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STRUCTURAL CONTROL USING SOIL-STRUCTURE INTERACTION

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SUMMARY

The seismic behavior of different soil-structure systems is numerically simulated. Special attention is given to the investigation of the influence of plate foundations, pile foundations and soil improvement blocks on the reduction of seismically induced vibrations into the structures. The separate influences on the structural response of three aspects are identified: the response of the soil without structure, the kinematic interaction, and the inertial interaction.
The reduction of seismic induced vibrations in structures take advantage of the ability of deep foundations to modify the structural behavior in two different ways. First, deep foundations reduce the vibration amplitudes in comparison with those experienced at the ground surface if there were no structure; second, deep foundations are able to shift the first resonance frequency of the total soil-structure system away from the frequency range of high amplitudes. In case of horizontal excitations, both factors are found to be of importance. In case of vertical excitations, only the first factor is found to be of importance.

INTRODUCTION

Traditional structural control procedures usually ignore the influence of the soil in the structural behavior. In such cases, the seismic excitation is considered as a given variable, under which the structural behavior should be investigated. In the following, a numerical investigation, focused on the seismic vibration reduction in structures through soil-structure interaction is described. Instead of the introduction of an external device, the structural sub-system *foundation* is used as a vibration control device.

NUMERICAL FORMULATION

In the general case of embedded structures, the soil-structure system is divided into three sub-regions according to the Flexible Volume Method (Lysmer et al., 1988): the original soil *deposit* without the presence of the structure, the *structure*, and the soil displaced for the basement, in the following called *excavated* soil as displayed in Figure 1. The three subsystems are connected through the *interaction nodes*: nodes belonging to all three subsystems. The degrees of freedom of the *structure* are subdivided into those connected with the *interaction nodes* (located at or below the ground level) and those situated on the *superstructure* (located above the ground level).

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The calculation is performed in the frequency domain, where the input (loads) and output (displacements) are connected to the time domain through the Fourier Transformation. Material energy dissipation is introduced in form of a complex elasticity modulus $E=(1+i2\beta)$, where E is the Youngs modulus, $i^2=-1$ and β the hysteretic damping coefficient. Special consideration is given to a sufficient representation of pile foundations.

We consider one spectral component with circular frequency ω.

The equation of motion of the system is than given by:

$$\tilde{\mathbf{K}}\,\tilde{\mathbf{U}}=\tilde{\mathbf{P}}, \tag{1}$$

where $(\tilde{\ })$ indicates complex and frequency-dependent values, $\tilde{\mathbf{U}}$ is the vector of total displacements at the nodal points, $\tilde{\mathbf{P}}$ is the load vector, and $\tilde{\mathbf{K}}$ is the dynamic stiffness matrix or impedance matrix.

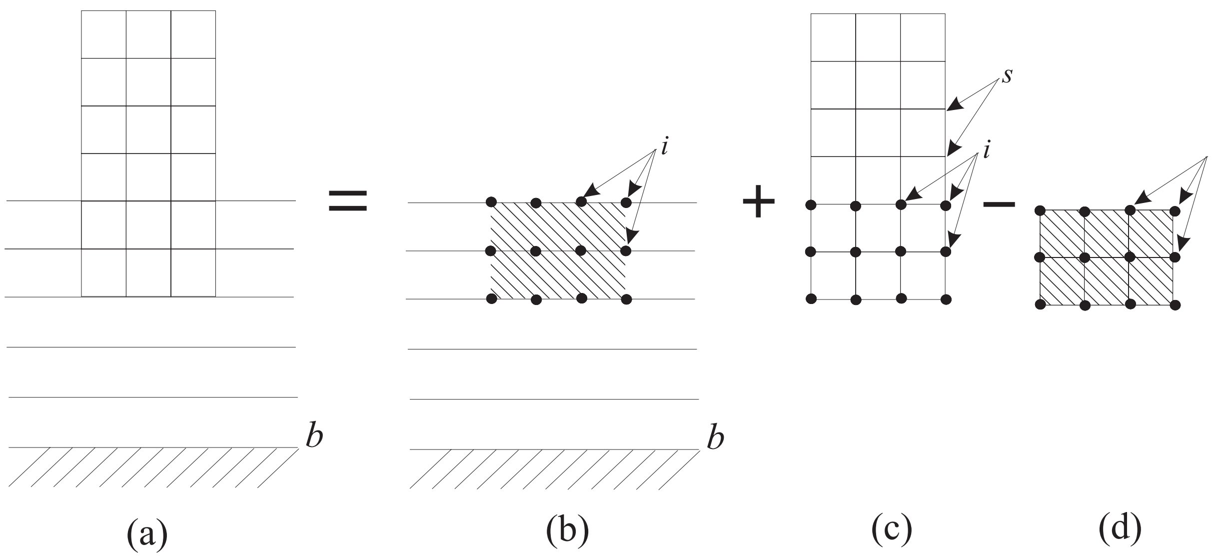


Figure 1 Substructures of the system: (a) *total* system; (b) soil *deposit*; (c) *structure*; (d) *excavated* soil (modified after Lysmer et al., 1988).

The seismic excitation shall be defined as any combination of body waves. Considering an excitation at the base b and partitioning the matrices according to Figure 1, equation (1) can be written as:

$$\begin{bmatrix} \tilde{\mathbf{K}}^s_{ss} & \tilde{\mathbf{K}}^s_{si} \\ \tilde{\mathbf{K}}^s_{is} & \left(\tilde{\mathbf{K}}^s_{ii}+\tilde{\mathbf{K}}^d_{ii}-\tilde{\mathbf{K}}^e_{ii}\right) \end{bmatrix} \begin{Bmatrix} \tilde{\mathbf{U}}_s \\ \tilde{\mathbf{U}}_i \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \left[\tilde{\mathbf{K}}^d_{ii}\right]\left\{\tilde{\mathbf{U}}'_i\right\} \end{Bmatrix}. \tag{2}$$

The lower indices s and i correspond to *superstructure nodes* and *interaction* nodes, respectively. The upper indices d, s and e correspond to soil *deposit*, *structure* and *excavated* soil, respectively. $\tilde{\mathbf{U}}'_i$ is the vector of seismic *free field* displacements, namely without the consideration of the structure, at the *interaction* nodes.

The impedance matrices for the *structure* and the *excavated* soil are formulated with help of the Finite Element Method (Bathe 1974). The soil *deposit* impedance matrix is obtained through a semi-discrete technique called Thin Layer Method (Kausel 1999):

$$\left[\tilde{\mathbf{K}}_{ii}^{d}\right]=\left[\tilde{\mathbf{F}}_{ii}^{d}\right]^{-1}, \tag{3}$$

where $\tilde{\mathbf{F}}_{ii}^{d}$ is the soil *deposit* compliance matrix, whose elements f_{ij} are determined by successively applying unit amplitude loads at each degree of freedom *j* of the interaction nodes and computing the corresponding complex displacements at each degree of freedom *i* of the interaction nodes.

