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THREE-DIMENSIONAL INTERACTION BETWEEN STRUCTURES ON LAYERED SOIL UNDER SEISMIC EXCITATION

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ABSTRACT

Interaction between structures under seismic excitation are important to analyse especially for sensible constructions. The influence of an adjacent structure may increase or decrease the response of the dynamic structural behaviour depending on the frequency content of the seismic-input-motion and the soil properties. To predict the maximum dynamic amplitudes numerical investigations are required. The presented paper describes a numerical procedure to analyse structures of arbitrary geometry on the surface of a layered soil with constant stiffness and damping in each layer. The mixed boundary value problem is solved numerically using influence-functions for the layered soil. The soil-structure interaction is realized by a discrete weighted residual technique formulated in the frequency domain. Structures based on arbitrarily shaped foundations at the soil-surface can be easily described.

KEYWORDS

Three dimensional; soil structure interaction; dynamic soil coupling; adjacent structures; layered soil; seismic excitation; rigid foundations

INTRODUCTION

The dynamic subsoil coupling of foundations is an important factor when considering dynamic soil-structure interaction problems for foundation systems. A number of methods were introduced during the past decades to solve this mixed boundary value problem in the frequency domain. Semi-analytical methods, cf. Savidis and Richter (1977), Savidis and Sarfeld (1980), Wong and Luco (1986), numerical finite element and boundary element techniques, Roesset and Gonzalez (1977), Mohammadi and Karabalis (1995), as well as analytical methods, Triantafyllidis and Prange (1987) were used. While numerical techniques allow the treatment of foundation systems of arbitrary geometry, analytical methods are restricted to regular geometries.

Regarding the soil, as nonhomogeneous and layered, special influence functions are required to construct the corresponding stiffness matrix. One of the possibilities is to use half-space influence functions in terms of displacements for dynamic point loads determined by the thin-layer method developed by Waas (1972) and Kausel (1981). Using this method and the substructure technique, cf. Wolf (1985), the interaction effects between two structures with foundations of irregular geometry on a layered soil and excited by a seismic wave are studied here.

SOIL-FOUNDATION SYSTEM

The system analyzed here is shown in Fig. 1. It consists of two structures based on rigid plate foundations resting on a layered soil. Foundation *A* is a circular plate with a radius of $r = 20\,\text{m}$. The superstructures are modelled by lumped masses connected by rigid massless rods. The masses *m* and mass moments of inertia θ are shown in Table 1. Foundation *B* is circumscribed by a rectangle of $32.6\,\text{m} \times 48\,\text{m}$. The side next to foundation *A* has a curved edge. The distance between the two structures is 5 m. The soil profile consists of three layers overlying a half-space. The first layer, representing sand, has a thickness of $h_1 = 8\,\text{m}$. The soil properties of the second layer with a thickness of $h_2 = 6\,\text{m}$ can be classified as marl. The third layer (dense sand) has a thickness of $h_3 = 15\,\text{m}$. The soil properties of the underlying halfspace are those of gravel. The values of the soil properties, i.e. density ρ, shear wave velocity v_s, Poisson's ratio ν and damping ratio β_s are given in Table 2.

Table 1. Mass distribution

	Node No.	m [Mg]	θ [Mg m^2]	z [m]
Struct. A	9	35000	4.2×10^6	0.0
	10	38000	4.6×10^6	10.0
	11	20000	1.2×10^6	22.0
	12	7000	0.8×10^6	35.0
Struct. B	27	31000	6.5×10^6	0.0
	28	34000	7.0×10^6	12.0
	29	5000	2.5×10^6	30.0

Table 2. Soil properties

Layer	ρ [Mg/m^3]	v_s [m/s]	ν	β_s	Thickn. [m]
1 Sand	1.8	160	0.33	0.01	8.0
2 Marl	2.0	220	0.45	0.02	6.0
3 Sand	1.9	250	0.33	0.01	15.0
4 Sand	1.9	300	0.33	0.01	∞

Both foundations are excited by a seismic base motion. As time input function a recorded accelerogram of the earthquake of Friaul is chosen (Fig. 2).

