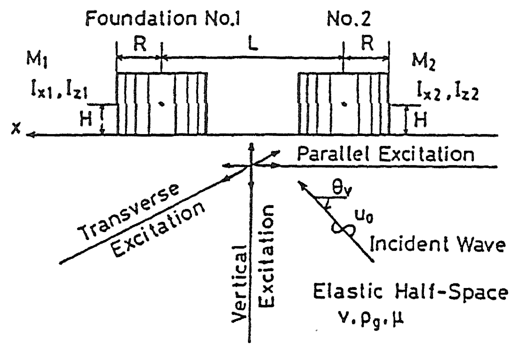

Fig. 1 Two-Foundation Model and Incident Wave

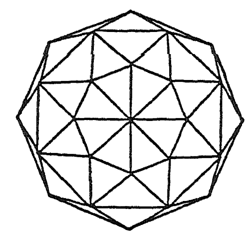

Fig. 2 Discretization of the Circular Base

varying functions of space coordinate within each subregion. The mixed boundary value problem is then discretized and solved numerically.

Comparing with the previous methods (Refs.2-4), mainly improved points are as follows:

(1) In order to enable the integrand of the derived equation to be integrated analytically, each of the real and imaginary parts of the Green's function is approximated by a polynomial or a linear function.

(2) The base is subdivided into a number of triangular subregions of various size and shape. The size of the edge subregion is reduced in order to estimate accurately the stress concentration near the fringe of the base (see Fig.2).

(3) The contact stress is assumed to vary linearly within each subregion.

(4) The displacement point, whose location was restricted to the center of the subregion in the previous studies, is placed also on the edge of the subregion and along the edge of the base. This makes it possible to estimate accurately the stress concentration near the fringe of the base.

It is quite impossible in the limited space to give details of derivations, therefore, only the final formula is shown as follows. References 5-7 should be consulted for additional details and examples.

$$\{U\} = ([I]- \frac{\omega^2}{\mu R}[C][M])^{-1}[S]\{U^g\} \tag{1}$$

in which $\{U\}$ is the 6M displacement vector for the foundations; $\{U^g\}$ is the 3M foundation input motion vector; $[I]$ is the 6Mx6M identity matrix; $[C]$ is the 6Mx6M compliance matrix for the rigid foundations; $[S]$ is the 6Mx3M input motion matrix; $[M]$ is the 6Mx6M mass matrix; ω is the circular frequency of the plane wave excitation; R is a standard length such as the radius of the circular base; and μ is the rigidity modulus of the medium.

Simplified method Let us consider the case in which the free-field motion of the ground surface is represented by $\exp(i\omega t)$. It is assumed that the response of a single foundation is given by $Q\exp\{i(\omega t-\phi)\}$ in which Q is the relative amplification factor, ϕ is the phase delay, and $Q\exp(-i\phi)$ is the complex frequency response function for the single foundation. The relative displacement between foundation no.1 (see Fig.1) and the free surface is then given by

$$Q\exp\{i(\omega t-\phi)\}-\exp(i\omega t) \tag{2}$$

This relative displacement generates a wave radiating from the foundation. If the source can be approximated by a point, this wave can be approximated by that propagating in an elastic half-space subjected to a concentrated pulse at the

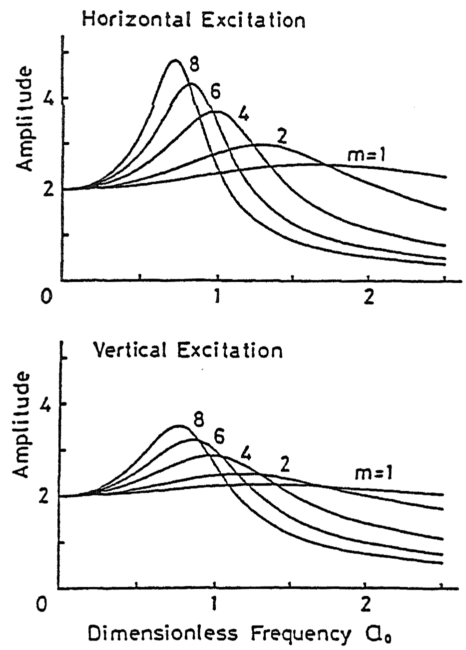

Fig. 3 Response of a Single Foundation

center of foundation no.1, and the ground motion at the center of foundation no.2 can be given using the Green's functions as follows.

