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KINEMATIC INTERACTION EFFECTS ON THE EFFECTIVE PARAMETERS OF SOIL-STRUCTURE SYSTEMS DUE TO INERTIAL INTERACTION

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ABSTRACT

Usually the interaction effects considered in design are those due to the inertial interaction solely under the assumption of linear structural behavior, namely: the period lengthening and the damping modification corresponding to the fundamental mode of vibration of the structure assumed with rigid base. Also, most available solutions do not take into account the influence of the foundation embedment, so that they are applicable only to surface foundations.

In this work a rigorous solution is presented for obtaining the effective period and damping of structures with embedded square foundations in a homogeneous viscoelastic half-space. This study differs from previous works in that the wave passage effects are also included in the effective parameters of coupled systems. The soil is replaced with impedance functions for the case of welded contact conditions between the footing and the surrounding soil, so that linear springs and viscous dashpots dependent on the excitation frequency are used. The influence of the kinematic interaction on the dynamic properties of the soil-structure system is explicitly included by correcting the effective period and damping due to the inertial interaction only, in such a way that the resonant shear force of a replacement oscillator with rigid base subjected to the surface free-field motion is equal to that of the coupled system subjected to the foundation input motion. Effective parameters of a number of coupled systems are computed by applying this solution, which are useful when employed in conjunction with static and dynamic methods of seismic analysis for evaluating the interaction effects on the fundamental mode of vibration.

KEYWORDS

Effective damping; effective period; embedded foundation; foundation input motion; impedance functions; inertial interaction; kinematic interaction; replacement oscillator; soil-structure interaction; wave passage effects.

INTRODUCTION

Dynamic soil-structure interaction produces kinematic and inertial effects on the structure and soil as a result of the soil flexibility under dynamic excitation. Essentially, the interaction modifies the dynamic properties of the structure as well as the characteristics of the ground motion around the foundation, whose evaluation requires determining the effective period and damping of the coupled system and the overall excitation at the subgrade.

The soil-structure interaction problem can be divided into two parts, commonly known as the inertial interaction and the kinematic interaction (Kausel *et al*, 1978). The lengthening of the fundamental period of vibration and the increase or decrease of the damping of the fixed-base structure are produced by the inertial interaction (Jennings and Bielak, 1973; Veletsos and Meek, 1974), basically due to the inertia and elasticity of the coupled system. Kinematic interaction reduces the foundation translation and induces torsion and rocking, while it filters the high frequency components of the excitation (Scanlon, 1976; Pais and Kausel, 1989), essentially because of foundation stiffness and geometry.

For most structures it is conservative to carry out only the inertial interaction analysis, whenever site effects are considered in the determination of the ground motion at the free surface, which is assumed as the effective motion at the base of the structure. Although this excitation has no rocking and torsional components, it is generally less favorable than the overall motion obtained from the kinematic interaction analysis alone.

It is well-known that the fundamental period of a structure interacting with the soil is always increased through inertial interaction, inasmuch as the flexibility of the coupled system is greater than that of the fixed-base structure. Also, the damping of the interacting system is generally increased since an additional energy dissipation is presented as a result of the material damping by hysteretic behavior of the soil and the geometrical damping by wave radiation into the soil. However, since the soil-structure interaction reduces the effectiveness of the structural damping, it is possible that the overall damping of the interacting system is less than the damping of the fixed-base structure, unless this reduction is compensated by the increase due to the soil damping (Veletsos and Meek, 1974).

Usually, the interaction criteria for design purposes consider only the inertial effects on the period and damping; the kinematic effects on the excitation are often neglected. Due to the lack of simplified solutions for the kinematic interaction, the wave passage effects have not been explicitly incorporated so far in major seismic codes. By using a two-dimensional model, Todorovska and Trifunac (1992) have studied the wave nature of the ground motion and the energy dissipated by the scattering and diffraction of the incident waves from the foundation, in order to evaluate the kinematic effects on both the period and damping of the coupled system. They have found that the system period practically does not depend on the type of incident waves and the angle of incidence, as well as the system damping is generally underestimated when the wave passage effects are excluded by assuming the surface free-field motion as the foundation input motion.