ANALYSIS PROCEDURE

Equation of motion

The formulation of the equation of motion in frequency domain is accomplished by using the substructure-method, where the soil and the rigid plates are defined as substructures. To compute the dynamic repsonse of the two structures with rigid foundations resting on a layered soil and subjected to horizontal seismic excitation, the equation of motion is

$$\mathbf{M}_f \ddot{\mathbf{u}}_a + \mathbf{D}_s \dot{\mathbf{u}}_r + \mathbf{C}_s \mathbf{u}_r = 0 \qquad (1)$$

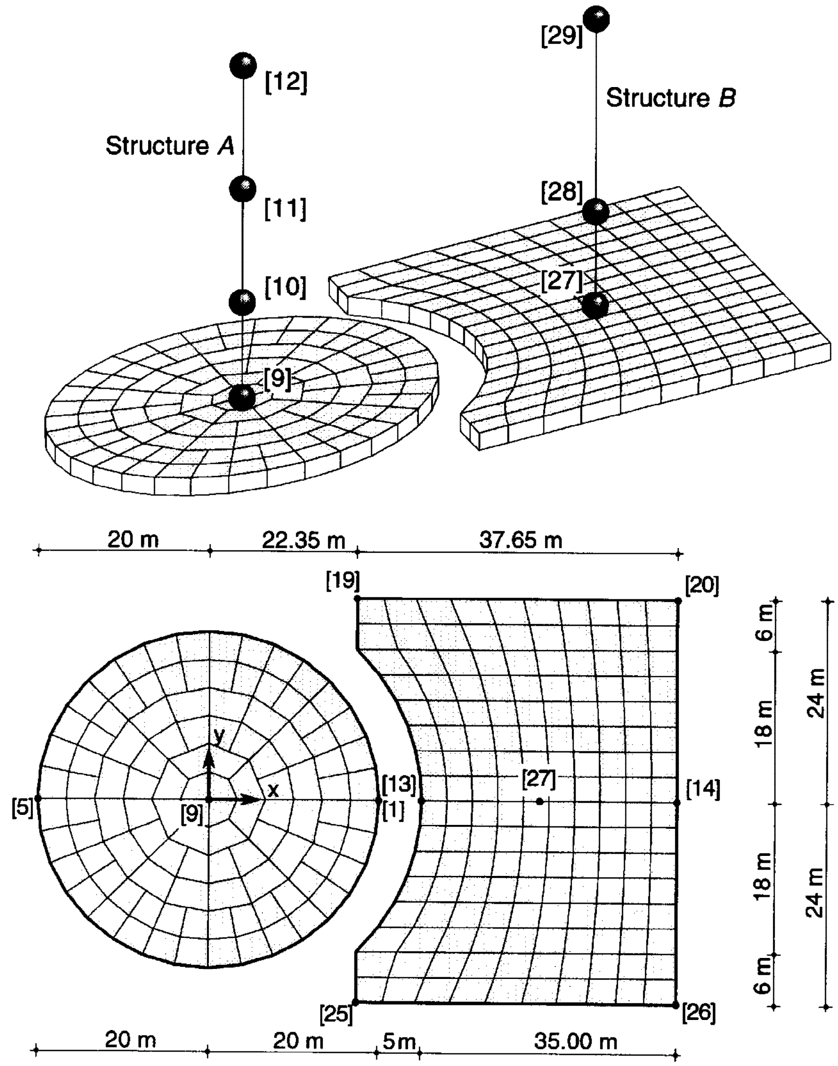

Fig. 1. Perspective view and ground plan of the system

where $\mathbf{M}_f$ represents the mass matrix of the rigid foundations, $\mathbf{D}_s$ and $\mathbf{C}_s$ describe the stiffness and damping matrix of the underlying layered soil. The vectors $\ddot{\mathbf{u}}_a$, $\dot{\mathbf{u}}_r$ and $\mathbf{u}_r$ represent the absolute acceleration, the relative velocity and displacement. Introducing the ground base motion $\mathbf{u}_0$ and performing the Fourier Transformation eq. (1) gives

$$\left[-\Omega^2 \mathbf{M}_f + \mathbf{K}_s\right] \mathbf{U}_a = \mathbf{K}_s \mathbf{U}_0 \qquad (2)$$

where $\mathbf{K}_s$ represents the complex stiffness matrix of the soil considering the boundary conditions at the soil surface for the rigid foundation. $\mathbf{U}_a$ and $\mathbf{U}_0$ denote the complex amplitudes of the respective quantities in the frequency domain Ω.