In case of pile foundations, the interaction nodes are selected along the pile axis. To simulate the load transfer from a pile with radius *r* in its cross section and inclined by an angle α with respect to a vertical line, as shown in Figure 2, the displacement field of ellipse-shaped distributed loads is approximated in terms of the displacement field of equivalent circular distributed loads. A disk load distribution with the same cross area as the horizontal ellipse is considered at the interaction node at the pile tip. A circle ring load distribution with the same circumference as the horizontal ellipse is considered at the remaining interaction nodes. The displacement field computed in terms of the radial, vertical and tangential components is transformed to cartesian coordinates.

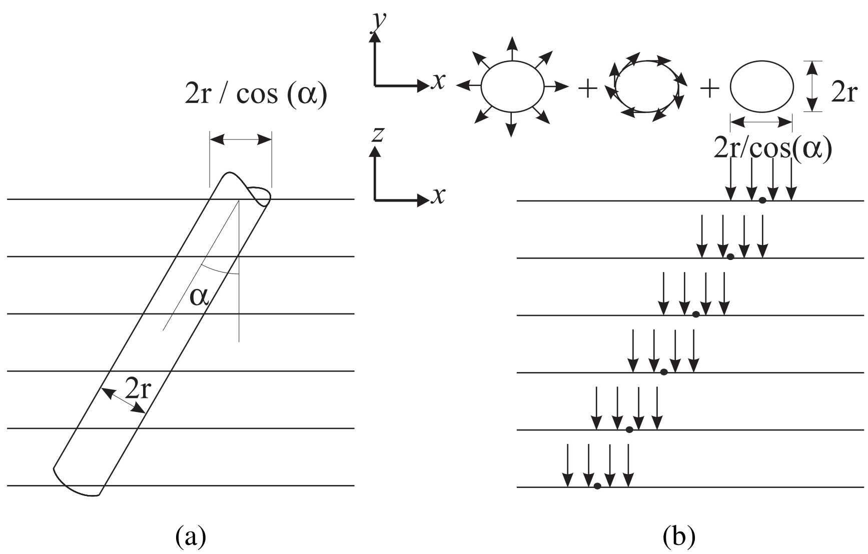


Figure 2 Inclined pile: a) physical model; b) ellipse-shaped load distributions at the interaction nodes.

The complex displacements, f_{ij}, at the interaction nodes are computed using closed-form solutions of three-dimensional Green's functions in a layered medium over a rigid base (Waas 1980, Tajimi 1980, Kausel & Peek 1982, Waas et al., 1985). This formulation has been implemented in the computer program SASSIG: A System for the Analysis of the Soil-Structure Interaction using Green's functions (García 2003) as an extension of the computer program SASSI (Lysmer et al., 1988). The extension gives high accuracy in the analysis of the soil *deposit* impedance and allows the analysis of soil-pile interaction.

The analysis of soil-structure interaction due to seismic excitation includes the following three aspects: amplification of the seismic motion in the free field, kinematic interaction and inertial interaction.

All three aspects could be analysed in a single step. However, in order to understand the complete interaction, the three single aspects stated above will be analysed first separately.

APPLICATION

The considered problem consists of a three-storey frame structure founded in a soft soil deposit overlaying a rock base and subjected to an upward vertically propagating body wave as displayed in Figure 3. The rock is assumed to be rigid. The mechanical and geometrical parameters are listed in table 1. A syntethic acceleration history with a maximum acceleration amplitude of 1 m/s^2 is used as input rock motion.

Table 1. (a) Mechanical and geometrical parameters of superstructure; (b) mechanical parameters of soil layer overlaying a rigid base.

(a)

Columns			Slabs		
H	EA	EI	B	t	dead+live loads
[m]	[MN]	[MNm^2]	[m]	[m]	[N/m^2]
3.5	3060	1480	8.13	0.3	10000

(b)

E	ν	ρ	β	H
[MN/m^2]	[-]	[kg/m^3]	[-]	[m]
42.0	0.40	1800.0	0.05	11.25

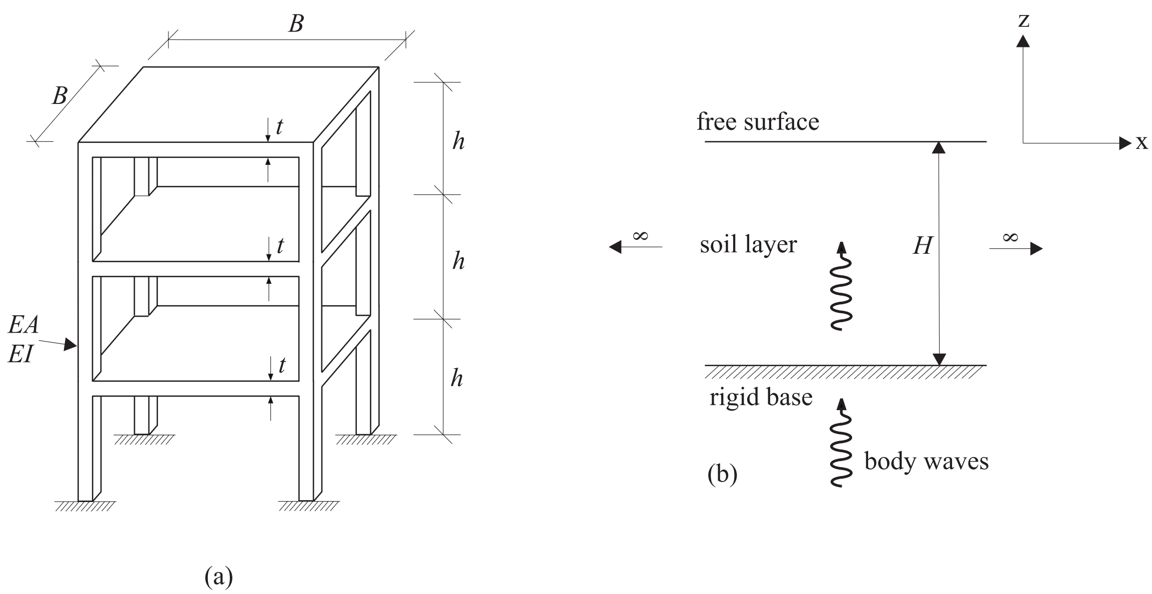


Figure 3 Mechanical model: (a) superstructure configuration; (b) subsoil conditions with seismic environment.

The considered superstructure is analysed with four different foundation configurations as displayed in Figure 4.