The effects of the scattering and diffraction of the incident waves from the building foundation on the system period and system damping, during building-soil interaction, have not been extensively studied so far. The aim of this work is to present a rigorous solution for determining the effective period and damping of soil-structure systems, considering the effects of both the inertial and kinematic interaction. A three-dimensional model is used which consists of a single oscillator, equivalent to the fixed-base structure vibrating in its fundamental mode, supported by a rigid square foundation embedded into a homogeneous viscoelastic half-space. Impedance functions and overall motions, dependent on the excitation frequency, are used for the case of welded contact conditions between the footing and the surrounding soil. Kinematic effects are considered in terms of the inertial ones by using an equivalence between a replacement oscillator with rigid base subjected to the surface free-field motion and the coupled system subjected to the foundation input motion. The practical advantage of this approach is that the structural response with both inertial and kinematic effects may be obtained from standard site response spectra. Effective parameters of a number of coupled systems are computed by applying this solution; the influence of the foundation embedment, which is one of the most critical parameters for the kinematic interaction, is studied for two typical values of the Poisson's ratio.

EQUILIBRIUM EQUATIONS OF THE SOIL-STRUCTURE SYSTEM

As the first mode contributes most to the building response, the contribution of the higher modes is neglected in this study. Thus, for multistory structures resting upon homogeneous soil that respond basically as a single oscillator in their fixed-base condition, the soil-structure system can be idealized as shown in Fig.1. The foundation is assumed square and rigid with two degrees of freedom, one of them in lateral translation and the other in rocking. The overall motion at the subgrade of the foundation is produced by vertically incident SH waves. This coupled system is suitable to consider the interaction effects on the fundamental mode of vibration.

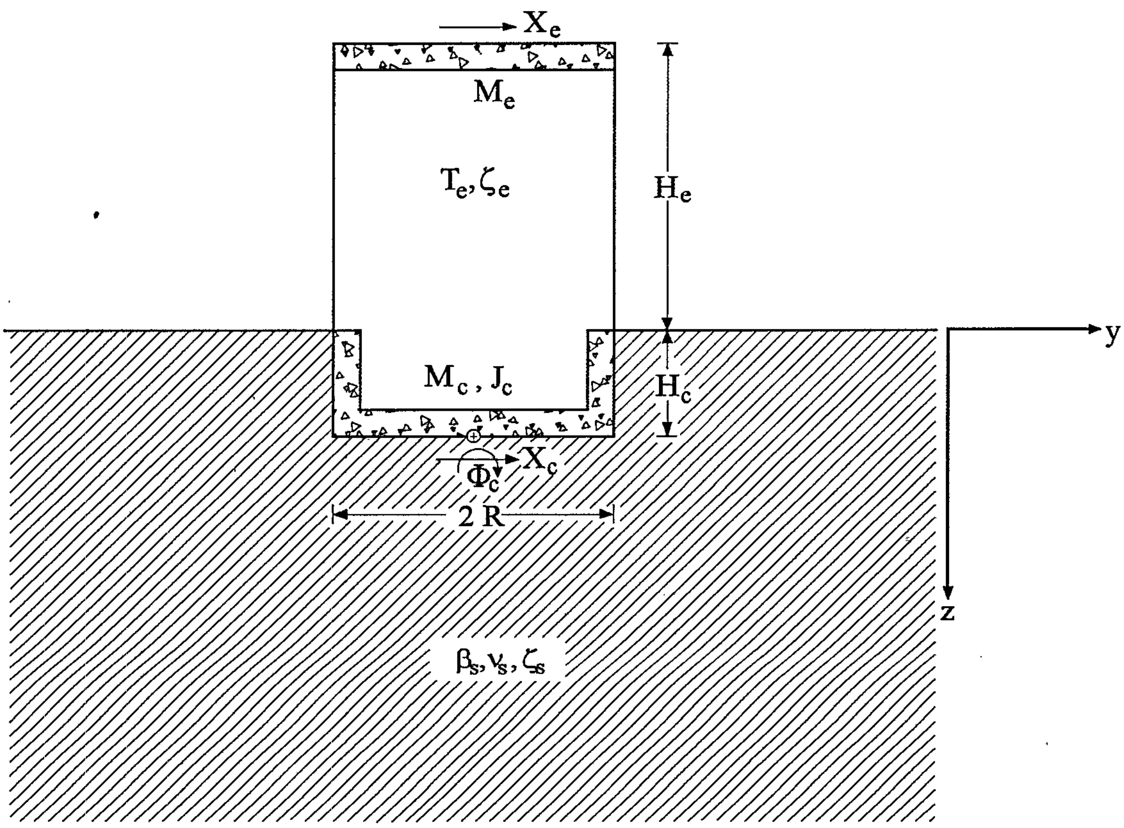

Fig. 1. Single structure with square foundation embedded in a homogeneous half-space.

