Dynamic Soil-Structure Interaction Effects on Response Spectra

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Abstract

A method which evaluates soil-structure interaction effects is presented. The method consists of an equivalent oscillator which includes the effects of the interaction, modifying its original fundamental period and damping. The new oscillator is treated like a replacement oscillator in the system with rigid base. The response contours concept displays the site effects and the soil-structure interaction at the same time, in terms of both the dominant site period and the fundamental structural one. Response contours profiles depict response spectra with soil-structure interaction at different sites.

Response contours are evaluated for different sites and different structure configurations, typical of Mexico city. Results of parametric analyses illustrate the importance of key parameters in soil-structure interaction effects, such as the depth of soil deposit, the embedment of the foundation and the slenderness of the structure.

Introduction

Many studies have determined that, in most cases, the structural response strongly depends on the soil properties where it is founded. This phenomenon leads us to dynamic soil-structure interaction (SSI) analysis.

An approximate technique to compute the dynamic soil-structure interaction for a simple structure supported in a single soil layer is presented. This technique uses a single degree-of-freedom (SDOF) oscillator with equivalent period and damping. These effective parameters, which account for interaction, are obtained analytically from simplified dynamic equations in which mass and inertial moment of foundation and coupled impedances can be neglected for relatively shallow foundations.

The foundation is axisymmetric and it is embedded in a single layer. Only two degrees of freedom are allowed for the foundation. Soil conditions correspond to two typical sites of Mexico City for which accelerations were recorded during the Michoacan earthquake of September 19, 1985.

In order to show the combined site and interaction effects for a wide range of periods, contours of spectral pseudo-accelerations are constructed using a unidimensional model.

Soil-structure interaction

Soft soil conditions produce inertial and kinematic effects in structures. The inertial effect changes fundamental period and damping of the structure. On the other hand, the kinematic effect affects the foundation motion, such that, high frequencies are filtered due to the geometry of the foundation (CIS, 1991).

Impedance Functions

The impedance functions are complex quantities and depend on the frequency. The real part of the impedance functions expresses the stiffness and the inertia of soil. This part is represented by springs. The imaginary part expresses the material and geometrical damping, and it is represented by springs. The imaginary part expresses the material and geometrical damping and it is represented by dashpots which reflect the viscosity of the soil-foundation system (Figure 1).

These functions represent the horizontal translation and the rotation modes of the foundation; furthermore, they also represent a coupled mode (Aviles and Perez-Rocha, 1992). The following equations relate the impedance coefficients k_m and c_m to the spring constant K_m and the damping C_m working in the foundation.

$$K_m = K_m^o (k_m - 2\zeta\eta_m c_m) \tag{1}$$

$$\omega C_m = K_m^o (\eta_m c_m + 2\zeta k_m) \tag{2}$$

where ω is the motion's circular frequency, ζ is the damping ratio of the soil, K_m^o is the static stiffness, η_m is a normalized circular frequency with respect to foundation radius, and m identifies the mode. For the horizontal translation mode m=h, for the rotational mode m=r, and for the coupled mode m=hr=rh. Kausel et al. (1978) developed approximate equations to obtain the static stiffness and the dynamic coefficients for shallow axisymmetric foundations. The foundation is assumed to be embedded in a homogeneous soil layer with rigid base (CIS, 1991).

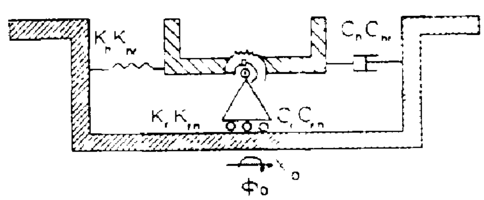


Figure 1. Soil-foundation system.