The contact area underneath the rigid plates is divided into a finite number of quadrilateral subareas A_i with uniformly distributed pressures $\mathbf{q}_i = \{q_x, q_y, q_z\}$ and weighted displacements $\mathbf{u}_i = \{u_x, u_y, u_z\}$ over each subregion. The soil underneath foundation *A* is subdivided in 108 soil elements, for foundation *B* the subdivision of soil comes to 160 elements. Introducing the influence matrix $\overline{\mathbf{F}}$ yields $\mathbf{u}_\mathrm{i} = \overline{\mathbf{F}}\mathbf{q}_\mathrm{k}$. Imposing a relaxed boundary condition at the contact area, the influence matrix $\overline{\mathbf{F}}$ can be written $\overline{\mathbf{F}} = \mathbf{I}\bar{\mathbf{f}}$. Matrix $\mathbf{I}$ is the identity matrix. The components of the vector $\bar{\mathbf{f}} = \{\bar{f}_{xx}, \bar{f}_{yy}, \bar{f}_{zz}\}$ are derived by integrating the surface influence functions $\mathbf{f} = \{f_{xx}, f_{yy}, f_{zz}\}$ as described below over the area A_k. Assembling the influences $\bar{\mathbf{f}}$ over all soil elements leads to a frequency dependend flexibility matrix of the layered soil. Inversion of the flexibility matrix yields to the soil complex stiffness matrix $\mathbf{K}(i\Omega)$. The soil stiffness matrix $\mathbf{K}_s(i\Omega)$ which includes the condition of the rigid body motions $\mathbf{U}_a$ in eq. (1) is obtained by multiplying the matrix $\mathbf{K}$ with the transformation matrix $\mathbf{T}$ and its transposed $\mathbf{T}^t$.