The parameters of the single oscillator must be interpreted as the modal parameters of the multistory structure vibrating in its fixed-base fundamental mode. Thus, T_e and ζ_e are respectively the period and damping of the fundamental mode, M_e the effective mass participating in this mode and H_e the effective height of the resultant of the corresponding inertia forces (Jennings and Bielak, 1973). The square foundation is defined by the half-width R, depth H_c, mass M_c and mass moment of inertia J_c. And the soil is characterized with the shear wave velocity β_s, Poisson's ratio ν_s and damping factor ζ_s.

In all of the models commonly used for interaction provisions in building codes, the foundation excitation is taken as a horizontal driving motion with constant amplitude. Assuming now that the soil-structure system is subjected to the overall motion defined by the translation X_o and rocking Φ_o at the foundation subgrade, due to the control motion X_g at the free surface, it can be demonstrated that the equilibrium equations of the coupled system in the frequency domain are given by

$$\left[\mathbf{K}+i\omega\mathbf{C}-\omega^2\mathbf{M}\right]\{\mathbf{X}\}=-\ddot{X}_g\left\{Q_h\{\mathbf{M}_o\}+Q_r\{\mathbf{J}_o\}\right\} \tag{1}$$

in which $\mathbf{X}=\{X_e \quad X_c \quad \Phi_c\}^T$ is the displacement vector of the coupled system where X_e is the deformation of the structure, X_c the relative displacement of the foundation and Φ_c the relative rotation of the foundation; $\mathbf{M}_o$ and $\mathbf{J}_o$ are the load vectors

$$\mathbf{M}_o=\begin{Bmatrix} M_e \\ M_e+M_c \\ M_e(H_e+H_c)+M_cH_c/2 \end{Bmatrix} \tag{2}$$

$$\mathbf{J}_o=\begin{Bmatrix} M_e(H_e+H_c) \\ M_e(H_e+H_c)+M_cH_c/2 \\ M_e(H_e+H_c)^2+J_c \end{Bmatrix} \tag{3}$$

while $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are respectively the mass, damping and stiffness matrices of the coupled system, which are given by

$$\mathbf{M}=\begin{bmatrix} M_e & M_e & M_e(H_e+H_c) \\ M_e & M_e+M_c & M_e(H_e+H_c)+M_cH_c/2 \\ M_e(H_e+H_c) & M_e(H_e+H_c)+M_cH_c/2 & M_e(H_e+H_c)^2+J_c \end{bmatrix} \tag{4}$$

$$\mathbf{C}=\begin{bmatrix} 4\pi\zeta_e M_e/T_e & 0 & 0 \\ 0 & C_h & C_{hr} \\ 0 & C_{rh} & C_r \end{bmatrix} \tag{5}$$

$$\mathbf{K}=\begin{bmatrix} 4\pi^2 M_e/T_e^2 & 0 & 0 \\ 0 & K_h & K_{hr} \\ 0 & K_{rh} & K_r \end{bmatrix} \tag{6}$$

Besides, $Q_h(\omega)=\ddot{X}_o(\omega)/\ddot{X}_g(\omega)$ and $Q_r(\omega)=\ddot{\Phi}_o(\omega)/\ddot{X}_g(\omega)$ are the transfer functions for the translation and rocking components of the foundation input motion, respectively. The amplitudes and phases of the overall motion are dependent on the excitation frequency ω, the type of incident waves and the angle of incidence. Since the soil is replaced with impedance functions, linear springs and viscous dashpots dependent on the excitation frequency are used, so that K_h and C_h express the stiffness and damping of the soil in the translation mode of the footing, K_r and C_r the stiffness and damping of the soil in the rocking mode of the footing, and $K_{hr}=K_{rh}$ and $C_{hr}=C_{rh}$ the coupled stiffness and damping of the soil. The mass center of the foundation is assumed to be at $H_c/2$ above the subgrade so as to eliminate one parameter that has no significant influence on effective periods and dampings of coupled systems.