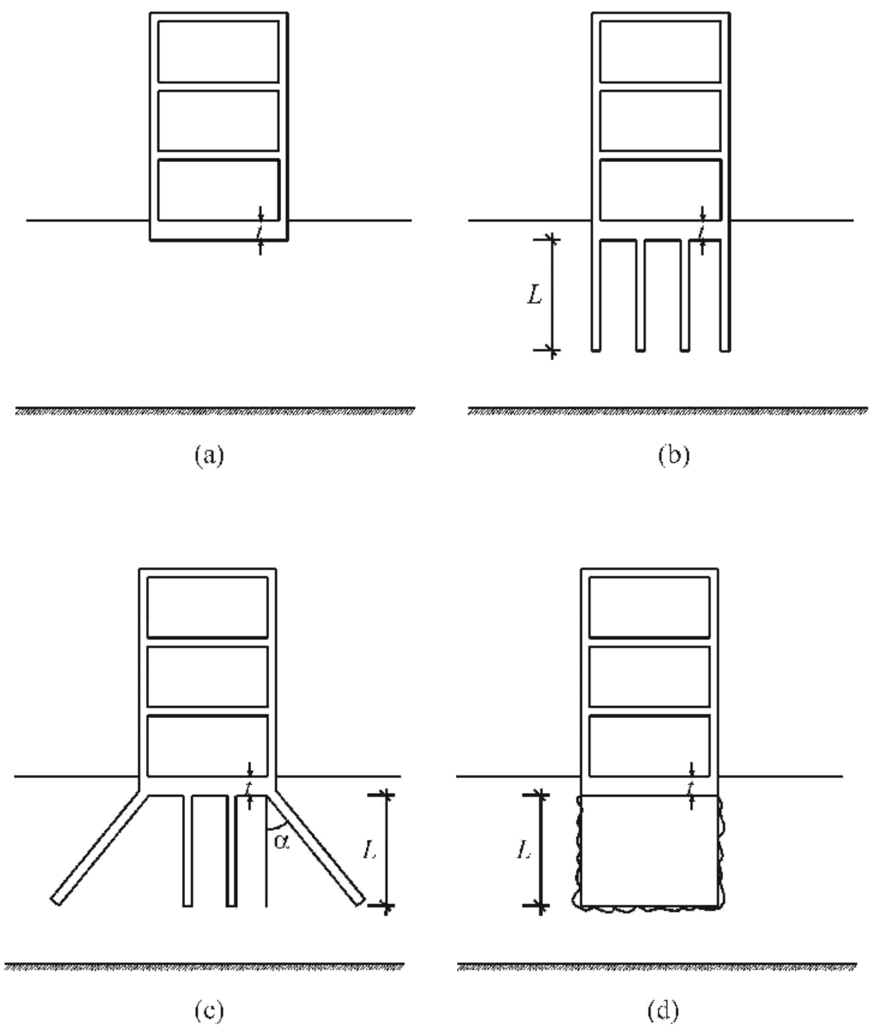


Figure 4 Foundation-Systems : (a) Plate foundation, *Case* 1; (b) Vertical pile group, *Case* 2; (c) Inclined and vertical pile group, *Case* 3; (d) Soil improvement block underlaying plate foundation, *Case* 4.

The following foundation systems are considered:

Case 1: A shallow embedded plate foundation with upper surface coinciding with the ground surface level.

Case 2: 4x4 vertical pile group rigidly connected to an embedded pile cap.

Case 3: 4x4 inclined and vertical pile group rigidly connected to an embedded pile cap.

Case 4: A soil improvement block underlaying a shallow embedded plate foundation.

The mechanical and geometrical parameters are listed in table 2 (see Figure 4).

Table 2 Mechanical and geometrical parameters of different foundation cases considered.

System	E [MN/m^2]	ν [-]	ρ [kg/m^3]	β [-]	t [m]	L [m]	d [m]	s [m]	n [-]	α [°]
Case 1	42000	0.25	2500.0	0.02	0.6	-	-	-	-	-
Case 2	42000	0.25	2500.0	0.02	0.6	9.00	0.60	2.5	16	0.00
Case 3	42000	0.25	2500.0	0.02	0.6	9.00	0.60	(on top) 2.5	16	53.10
Case 4	2950	0.45	1860.0	0.02	0.6	9.00	-	-	-	-

FREE FIELD RESPONSE

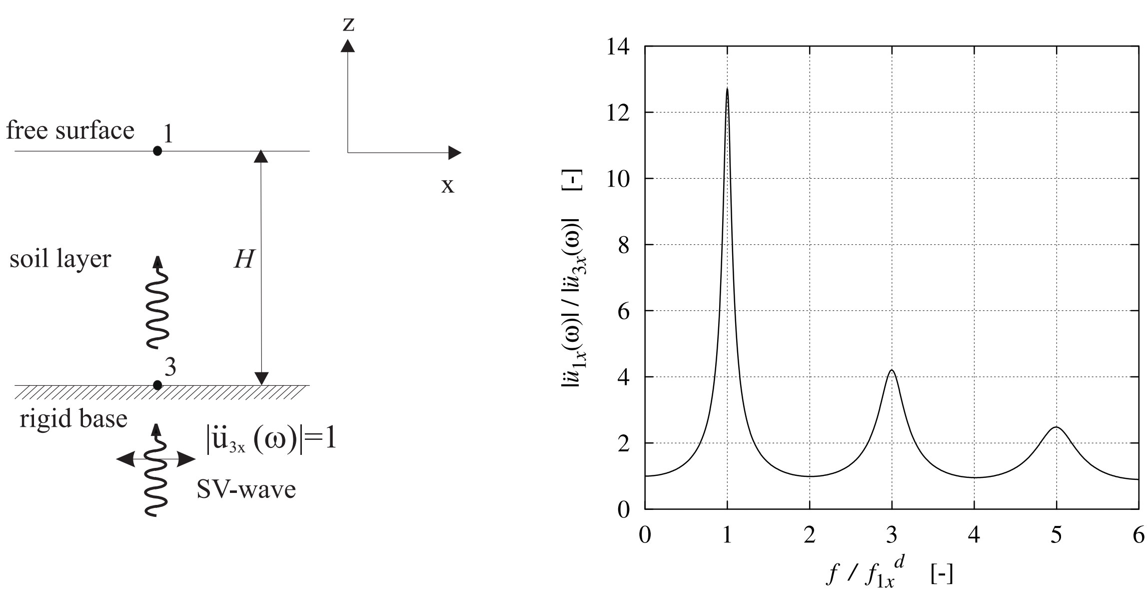
The soil deposit without the structure is analysed first. The model configuration is displayed in Figure 5(a). The soil layer is discretized with 15 thin layers.

Horizontal Excitation

It is assumed that the rigid base undergoes a horizontal motion, inducing the free field motion, shown in Figure 5(a), in the overlaying soil deposit. The first natural frequency, $f_{1x}{}^{d}$, of the soil *deposit* with deformations in *x*-direction is given by:

$$f_{1x}^{d} = \frac{c_s}{4H} = \frac{91.44\text{m/s}}{4(11.25\text{m})} = 2.03\text{Hz} \tag{4}$$

where the lower index 1 indicates the first natural frequency, the upper index *d* indicates the soil *deposit* , and c_s indicates the shear-wave velocity.