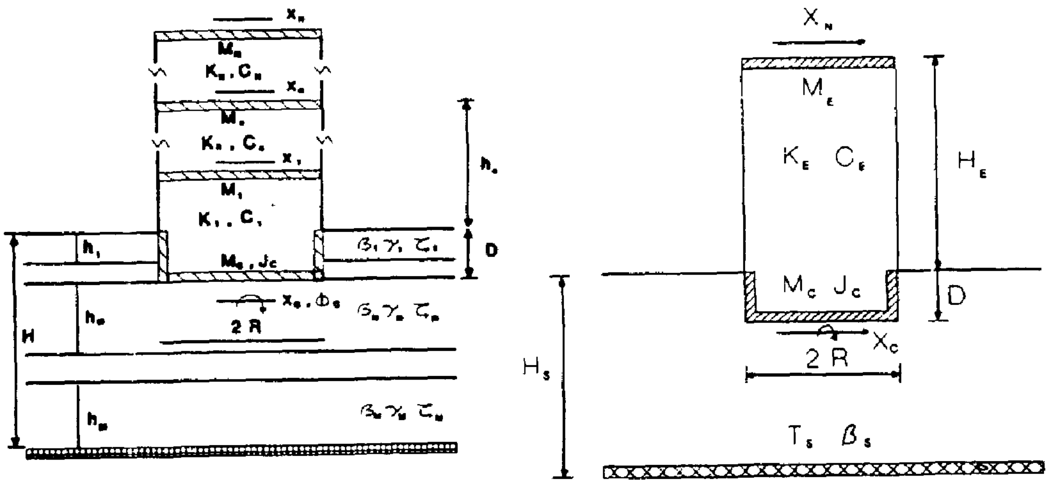
Effect of the interaction on structures

The response of systems with SSI presents an increment in the natural period (T_e) and a change in the structural damping (ξ). The modified parameters could be interpreted as effective period and damping (Aviles et al., 1992). The method is based on the determination of these effective parameters.

Under harmonic excitation, with time dependence given by $e^{i\omega t}$, the dynamic equilibrium equation could be expressed as

$$\left[\begin{bmatrix} K_e & 0 & 0 \\ 0 & K_h & 0 \\ 0 & 0 & K_r \end{bmatrix} + i\omega \begin{bmatrix} C_e & 0 & 0 \\ 0 & C_h & 0 \\ 0 & 0 & C_r \end{bmatrix} - \omega^2 \begin{bmatrix} M_e & M_e & M_e(H_e+D) \\ M_e & M_e & M_e(H_e+D) \\ M_e(H_e+D) & M_e(H_e+D) & M_e(H_e+D)^2 \end{bmatrix}\right] \begin{Bmatrix} X_e \\ X_c \\ \Phi_c \end{Bmatrix} = -\ddot{X}_o \begin{Bmatrix} M_e \\ M_e \\ M_e(H_e+D) \end{Bmatrix} \quad \ldots(3)$$

where K_h, K_r and C_h, C_r represent the stiffness and the damping of soil respectively. The excitation frequency is identified by ω, X_e is the relative structure displacement amplitude, X_c and Φ_c are the foundation displacement amplitude and rotation amplitude respectively. $\ddot{X}_o$ is the acceleration motion of the Fourier spectrum, K_e, C_e, M_e and H_e are the stiffness, damping, mass and height of a SDOF oscillator. The oscillator represents a structure of N degrees of freedom (Figure 2). This representation is possible if the structure and oscillator have the same base shear and overturning moment (CIS, 1991). The term D represents the depth of the foundation. The mass and inertial mass moment of the foundation have been neglected as well as the coupled mode in the impedance functions.



(a) . (b)

Figure 2. Original soil-structure system (a) and equivalent soil-structure system (b).

To obtain the period and damping with SSI, it is necessary to relate the real and imaginary parts of the solution to equation (3) with the real and imaginary parts of the equation of an equivalent oscillator without SSI, when both systems are in resonance.