SYSTEM PERIOD AND SYSTEM DAMPING WITH KINEMATIC EFFECTS

In order to improve the interaction provisions used in seismic codes, a criterion is suggested to account for the kinematic effects, which consists in the modification of the effective period and damping of the soil-structure system due to the inertial effects only, in such a way that the resonant shear force of a replacement oscillator with rigid base subjected to the control motion at the free surface is equal to that of the coupled system subjected to the overall motion at the foundation subgrade, as shown in Fig.2. The practical advantage of this approach is that the structural response with both inertial and kinematic effects can be obtained from standard free-field response spectra.

The effective period and damping with kinematic effects can be computed from the steady-state harmonic response of the soil-structure system, by solving Eq. (1) using standard procedures for complex algebraic equations. Assuming $Q_h = 1$ and $Q_r = 0$, the effective parameters with inertial effects only may be calculated. In both cases, the transfer function $H(\omega) = \omega_e^2 X_e / \ddot{X}_g$ for the pseudo-acceleration of the structure can be obtained in terms of the excitation frequency. The resonant period and peak amplification of this transfer function are associated with the effective period and damping, respectively, of the structure interacting with the soil.

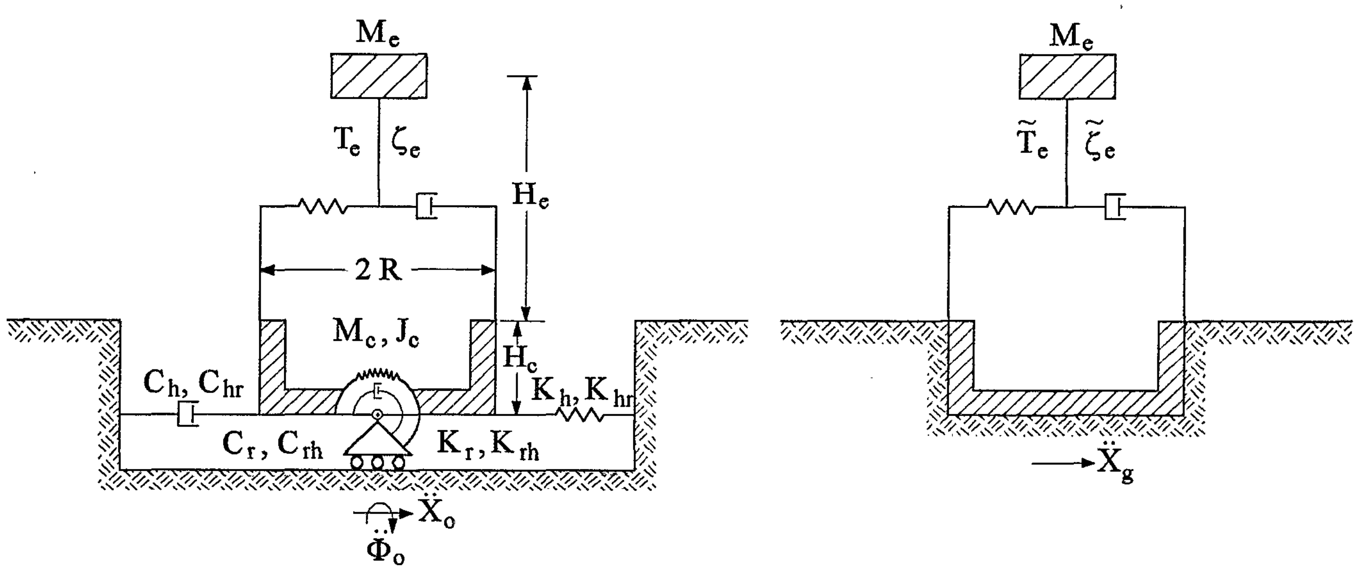

Fig. 2. Coupled system subjected to the overall motion $(\ddot{X}_o, \ddot{\Phi}_o)$ and replacement oscillator subjected to the control motion $(\ddot{X}_g)$.