$$[Q\exp\{i(\omega t-\phi)\}-\exp(i\omega t)]\cdot q\exp(-i\psi) \tag{3}$$

in which $q\exp(-i\psi)$ is the ratio of the complex value of the Green's function at the center of the base of foundation no.2 to that at a representative point (e.g., in the case of circular foundations, at half the radius) of the base of foundation no.1. This Green's function is for the elastic half-space subjected to a concentrated pulse applied at the center of foundation no.1. Therefore, the ground motion at foundation no.2 is given by the sum of the ground motion for the radiation wave given by Eq.(3) and the free-field motion of the ground surface

$$[Q\exp\{i(\omega t-\phi)\}-\exp(i\omega t)]\cdot q\exp(-i\psi)+\exp(i\omega t) \tag{4}$$

The response of foundation no.2 to such a ground motion can be obtained approximately by multiplying Eq.(4) by the complex frequency response function for the single foundation, $Q\exp(-i\phi)$.

Finally, the amplitude ratio of the motion of foundation no.2 to that of the corresponding isolated foundation is given as

$$\begin{aligned}&\left|[Q\exp\{i(\omega t-\phi)\}-\exp(i\omega t)]\cdot q\exp(-i\psi)+\exp(i\omega t)\right|\\ &=\left|[Q\exp(-i\phi)-1]\cdot q\exp(-i\psi)+1\right|\\ &=\sqrt{q^2(Q^2+1)+2qQ\cos(\phi+\psi)-2q^2Q\cos\phi-2q\cos\psi+1}\end{aligned} \tag{5}$$

If the value of Eq.(5) is larger than unity, the response of the foundation increases because of the interaction effects between the adjacent foundations, while if it is smaller than unity, the response decreases.

NUMERICAL RESULTS

Two-foundation model The methods developed in the preceding section are applied to the case in which two rigid circular foundations are placed parallel to the x axis as shown in Fig.1. In order to avoid the additional complication of the foundation response due to the effect of the coupling between the horizontal and rocking response, and to investigate only the effects of the adjacent foundations, numerical results will be presented only for the case where the height of each structure is zero, i.e., H=0. Also, the radii of the two foundations are each assumed to be equal to R. Thus, the effects not only of the mass M of each foundation but also of the separation L between the two foundations on the foundation response are studied.

The soil has been modeled as a semi-infinite elastic medium with a Poisson's ratio of 1/3. Three types of incident plane waves, namely, SV, SH, and P waves, are then considered, and the results for the waves incident vertically from below are presented in this paper. These three cases are referred to as the parallel, transverse, and vertical excitations, respectively (see Fig.1).

Response of a single foundation Before the effects of adjacent foundations are studied, the response of the single foundation isolated from the other foundations is analyzed. The base has been discretized as shown in Fig.2 by use of triangular subregions. For such a discretization of the single foundation,