Doing this, we can obtain equation (4) which accounts for the effective period

$$\tilde{T}_e = (T_e^2 + T_h^2 + T_r^2)^{0.5} \quad (4)$$

where

$$T_h = 2\pi(M_e/K_h)^{0.5} \quad (5)$$

$$T_r = 2\pi(H_e + D)(M_e/K_h)^{0.5} \quad (6)$$

T_h and T_r are natural periods in horizontal translation and rotation modes, respectively. Since the periods T_r and T_h are unknown the effective period $\tilde{T}_e$ is obtained by iteration. The first approximation could be done considering the static stiffness of the impedance functions. It yields a first effective period which can be used to evaluate the dynamic stiffness for computing a new effective period of the soil-structure system. The procedure continues until the difference between two solutions of equation (4) is equal to a given convergence tolerance.

Effective damping is computed with the next equation by using the last effective period.

$$\tilde{\xi} = \xi(T_e/\tilde{T}_e)^3 + \zeta_h(T_h/\tilde{T}_e)^2 + \zeta_r(T_r/\tilde{T}_e)^2 \quad (7)$$

This equation is obtained by relating the imaginary parts of the associated equations of the oscillator with and without SSI, neglecting damping terms of second order. A closer approximation to the rigorous solution can be achieved using the improved equation:

$$\tilde{\xi} = \xi(T_e/\tilde{T}_e)^3 + (\zeta_h/(1 + 2\,\zeta_h^2))(T_h/\tilde{T}_e)^2 + (\zeta_r/(1 + 2\,\zeta_r^2))(T_r/\tilde{T}_e)^2 \qquad (8)$$

where the dampings ζ_h and ζ_r are related with the soil stiffness and damping. Figure 3 shows the equivalent oscillator with rigid base, characterized by its effective period and damping.

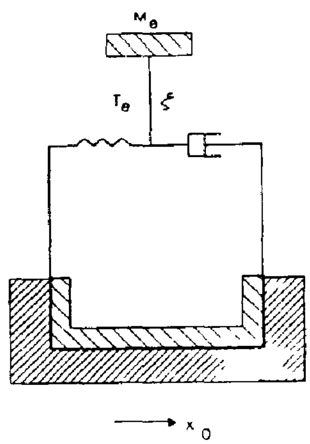


Figure 3. Equivalent oscillator with hard base.

Parameters of the soil-structure interaction

The most important parameters involved in the SSI are those that are related to the material, such as the Poisson ratio (ν) and the internal damping of soil (ζ) and structure (ξ); and those that are related to the geometry, such as the relative depth of the soil layer (H_s/R), the relative embedment depth of the foundation (D/R) and the slenderness ratio of the structure (H_e/R). The foundation radius R is used as the normalization parameter (CIS, 1991). The intensity of the SSI induces effects controlled by the stiffness contrast between the soil and the structure, which is given by the factor $4\,H_e/\beta\,/T_e$, where β is the shear wave velocity of the layer.

In this paper, the soil and the structure damping ratios are 5% for both cases. The Poisson ratio obtained experimentally for Mexico valley's soft soil is close to 0.5.

Site Effects

Motion source at the base of soil layer

Because of the geometrical characteristics of the Mexico City valley area, it is acceptable to assume that the motion at the hill zone is similar to the motion at the base of the soil layer. Therefore, the ground motion recorded at CU station in Mexico City during the 1985 Michoacan Earthquake (M_s =8.1) is used. Considering a homogeneous soil layer and a half space (Figure 4), the transfer function is evaluated by the one-dimensional wave propagation theory as follows,

$$\nu = (\nu_o/(Cos(n_2H_s) + i\psi Sin(n_2H_s)))e^{i\omega t} \qquad (9)$$

where v_o is the ground motion at the base of the soil layer, n is the wave number and $\Psi = \rho_2\beta_2/\rho_1\beta_1$ is the impedance soil ratio between the soil and rock and ρ is the density.