This approach, which is an extension of that presented by Jennings and Bielak (1973) and Veletsos and Meek (1974), leads to equating the peak pseudo-acceleration and resonant period of the coupled system with those corresponding to the replacement oscillator. As the damping values of soil-structure systems can considerably exceed those of the associated fixed-base structure, the damping terms of second order cannot be neglected. Considering this situation and applying that equivalence, the effective damping of the coupled system is determined as

$$\tilde{\zeta}_e^2 = \frac{1}{2}\left(1 - \left(\frac{H_{res}^2 - 1}{H_{res}^2}\right)^{1/2}\right) \tag{7}$$

and the effective period of the coupled system is obtained as

$$\tilde{T}_e = \frac{2\pi\left(1 - 2\tilde{\zeta}_e^2\right)^{1/2}}{\omega_{res}} \tag{8}$$

where ω_{res} is the resonant frequency and H_{res} the corresponding peak pseudo-acceleration observed at the transfer function of the interacting system.

IMPEDANCE FUNCTIONS AND INPUT MOTIONS

Dynamic stiffnesses and overall motions depend not only on the characteristics of the soil and foundation, but also on the value of the excitation frequency, which makes the analysis of soil-structure systems one of the more complex problems in structural dynamics.

Tables of soil impedance functions and foundation input motions for rigid square foundations embedded in a uniform elastic half-space have been reported by Mita and Luco (1989). These tables include numerical results for different Poisson's ratios and several foundation embedments. The impedance functions taken from the tables are those corresponding to the horizontal, rocking and coupling modes. The input motions taken from the same tables correspond only to the vertically incident SH waves.

The presence of material damping in the soil can be incorporated by using the correspondence principle for viscoelastic behavior (Gazetas, 1985). Thus, the impedance function for any vibration mode of the foundation is expressed as

$$\tilde{K}_m = K_m^o\left(k_m + \frac{i}{\sqrt{1+i2\zeta_s}}\eta c_m\right)(1+i2\zeta_s); \quad m = h,r,hr \tag{9}$$

The term K_m^o is defined as the static stiffness, while the terms k_m and c_m are designated as the stiffness and damping coefficients, respectively, which depend on the dimensionless frequency $\eta = \omega R/\beta_s$.

As the impedance function is alternatively represented by means of the complex expression

$$\tilde{K}_m = K_m + i\omega C_m; \quad m = h,r,hr \tag{10}$$

the linear spring K_m and viscous dashpot C_m are then related with K_m^o, k_m and c_m through the following expressions:

$$K_m = K_m^o(k_m - \zeta_s \eta c_m); \quad m = h,r,hr \tag{11}$$

$$\omega C_m = K_m^o(\eta c_m + 2\zeta_s k_m); \quad m = h,r,hr \tag{12}$$

Values of $K_m^o k_m$ and $K_m^o c_m$ referred to the foundation subgrade are reported in the reference data base for different Poisson's ratios ν_s and normalized foundation depths H_c/R.

Two types of wave excitations could be considered for the adopted interaction model, namely vertically and horizontally incident SH waves, whose particle motion is in the x-direction normal to the plane y-z. The free-field ground motion that would exist in the absence of the footing is given for each case by

$$X_v = X_g \cos\left(\frac{\omega z}{\beta_s}\right) \tag{13}$$

$$X_h = X_g e^{-i\omega y/\beta_s} \tag{14}$$

in which X_g represents the amplitude of the free-field ground motion at the half-space surface; the time dependence $e^{i\omega t}$ for harmonic waves has been omitted. This control motion induces input motions at the foundation subgrade, whose components of translation and rocking are denoted by the amplitudes X_o and

Φ_o, respectively. The reference data base includes values for the real and imaginary parts of the ratios X_o/X_g and $R\Phi_o/X_g$ for different Poisson's ratios ν_s and normalized foundation depths H_c/R.

EFFECTS OF THE TYPE OF INCIDENT WAVES AND INCIDENCE ANGLE

Effective periods and dampings can be expressed in terms of characteristic parameters of the soil-structure system. Such dimensionless parameters are: 1) the ratio of the foundation mass to that of the structure, M_c/M_e; 2) the ratio of the mass moment of inertia of the foundation to that of the structure, $J_c/M_e(H_e+H_c)^2$; 3) the relative mass density between the structure and soil, $M_e/\rho_s\pi R^2 H_e$; 4) the damping ratios for the structure with rigid base and soil, ζ_e and ζ_s; 5) the Poisson's ratio for the soil, ν_s; 6) the relative foundation depth, H_c/R; 7) the slenderness ratio of the structure, H_e/R; and 8) the relative stiffness between the structure and soil, $H_e/\beta_s T_e$.