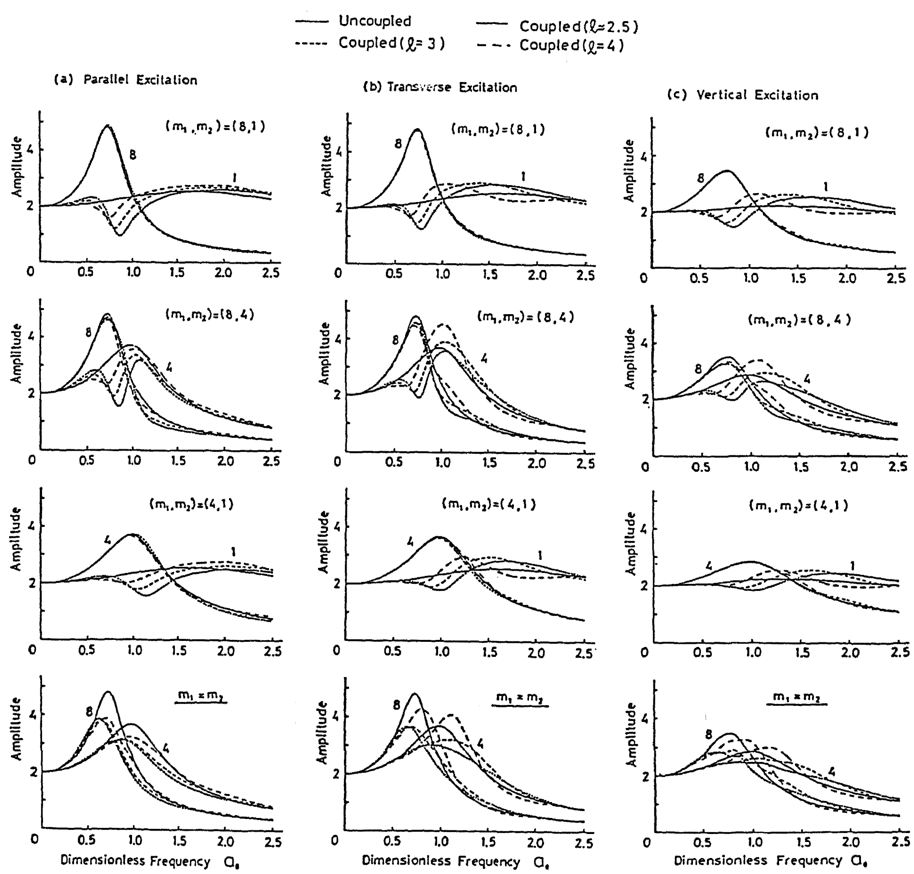

Fig. 4 Frequency Response Functions for Two-Foundation Model

compliance functions and contact stress were compared in Ref.5 with the results by Luco and Westmann (Ref.8) and those by Bycroft (Ref.9), respectively, and a sufficient accuracy has been obtained.

Fig.3 shows the amplitude of the foundation response normalized by the amplitude of the incident wave as functions of the dimensionless frequency, $a_0 = \omega R/V_s$ (V_s is the shear wave velocity in the half-space), for the incident S and P waves, and for different values of dimensionless mass, $m=M/(\rho R^3)$ (ρ is the density of the soil), of the rigid foundation. It should be noticed that the maximum amplitude is not an infinite but a finite value, even though no damping of the medium is assumed. This is because of the radiation damping.

Interaction between two foundations Numerical results for the case of two rigid circular foundations (Fig.1) are presented when they are excited by vertically incident plane waves of the three types described above. Each base is discretized into 40 subregions as shown in Fig.2. Fig.4 shows the amplitude of the foundation response normalized by the amplitude of the incident wave as functions of the dimensionless frequency a_0 for the parallel, transverse, and vertical excitations, i.e., for the incident SV, SH and P waves. For five combinations of m_1 and m_2, which denote the dimensionless mass of the adjacent foundations, and for three separations between the two foundations, $\ell = L/R$ = 2.5, 3, 4, the results are shown in comparison with the case of the single foundation.