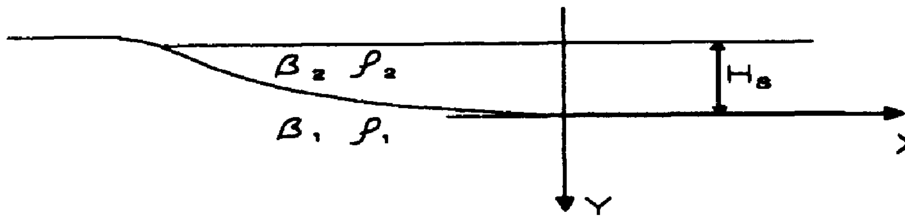


Figure 4. Homogeneous layer and half-space.

Response contours

A graphic scheme of site effects and SSI effects using pseudoacceleration contours is proposed. In this approach, variations of Poisson's ratio, density of soil and damping of soil and structure are determined. For a given geometrical condition, represented by the values H_s, H_e and D, the shear wave velocity of the layer can be computed, in terms of the period of the site (T_s), using equation (10).

$$\beta = (4H_s)/T_s \qquad (10)$$

This allows us to compute a transfer function to account for site effects, by using some results of the one-dimensional wave propagation theory. The transfer function of the oscillator is computed by the effective period and damping technique. Response spectrum is obtained from these transfer functions modulated with the Fourier spectrum acceleration at the hill zone outcrop.

For each site period the procedure is repeated. For that reason, it is possible to obtain different response spectra for the same structure and the same layer depth, but for different site periods.

Figure 5a shows spectral response contours without SSI. The site period T_s is represented in the vertical axis and the structure period T_e in the horizontal axis. A line parallel to the horizontal axis, at a site with period of 2s, defines the response spectrum for this site. This profile is a good approximation to the response spectrum obtained at SCT site (T_s = 2s), using the recorded ground motion *in situ* for the same earthquake (Figure 5b). In the same way, it is possible to obtain a response spectrum similar to that at CAO site (T_s~3.5s) with the ground motion recorded *in situ*, defining a profile for the fundamental period of site of 3.5s (Figure 5c).

Figures 6, 7 and 8 display response spectral contours for some structures with shallow foundation and different depths of the soil layer in Mexico city valley. The contours are evaluated for the following geometrical conditions: H_e/R=3, 4, 5; H_s/R = 3, 5, 7; and D/R = 0, 1/2, 1.

In these Figures, it is possible to observe the second mode of vibration of structures for small slenderness ratios (H_e/R =3).

In contours where the SSI effects are small, the peak amplitudes are located on a line with slope equal to one in the T_e -T_s plane. This slope increases when the relative depth of the soil layer is reduced and the slenderness ratio is increased, that is, when the intensity of SSI is important. Higher modes can appear on lines with slope equal to three, five, seven, etc.

The period range associated with the peak amplitude of the response spectra expands when the SSI effects are larger. Therefore, a wider set of structures is strongly affected.

The SSI effects are more severe in structures with high slenderness ratio, superficial foundation and small depth ratio of the soil layer.

Since SSI shifts the peak spectral responses, the spectral acceleration for a given structure could increase or decrease depending on the location of its fixed period.

Conclusions

An approximate technique to compute the response of a soil-structure interaction system was presented. It makes use of effective structural parameters which remain the effects of the soil-structure system.

On the other hand, a complete parametric analysis was presented to study a great set of site-foundation-structure conditions. In this analysis, material properties, geometrical relationships and stiffness contrasts between soil and structure define the interaction conditions. This approach guided us to propose a scheme which allows us to analyze the response of the structure interacting with the soil in terms of the structure and the soil periods. This representation can be useful in determining the spectral response of soil-structure systems, when the SSI should be taken into account for engineering purposes.