Assuming the following values $M_c/M_e = 0.2$, $J_c/M_e(H_e+H_c)^2 = 0.05$ and $M_e/\rho_s\pi R^2 H_e = 0.15$, which are representative for buildings and soils, and adopting the conventional damping values $\zeta_e = \zeta_s = 0.05$, effective periods and dampings of soil-structure systems were computed for different ν_s, H_c/R and H_e/R, into the range of interest $0 \le H_e/\beta_s T_e \le 0.5$. Most typical cases encountered in practical applications are covered with this parametric analysis.

In practice, the wave nature of the seismic excitation for structures is usually ignored. Nevertheless, because of the scattering and diffraction of the incident waves from the foundation and due to the filtering of the high frequency components of the incident waves by the footing, the foundation input motion differs from the surface free-field motion, which implies that the system period and the system damping are modified by the type of incident waves and their angle of incidence.

Figure 3 shows effective periods and dampings of coupled systems for vertically incident SH waves, the Poisson's ratios $\nu_s = 0.25, 0.4$, in columns, and the relative foundation depths $H_c/R = 0, 0.5, 1$, in rows. Each box contains results for the slenderness ratios of the structure $H_e/R = 1, 2, 3, 4, 5$; effective parameters including only the inertial interaction effects are depicted with thin line, whereas results involving the kinematic interaction influence are described with thick line. The system periods are normalized with respect to the fundamental period of the associated fixed-base structure. Similar results for horizontally incident SH waves could be obtained; the torsional input motion induced by this kind of excitation should be omitted because the degree of freedom in torsion is uncoupled. The general trends and features of the effective parameters are in agreement with those obtained by Bielak (1975) for circular embedded foundations in a half-space, considering the inertial interaction only.

From these results the influence of the wave passage effects on the effective parameters of soil-structure systems can be evaluated. It can be noted that the system period is practically insensitive to the scattering and diffraction of the incident waves from the foundation, except for $H_e/R = 1$ where some slight differences are observed. However, the wave passage effects on the system damping is very important, being more pronounced for short and squat structures $(H_e/R = 1)$ than for tall and slender structures $(H_e/R = 5)$. It is also verified that for surface foundations $(H_c/R = 0)$ subjected to vertically incident SH waves, the kinematic interaction does not take place at all. In general, the wave passage effects always result in an increment of the system damping with respect to that obtained from the inertial interaction alone. This damping increment enhances as the foundation depth increases and, as expected, the interaction effects enlarge with the relative stiffness between the structure and soil.

The reason for the variations in the dependency of the system damping on the type of incident waves and their incidence angle comes from the characteristics of the induced foundation input motion. For instance, the vertically incident SH waves produce a considerable amount of overall rotation as compared with that generated by the horizontally incident SH waves.