$$\mathbf{K}_s = \mathbf{T}^t \mathbf{K} \mathbf{T} \tag{3}$$

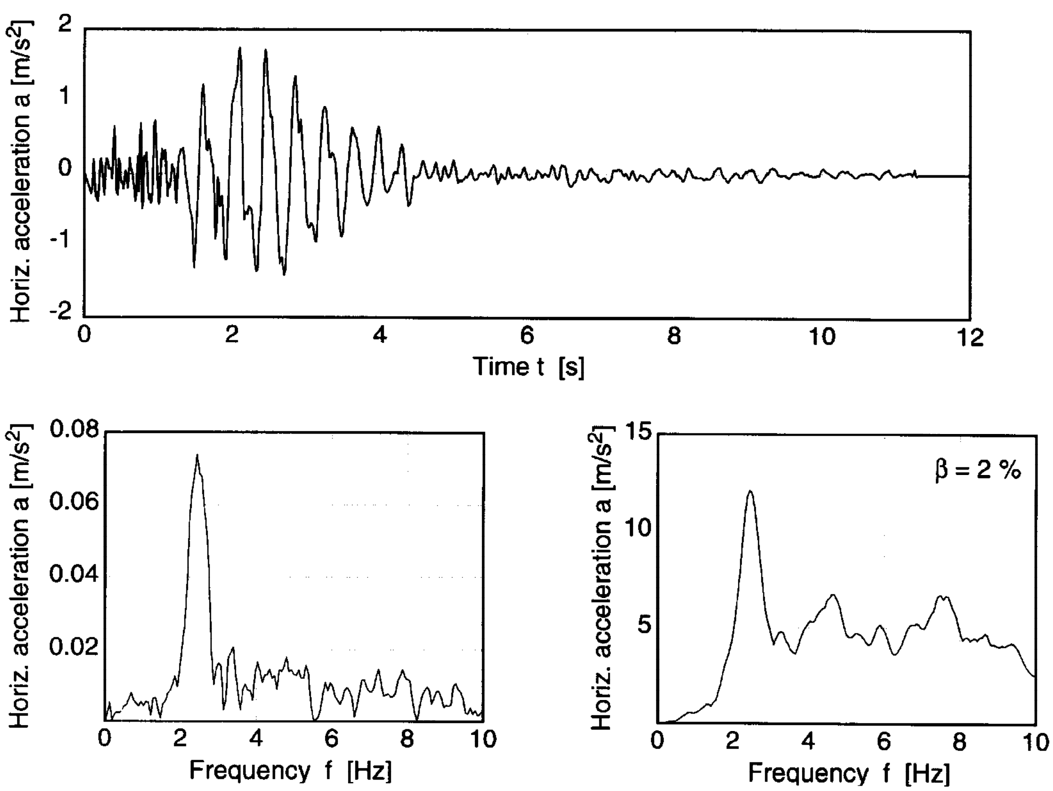

Fig. 2. Time History, Fourier and response spectrum of Friaul eathquake

The surface influence functions $\mathbf{f} = \{f_{xx}, f_{yy}, f_{zz}\}$ for the case considered here are determined by using the thin layer method by Kausel (1981). The method is a semi-analytical technique, in which the layered soil is discretized in vertical direction by Lagrange polynoms and in horizontal direction described by analytical functions. This formulation leads to algebraic expressions, whose integral transforms can readily be evaluated. The frequency dependend influence functions for layered media due to dynamic unit loads are then computed with high accuracy and reasonable computational effort. By using the thin layer method to compute the influence functions, the finite layers of the above soil profile have to be divided into sublayers in order to linearize the transcendental functions which govern the displacements in the direction of layering. The thickness of the sublayers have to be small compared to the wavelengths involved. Here, the soil model used consists of 116 sublayers.

RESULTS AND DISCUSSION

The system response due to a seismic excitation is computed for two cases. In case 1 only the response of structure A is calculated, whereas in case 2 the complete system, i.e. both structures is analyzed. In all graphs the results are denoted by dashed lines for case 1 and with solid lines for case 2.

Figure (3) shows the normalized horizontal acceleration on node 9 and 12 due to a unit horizontal harmonic ground acceleration. At both graphs amplifications at the frequencies of $f_1 = 1$ Hz and $f_2 = 1.8$ Hz can be seen clearly. The amplification at frequency f_1 increases from the bottom (node 9) to the top (node 12) of the superstructure. This indicates that the rocking eigenmode around the y-axis is located at this frequency. The amplification at frequency f_2 can interpreted as a horizontal translation eigenmode combined with a rocking mode. A significant effect of interaction appears only in the frequency range of 1.5 to 2.5 Hz.

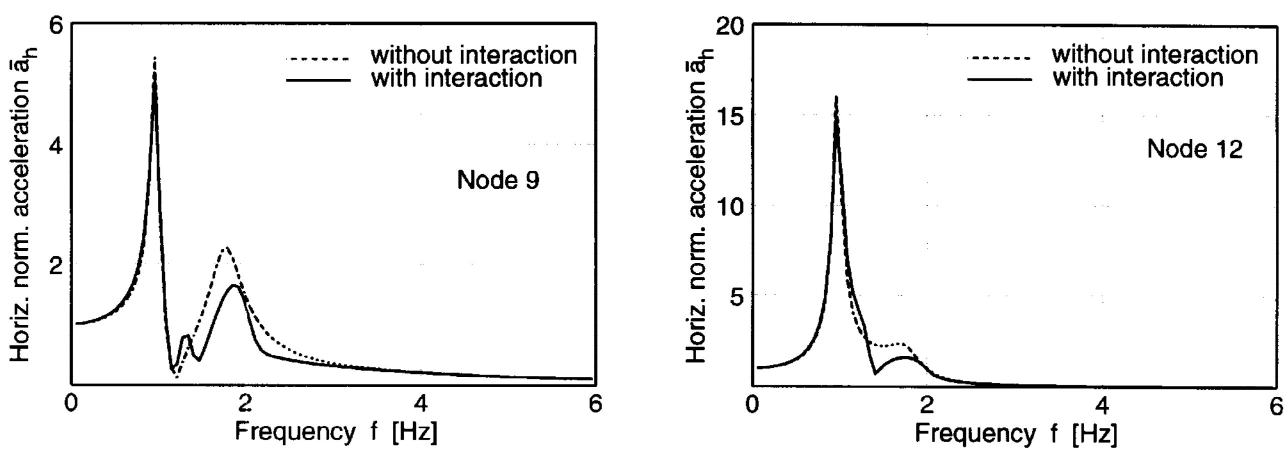

Fig. 3. Normalized horizontal acceleration for nodes 9 and 12

Figure (4) shows the vertical normalized accelerations on node 1 and 5 for the same unit horizontal ground acceleration. Again the two dominant frequencies f_1 and f_2 can be identified. The interaction effects are stronger on node 1, since this node is located next to the structure B. At node 5 the interaction effects are less profound.

In Fig. (5) the reponse spectra for the horizontal acceleration for Node 9 and 12 are plotted. Since the dominant frequencies of the input function are located in the range of 2 to 3 Hz and the eigenfrequency for the horizontal translation mode is in the same range an amplification occurs in this range. The same effect can be seen in the response spectra for the vertical accelerations in Fig. (6). In order to illustrate the interaction influence between both structures the response curves for case 2 are divided by the respective curves for case 1 by defining the parameters $\overline{Y}_h$ and $\overline{Y}_v$ for the horizontal and vertical response. The variation of these parameters with frequency is also shown in Fig. 5 and 6.