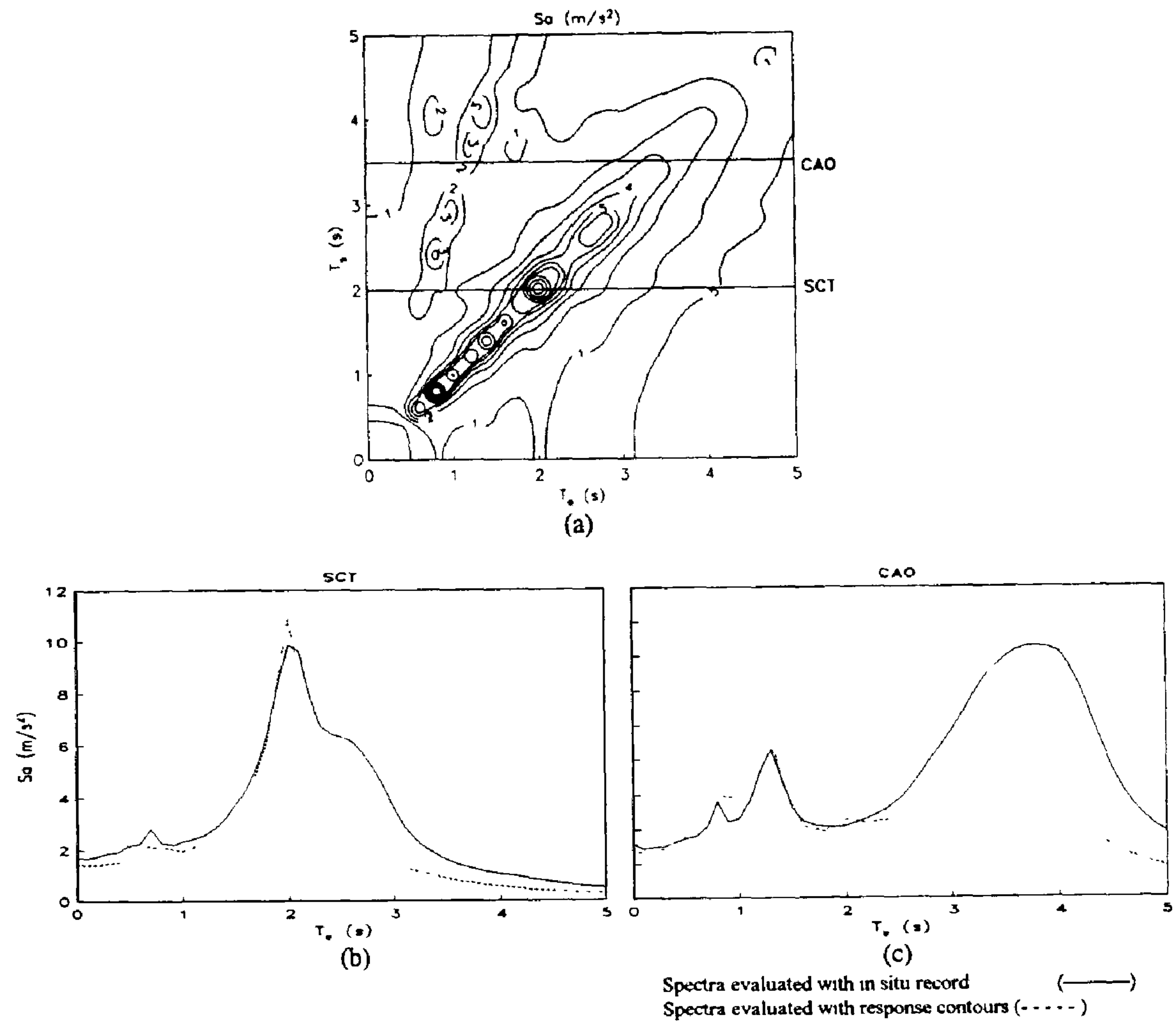


Figure 5. Response spectra in contours without SSI