(a) (b)

Figure 5 (a) System configuration; (b) free field surface response function due to horizontal excitation.

The amplitude of transfer function $\left|\ddot{u}_{1x}(\omega)\right| / \left|\ddot{u}_{3x}(\omega)\right|$ defined as the ratio between the response at the ground surface and the excitation at the base rock as function of the excitation frequency normalized by f_{1x}^{d}, is shown in Figure 5(b). Resonance amplitudes are observed at the natural frequencies of the soil deposit and the maximum amplitude is reached at f_{1x}^{d}.

The presence of soil deposit overlaying a rock base produces an amplification of the seismic motions in the soil in comparison with that transmitted by the rock. The magnitude of this amplification is a function of the mechanical and geometrical parameters of the soil. Although this phenomena is independent of the presence of the structure, it influences the excitation to be transmitted to the structure.

Vertical Excitation

A vertical motion on the rigid base is considered, inducing the free field motion, shown in Figure 6(a) in the overlaying soil deposit.

The first natural frequency, f_{1z}^{d}, of the soil *deposit* with deformations in *z*-direction is given by:

$$f_{1z}^{d} = \frac{c_p}{4H} = \frac{224\text{m/s}}{4(11.25\text{m})} = 4.98\text{Hz} \tag{4}$$

where the lower index 1 indicates the first natural frequency, the upper index *d* indicates the soil *deposit* , and c_p indicates the P-wave velocity.

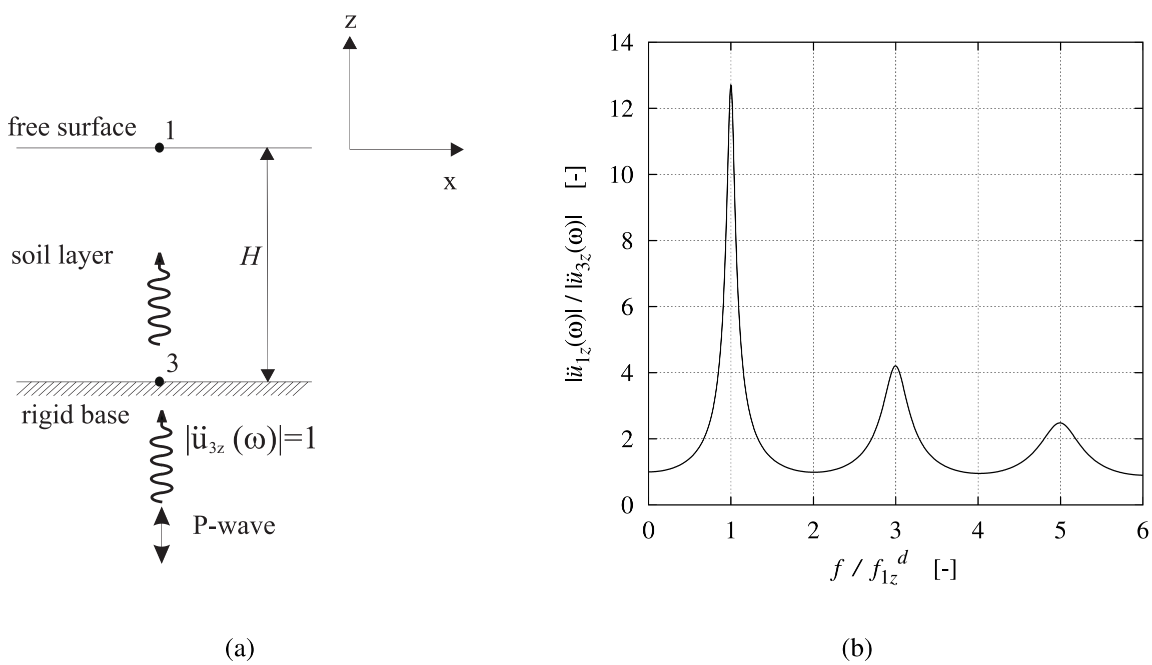


Figure 6 (a) System configuration; (b) free field surface response function due to vertical excitation.

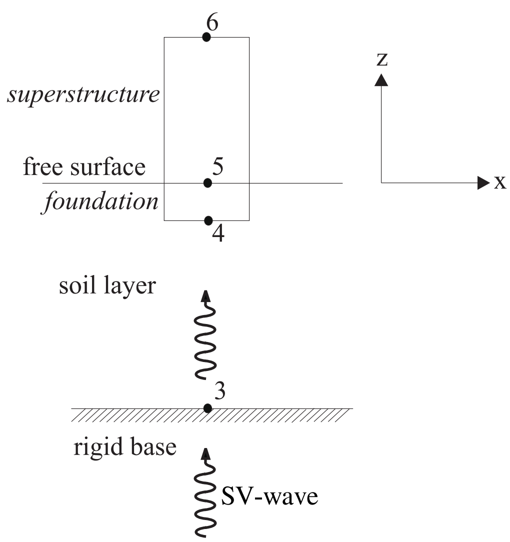
The amplitude of transfer function $\left|\ddot{u}_{1z}(\omega)\right| / \left|\ddot{u}_{3z}(\omega)\right|$ defined as the ratio between the response at the ground surface and the excitation at the base rock as function of the excitation frequency normalized by

$f_{1z}{}^{d}$, is shown in Figure 6(b). Resonance amplitudes are observed at the natural frequencies of the soil deposit and the maximum amplitude is reached at $f_{1z}{}^{d}$.

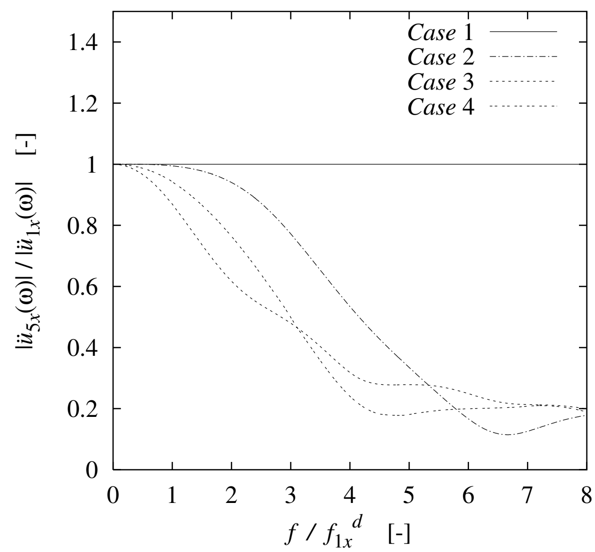
A comparison with Figure 5(b) indicates that the same normalized resonance amplitudes are calculated for both horizontal and vertical directions, due to the uncoupled nature of vertical propagation of P- and S-waves. However, as the resonance frequencies in *x*- and *z*- directions depend from c_s and c_p, respectively, the horizontal resonance frequencies are lower than the vertical resonance frequencies.