The effects of the interaction between adjacent foundations on the

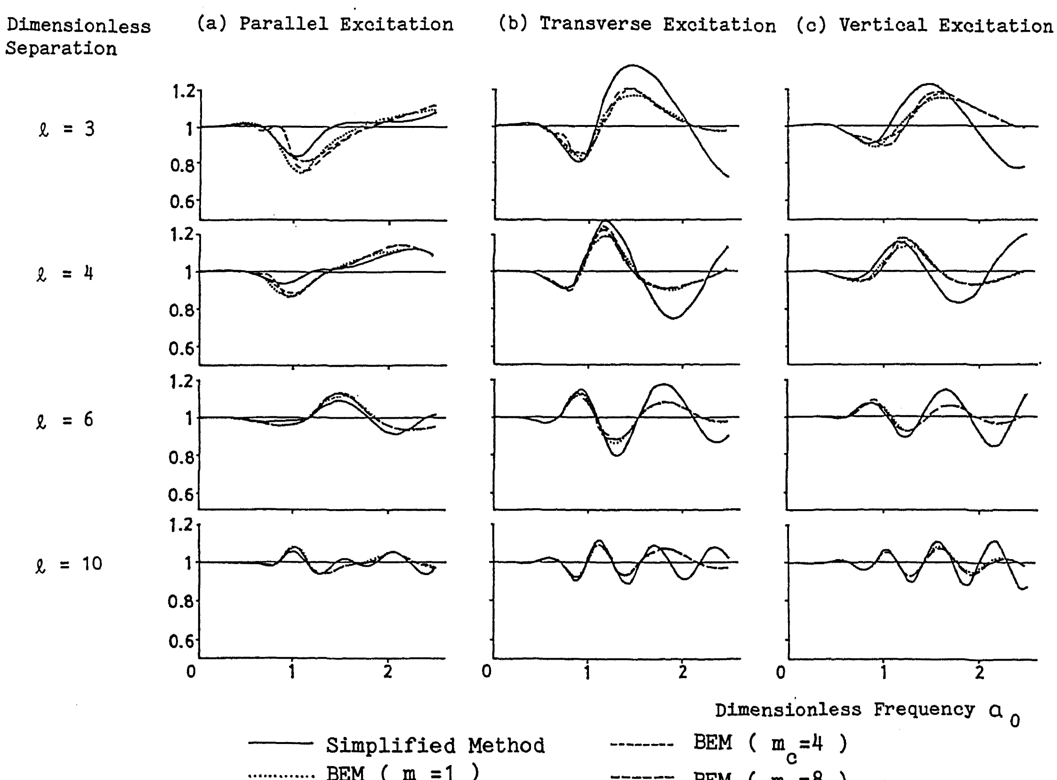

Fig. 5 Effect of Adjacent Foundation (Dimensionless Mass of m_a=4) on Frequency Response Functions

amplitude of the response of the foundation depends in a complicated manner upon the numerical values of the frequency of the excitation, the separation between the two foundations, the mass of the foundations, and the type of the incident wave.

The results obtained above in Fig. 4 are very complicated. Therefore, in order to show only the effects of the interaction between the two foundations, the ratio of the amplitude of the motion of each foundation to that of the corresponding isolated foundation is plotted in Fig. 5 as functions of dimensionless frequency for different values of the separation. A comparison of the four sets of curves of Fig. 5 makes it evident that the effect varying the mass of the rigid foundation under consideration, m_c, is not so significant as that of the adjacent foundation, m_a, and that the agreement between the results of the proposed two methods is reasonably good. Whether the amplitude of the response of the foundation increases or decreases depends upon the exciting frequency and the separation in a cyclic manner. And the peak of the variance shifts to the lower frequency with increasing separation. Such a result can be explained using a wave radiating from the foundation.

CONCLUSIONS

The effects of through-the-soil coupling for two adjacent foundations are evaluated using the proposed two methods. The variation of such effects is shown as functions of the frequency of the incident wave and the separation distance between the foundations. The agreement between the results of the two methods is reasonably good, and the accuracy of the simplified method is verified. Whether the amplitude of the response of the foundation increases or decreases depends upon the exciting frequency and the separation in a cyclic manner. And such a result can be explained using a wave radiating from the foundation.

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