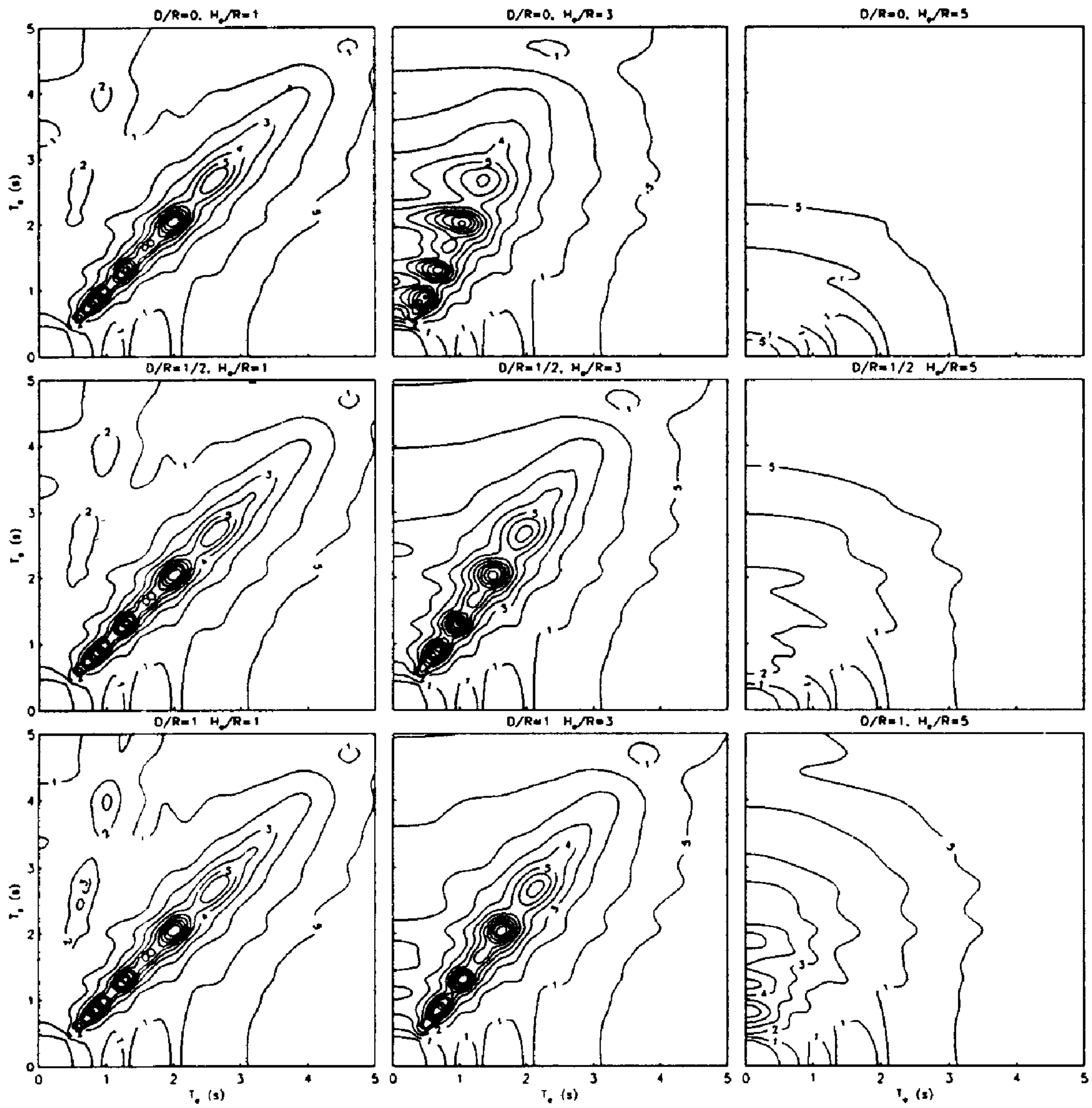


Figure 6. Response contours to $H_s/R = 3$