KINEMATIC INTERACTION

The interaction between the rigidity of the structure and the soil *deposit* is known as *kinematic interaction*. To analyse it, the structure will be considered massless at this stage. The model configuration is displayed in Figure 7(a).



(a)



(b)

Figure 7 (a) System configuration with massless structure; (b) ratio of transfer functions due to horizontal excitation.

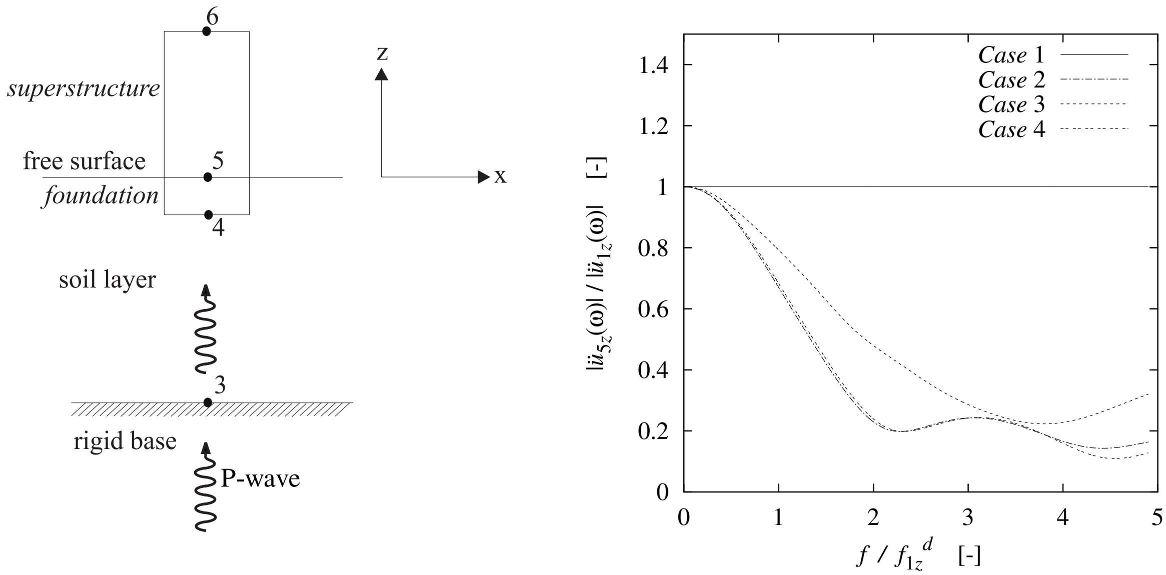
The superstructure is discretized with finite elements. Each column is discretized with four beam elements, which amounts to 48 beam elements in the superstructure. Each slab is discretized with 64 plate elements, which results in a total of 192 plate elements in the superstructure. The plate foundation as well as the pile cap is modeled with 144 volume elements. The piles are modeled with 16x12=192 beam elements. The soil improvement block is modeled with 192 volume elements.

Horizontal Excitation

For the four cases, the ratio of the amplitude of transfer functions $|\ddot{u}_{5x}(\omega)|/|\ddot{u}_{1x}(\omega)|$ as function of the excitation frequencies normalized by $f_{1x}{}^{d}$ are compared in Figure 7(b), where $\ddot{u}_{1x}(\omega)$ is the response at the surface of the free field. A ratio $\left|\ddot{u}_{5x}(\omega)\right| / \left|\ddot{u}_{1x}(\omega)\right|$ lower than one for normalized frequencies around one indicates that the foundation experiences lower vibration amplitudes than those expected at the surface of the free field, as it is observed for *Cases* 3 and 4.

Vertical Excitation

The model configuration is displayed in Figure 8(a). For the four cases, the ratio of the amplitude of transfer functions $\left|\ddot{u}_{5z}(\omega)\right| / \left|\ddot{u}_{1z}(\omega)\right|$ as function of the excitation frequencies normalized by $f_{1z}^{\,d}$ are compared in Figure 8(b), where $\ddot{u}_{1z}(\omega)$ is the response at the surface of the free field.



(a) (b)

Figure 8 (a) System configuration with massless structure; (b) ratio of transfer functions due to vertical excitation:.

A ratio $\left|\ddot{u}_{5z}(\omega)\right| / \left|\ddot{u}_{1z}(\omega)\right|$ lower than one for normalized frequencies around one indicates that the foundation experiences lower vibration amplitudes than those expected at the surface of the free field, as it is observed for *Cases* 2, 3 and 4.

INERTIAL INTERACTION

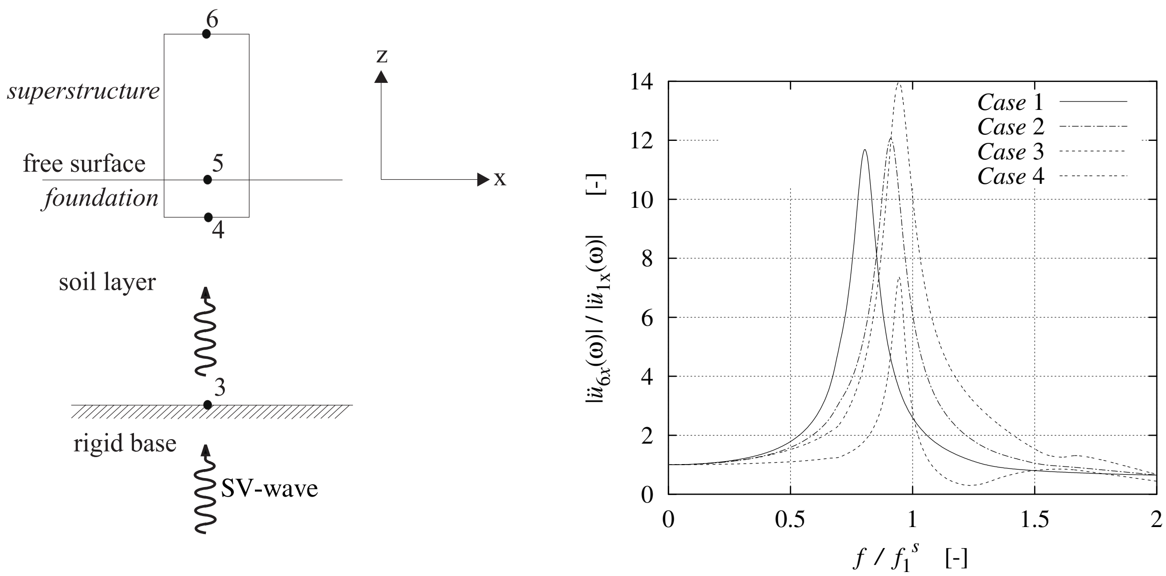
The interaction between the mass of the structure and the soil *deposit* is known as *inertial interaction*. The acceleration field induces inertial forces in the structure, which are transmitted to the foundation. They modify additionally the dynamic behavior of the system.