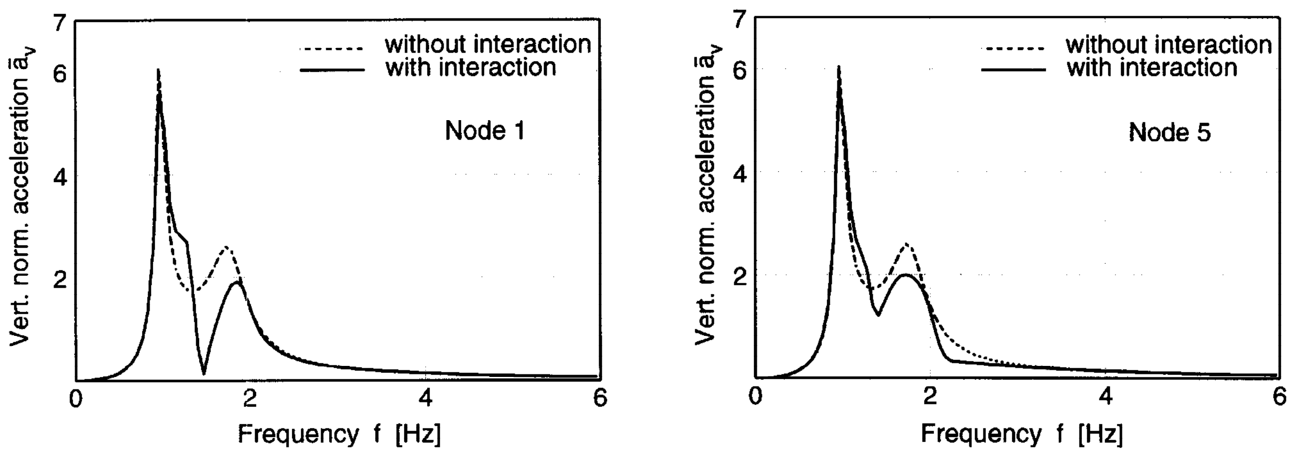

Fig. 4. Normalized vertical acceleratio for nodes 1 and 5

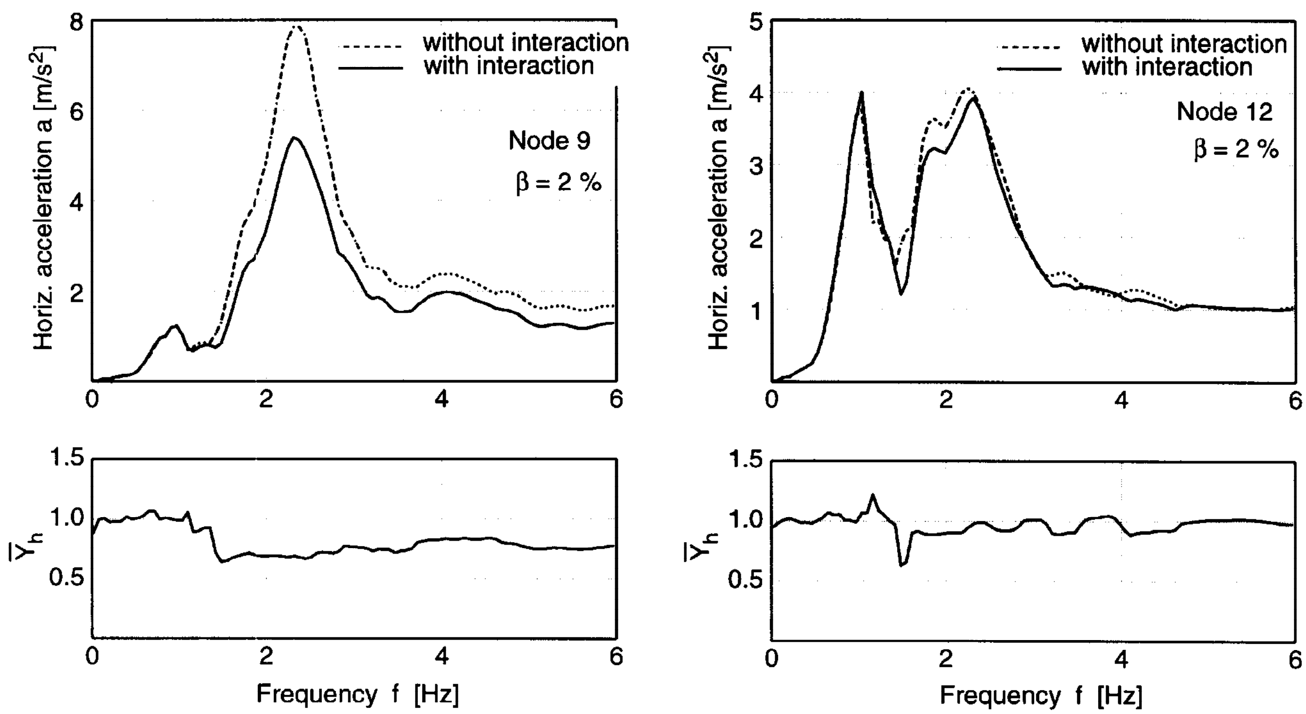

Fig. 5. Response spectra and interaction influence factor of the horizontal acceleration for node 9 and 12

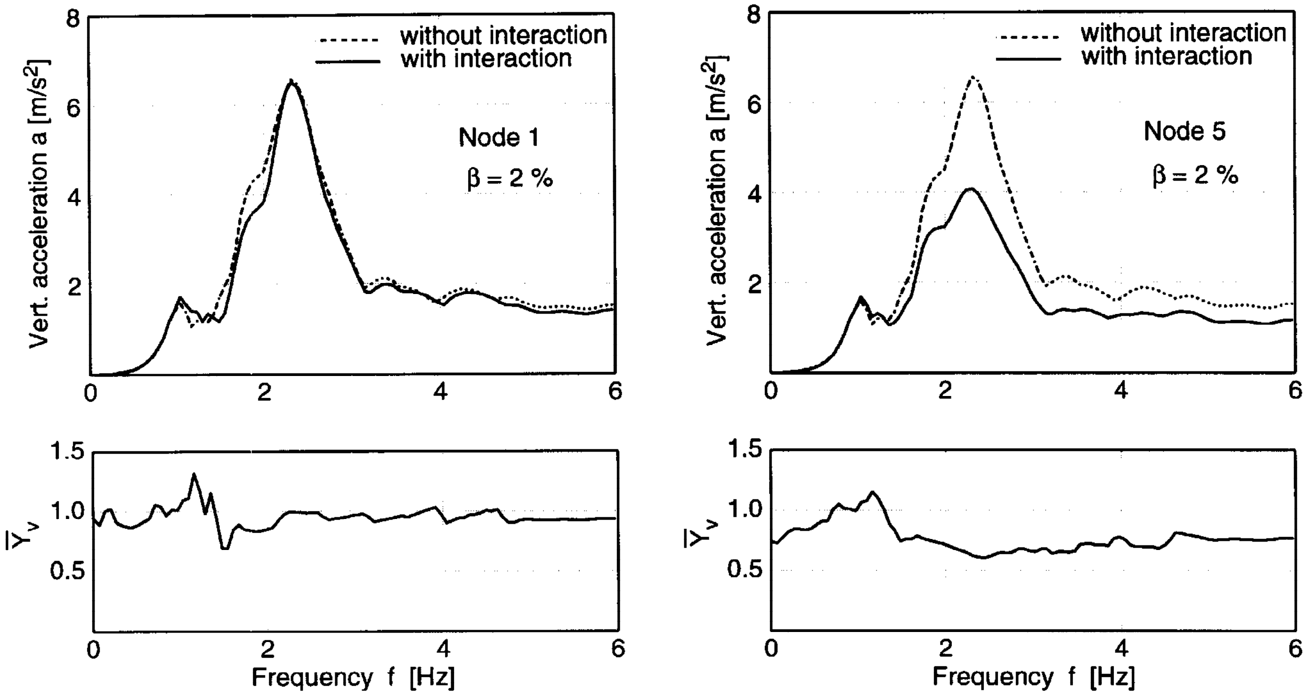

Fig. 6. Response spectra and interaction influence factor of the vertical acceleration for node 1 and 5

CONCLUSIONS

The dynamic interaction of two adjacent structures supported by rigid foundations is presented for a horizontal seismic excitation. The numerical procedure applied includes the complete dynamic subsoil coupling and can be used to model arbitrary shaped foundation resting on layered soil. Acceleration response spectra are given to demonstrate the influence of frequency in the dynamic soil coupling for the particular soil-foundation system.

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