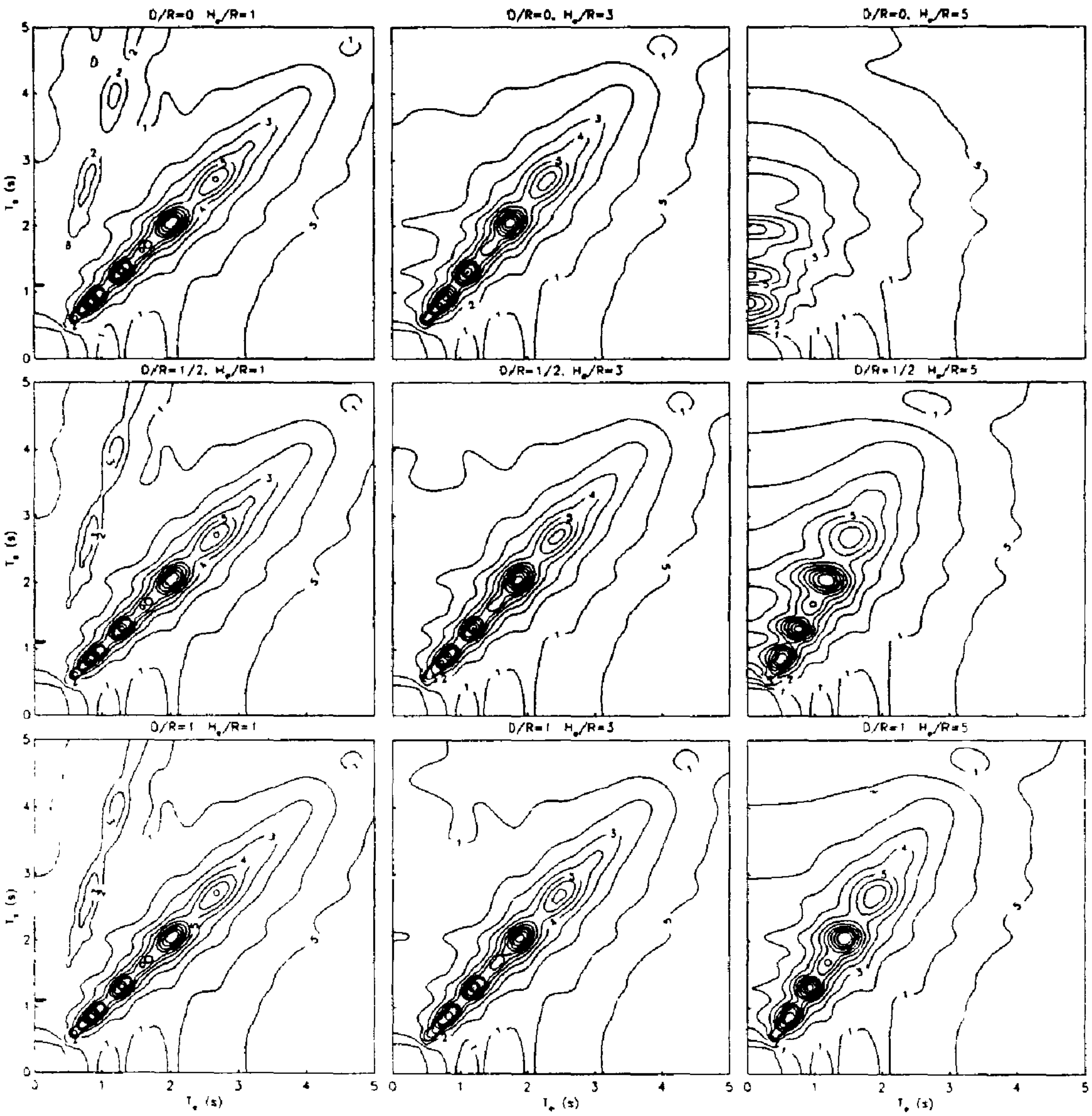


Figure 7. Response contours to H_s/R =5

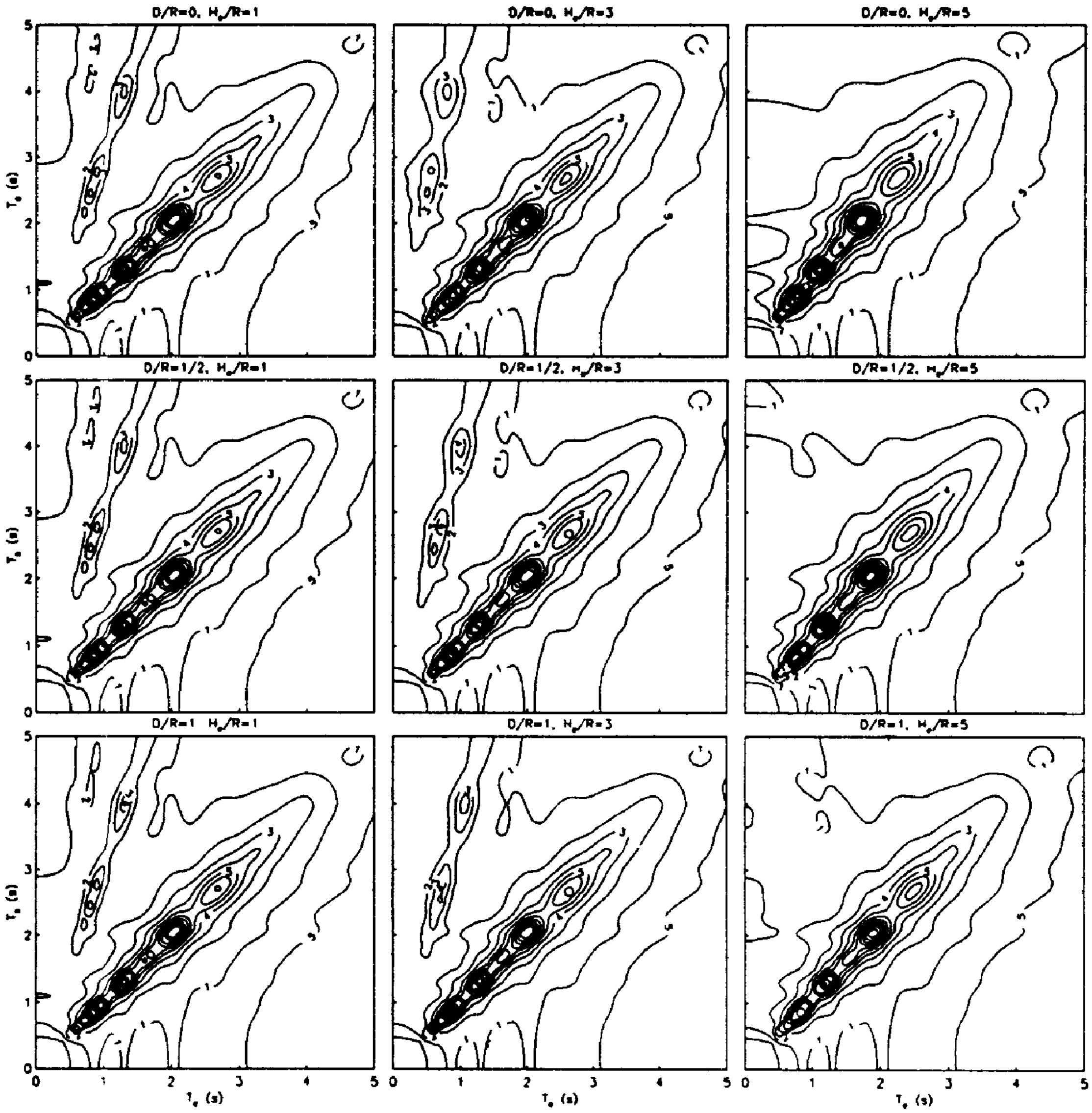


Figure 8. Response contours to H_s/R =10

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