To analyse it, the mass of the structure will be included at this stage. The model configuration is displayed in Figure 9(a). The distributed dead and live load at the slabs is considered through an equivalent mass density.

A modal analysis of the structure with a fixed base provides its natural frequencies, without considering the soil-foundation subsystem.

The first and second natural frequencies of the structure are $f_1^{\,s}$ = 2.92 Hz and $f_2^{\,s}$ = 15.48 Hz.

A horizontal excitation is considered. For the four cases the ratio of the amplitude of transfer function $\left|\ddot{u}_{6x}(\omega)\right| / \left|\ddot{u}_{1x}(\omega)\right|$ as function of $f / f_1^{\,s}$ are compared in Figure 9(b), where $\ddot{u}_{1x}(\omega)$ is the response at the surface of the free field. They display the resonance frequencies of the *total* soil-structure system for each of the four cases. The first resonance frequency of the total system for all four cases investigated is lower than the first natural frequency of the structure. *Case* 1 has a normalized resonance frequency of about 0.79, *Case* 2 has a normalized resonance frequency of about 0.91, *Case* 3 has a normalized resonance frequency of about 0.94, and *Case* 4 has a normalized resonance frequency of about 0.94.



(a) (b)

Figure 9 (a) System configuration: with consideration of structure mass; (b) ratio of transfer functions due to horizontal excitation.

Considering a vertical excitation, it has been found that the resonance frequencies of the *total* soil-structure system for each of the four cases do not change considerably from the first natural frequency of the structure (García, 2003).

VIBRATION REDUCTION IN THE SUPERSTRUCTURE

Horizontal Excitation

The systems displayed in Figure 4 are considered. The deformation states for a harmonic excitation frequency equal to $f_1^{\,d}$ are exhibited in Figure 10. For *Case* 1, an evident coupling between translational *x*- and rotational *y*-deformations can be observed at the foundation level; high elastic deformations are observed in the superstructure. For *Case* 2, almost no rocking is observed at the foundation; the elastic superstructure deformations are considerable lower than for *Case* 1. For *Case* 3, almost no rocking is observed at the foundation; considerably lower amplitudes are observed. For *Case* 4, little rocking is present and similar elastic superstructure deformations are observed as those for *Case* 2.

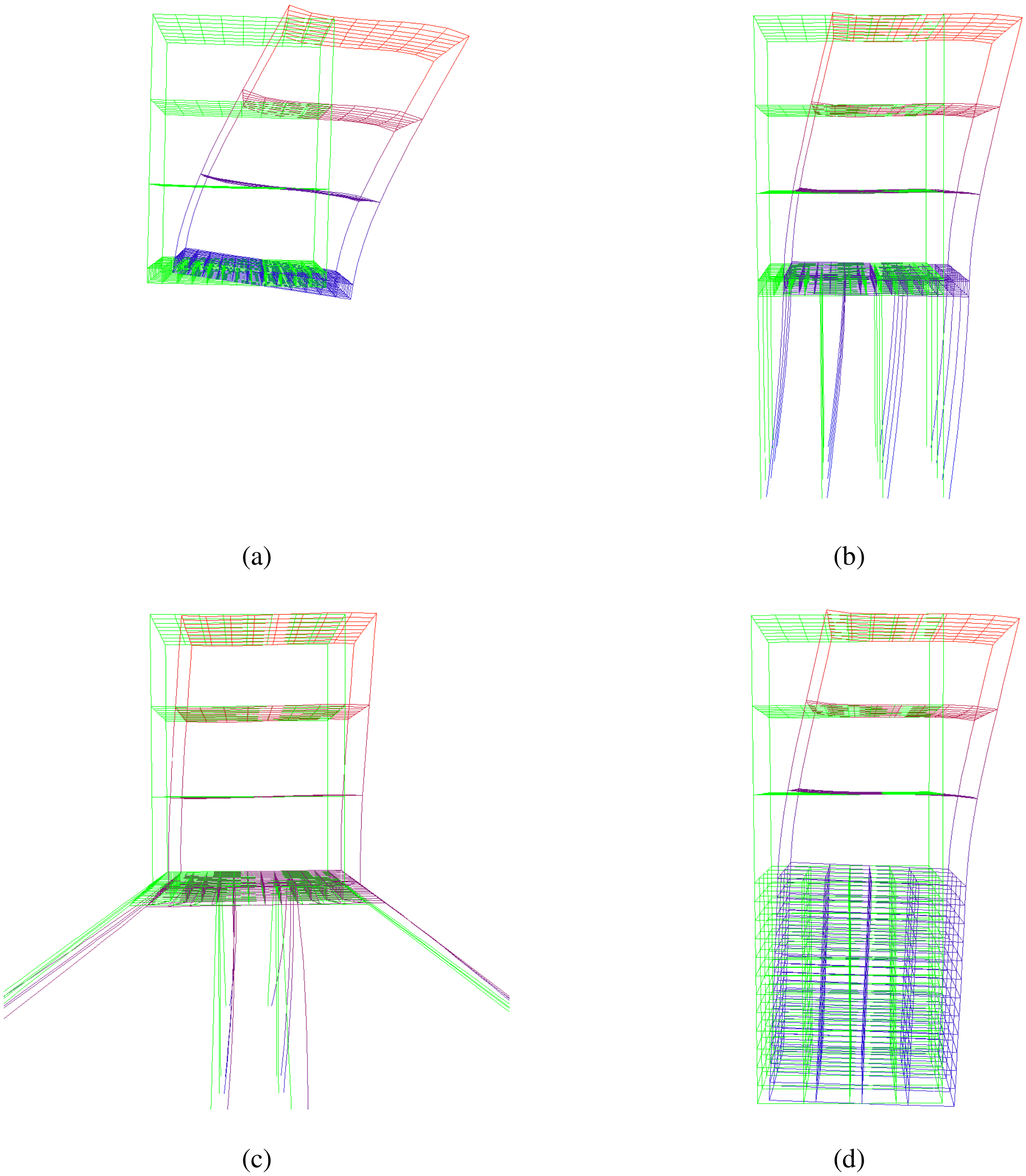


Figure 10 Deformation states for a harmonic excitation frequency equal to $f_1^{\,d}$. (a) Plate foundation, *Case* 1; (b) Vertical pile group, *Case* 2; (c) Inclined and vertical pile group, *Case* 3; (d) Soil improvement block underlaying plate foundation, *Case* 4.

The relative displacements in the structural members are proportional to their internal forces and stresses. The structural relative displacement time histories $u_{6x}(t)$-$u_{5x}(t)$ are displayed in Figure 11. The amplitude obtained for *Case* 2 represents 64% of the amplitude computed for the structure with plate foundation (*Case* 1). The amplitude obtained for *Case* 3 represents 20% of the amplitude computed for *Case* 1. The amplitude obtained for *Case* 4 represents 60% of the amplitude computed for *Case* 1.