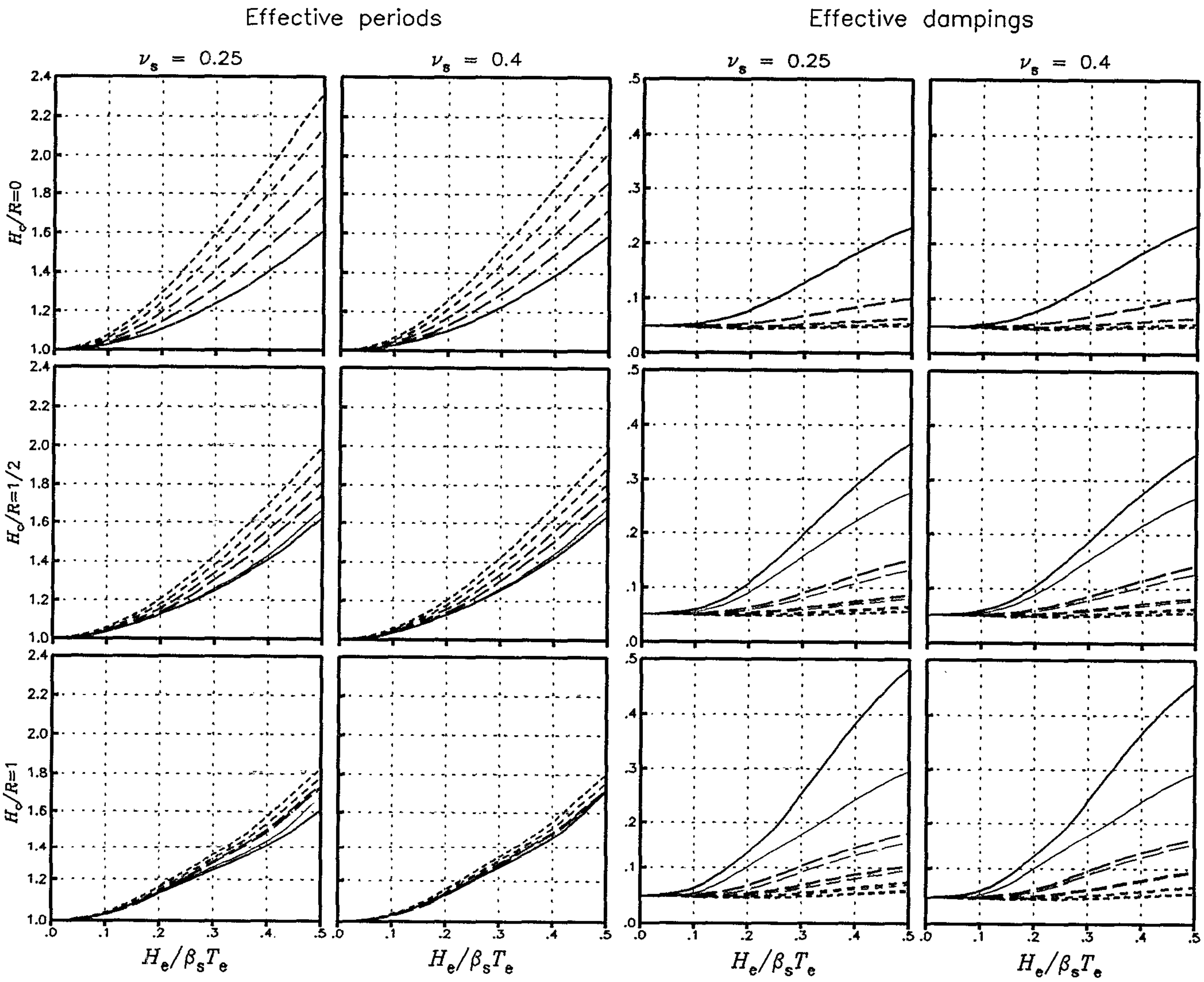

Fig. 3. Effective periods ($\tilde{T}_e/T_e$) and dampings ($\tilde{\zeta}_e$) with inertial (thin line) and kinematic (thick line) interaction for $\nu_s = 0.25, 0.4$ (in columns) and $H_c/R = 0, 0.5, 1$ (in rows); results correspond to $H_e/R = 1$(——), 2, 3, 4, 5(······).

CONCLUSIONS

A three-dimensional model has been implemented to measure the influence of the wave passage effects on the effective period and damping of soil-structure systems due to the inertial interaction only. The model consists of a single oscillator, equivalent to the fixed-base structure vibrating in its fundamental mode, placed on a rigid square foundation embedded into a homogeneous viscoelastic half-space. Rigorous impedance functions and overall motions, dependent on the excitation frequency, are used for the case of welded contact conditions between the foundation and the surrounding soil. The system period and the system damping with both the inertial and the kinematic interaction have been obtained from the transfer function for the structural pseudo-acceleration, by using an analogy between the coupled system subjected to the foundation input motion and a replacement oscillator with rigid base subjected to the surface free-field motion. Foundation input motions for vertically incident SH waves are employed.

The influence of the following characteristic parameters on the effective period and damping of coupled systems including the kinematic interaction was studied: the damping ratios of the fixed-base structure and soil, the Poisson's ratio of the soil, the relative foundation depth, the slenderness ratio of the structure, and the relative stiffness between the structure and soil. Results presented herein show that the system period depends weakly on the wave passage effects, while the system damping depends strongly on those effects.

It can be concluded that, if the wave passage effects are excluded from the interaction analysis by adopting the control motion as the design excitation instead of the overall motion, the effective damping of the coupled system and therefore the relative response of the structure interacting with the soil may be underestimated.

Finally, the energy dissipated by scattering and diffraction of the incident waves from the building foundation should be thoroughly studied, considering different soil conditions and types of incident waves, so as to understand the damping capacity of the foundation for reducing the deformation amplitudes of the structure.

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