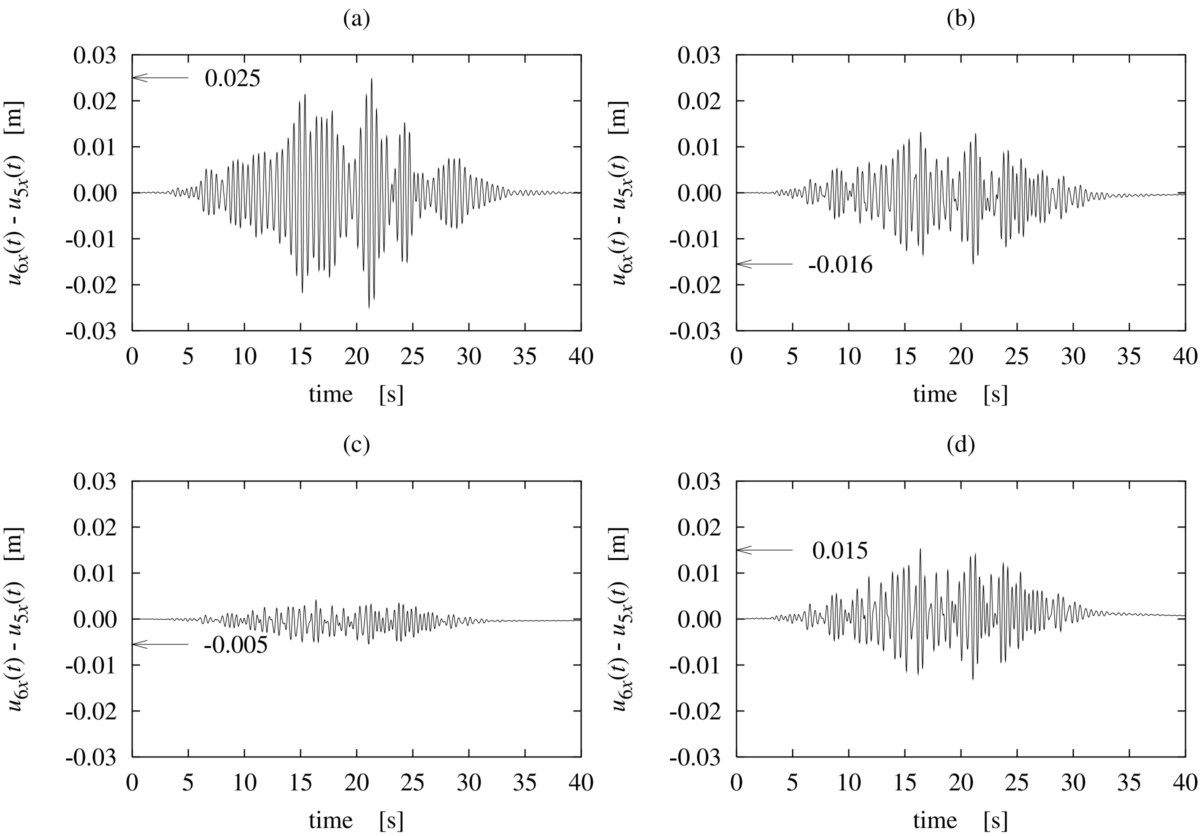


Figure 11. Horizontal relative displacement time histories at the superstructure due to a horizontal excitation: (a) Plate foundation, *Case* 1; (b) Vertical pile group, *Case* 2; (c) Inclined and vertical pile group, *Case* 3; (d) Soil improvement block underlaying plate foundation, *Case* 4.

Vertical Excitation

The vertical acceleration time histories at the top of the foundation $\ddot{u}_{5z}(t)$ are displayed in Figure 12. The amplitude obtained for *Case* 1 represents 94% of the amplitude computed at the ground surface for the free field condition. The amplitude obtained for *Case* 2 represents 72% of the amplitude computed for *Case* 1. The amplitude obtained for *Case* 3 represents 84% of the amplitude computed for *Case* 1. The amplitude obtained for *Case* 4 represents 64% of the amplitude computed for *Case* 1.

The time histories, $u_{6z}(t)$-$u_{5z}(t)$, of the vertical structural relative displacements in the superstructure are displayed in Figure 13. The amplitude obtained for *Case* 2 represents 93% of the amplitude computed for *Case* 1. The amplitude obtained for *Case* 3 represents 93% of the amplitude computed for *Case* 1. The amplitude obtained for *Case* 4 represents 113% of the amplitude computed for *Case* 1.

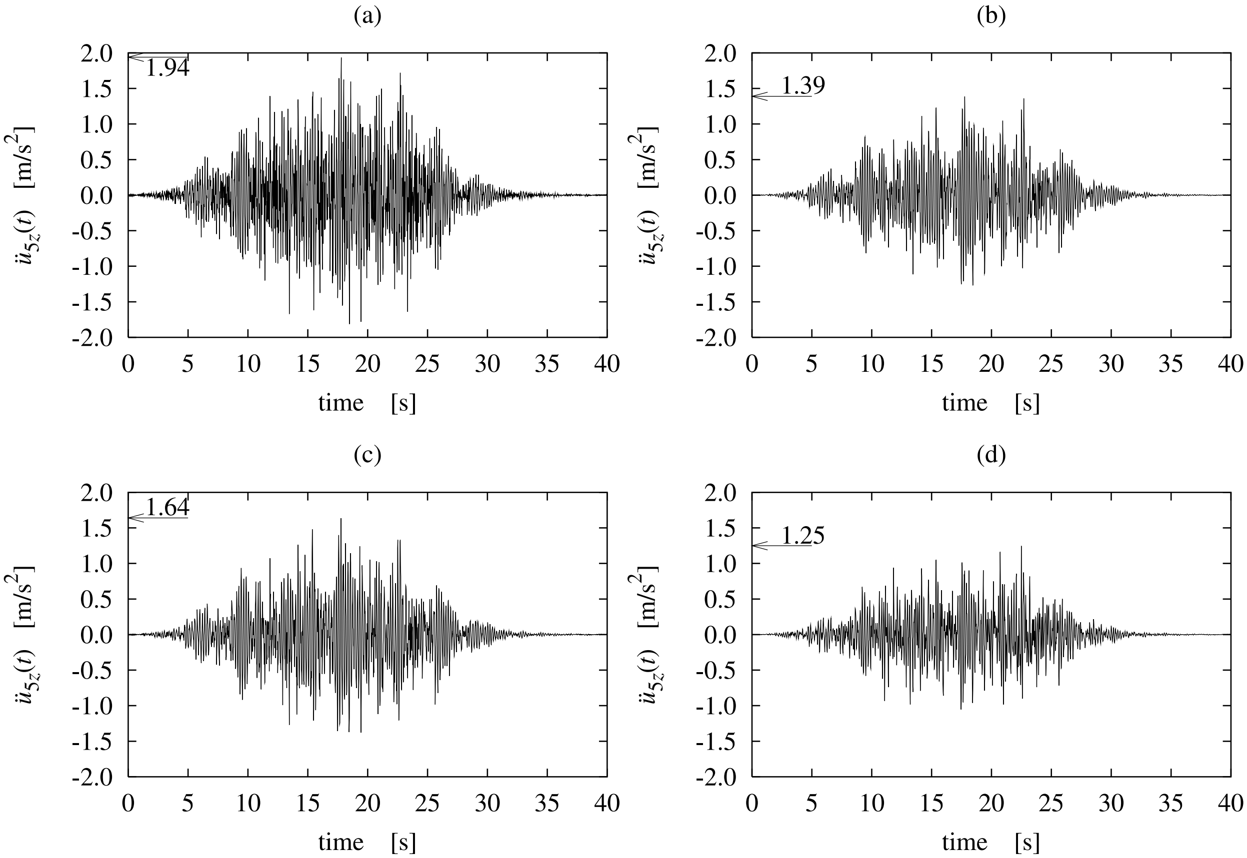


Figure 12 Vertical acceleration time histories at the top of foundation due to a vertical excitation: (a) Plate foundation, *Case* 1; (b) Vertical pile group, *Case* 2; (c) Inclined and vertical pile group, *Case* 3; (d) Soil improvement block underlaying plate foundation, *Case* 4.

SUMMARY AND CONCLUSIONS

The seismic behavior of different soil-structure systems is numerically simulated. Special attention is given to investigate the influence of plate foundations, pile foundations and soil improvement blocks on the reduction of seismically vibrations induced into the structures.

The separate influences on the structural response of three aspects are identified: the response of the soil without structure (free field response), the kinematic interaction, and the inertial interaction.

The following behavior has been observed:

The free field response shows that a soil medium over a rigid rock filters the frequencies and amplifies the amplitudes of certain frequencies of the incoming seismic waves. This phenomena influences the excitation to be transmitted to the structure.

A reduction of the vibration amplitudes at the foundation can be reached through a foundation with high stiffness such as deep foundations (for example piles and soil improvement foundations). Vertical piles are found to be suitable to reduce vibration amplitudes due to vertical excitations, while inclined piles behave better to reduce horizontal vibrations.

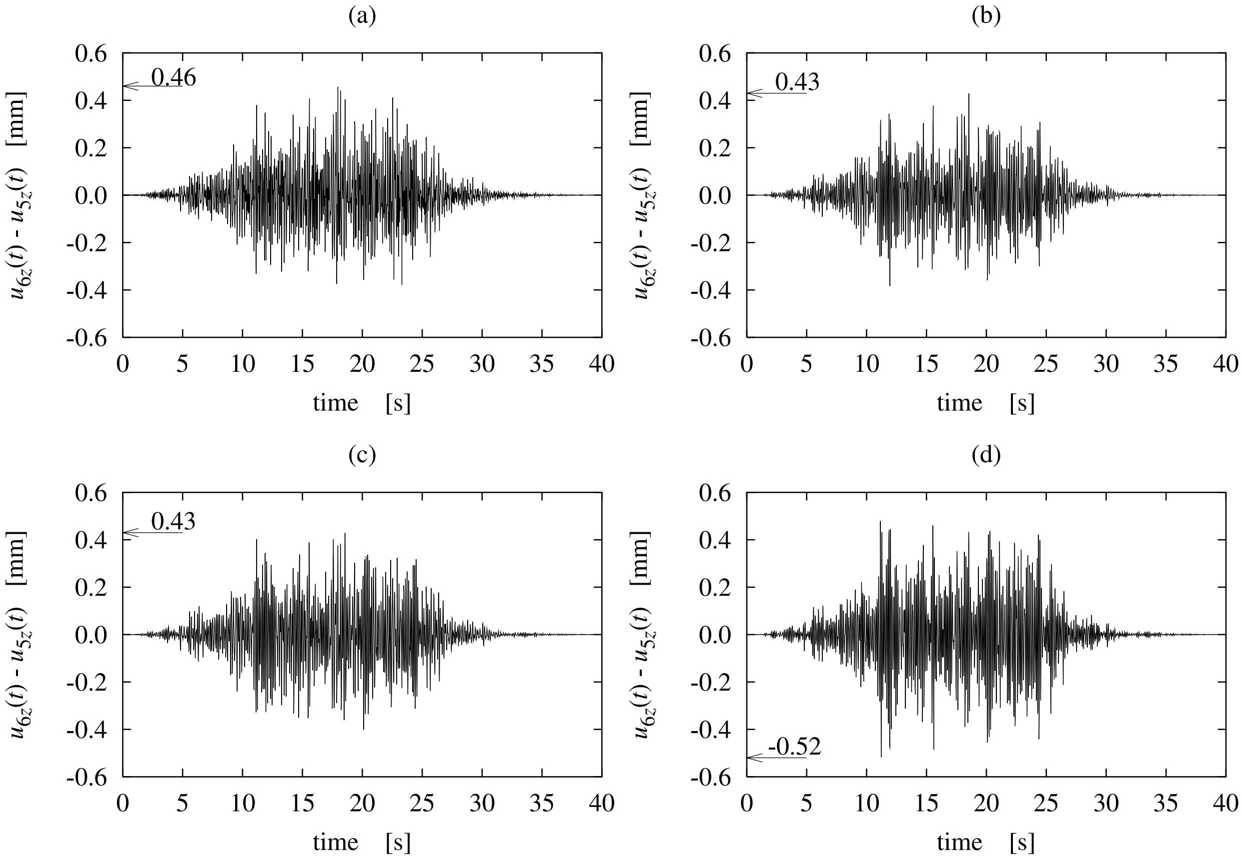


Figure 13 Vertical relative displacement time histories at the superstructure: (a) Plate foundation, *Case* 1; (b) Vertical pile group, *Case* 2; (c) Inclined and vertical pile group, *Case* 3; (d) Soil improvement block underlaying plate foundation, *Case* 4.

A procedure is established to identify the resonance frequencies of a total soil-structure system. Deep foundations are found more suitable to modify the resonance frequencies of the total soil-structure system in the horizontal direction, than in the vertical direction, because of their ability to restrict the rocking deformatibility. The selection of a suitable foundation system can avoid the coincidence between the first resonance frequency of the total soil-structure system and the frequency range of high amplitudes under horizontal excitations.

The reduction of the vibration amplitudes at the foundation through kinematic interaction and the ability of the foundation to shift the first resonance frequency of the total soil-structure system away from the frequency range of high amplitudes through inertial interaction are the main features which can reduce the seismically horizontal vibrations induced into the structures.

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