

# Dynamic Structure-Soil-Structure Interaction Between Nearby Piled Buildings Under Seismic Excitation by BEM-FEM model \*

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## Abstract

The dynamic through-soil interaction between nearby pile supported structures in a viscoelastic half-space, under incident S and Rayleigh waves, is numerically studied. To this end, a three-dimensional viscoelastic BEM-FEM formulation for the dynamic analysis of piles and pile groups in the frequency domain is used, where soil is modelled by BEM and piles are simulated by one-dimensional finite elements as Bernoulli beams. This formulation has been enhanced to include the presence of linear superstructures founded on pile groups, so that structure-soil-structure interaction (SSSI) can be investigated making use of a direct methodology with an affordable number of degrees of freedom. The influence of SSSI on lateral spectral deformation, vertical and rotational response, and shear forces at pile heads, for several configurations of shear one-storey buildings, is addressed. Maximum response spectra are also presented. SSSI effects on groups of structures with similar dynamic characteristics have been found to be important. The system response can be either amplified or attenuated according to the distance between adjacent buildings, which has been related to dynamic properties of the overall system.

## 1 Introduction

Soil-structure interaction (SSI) in buildings has been focus of attention for more than thirty years. Pioneering works, investigating the influence of soil compliance on the dynamic behavior of one-storey shear-structures, were presented by Parmelee [1], Perelman et al [2], Parmelee et al [3] and Sarrazin et al [4]. Following these studies, Veletsos and Meek [5] and Bielak [6] proposed, separately, approximate one-degree-of-freedom substructure models for design purposes. In these cases, the available results for the soil impedance functions, *i.e.* rigid shallow circular plate solutions, were used. A decade later, Wolf presented a comprehensive study on SSI in his classic text [7]. Subsequent works enhanced these approaches and considered the effects of foundation embedment and kinematic interaction effects (*e.g.* [8, 9, 10, 11]).

The problem of the interaction of adjacent structures through the underlying and surrounding soil has received less attention. Lee and Wesley, in their pioneering work [12], investigated the influence of structure-soil-structure interaction (termed hereafter as “SSSI”) on the seismic response of several adjacent nuclear reactors using a three-dimensional scheme and an approximate solution for the dynamic interaction between rigid surface circular plates. Soon after, Luco and Contesse [13], followed by Wong and Trifunac [14], addressed the two-dimensional antiplane problem of the interaction between infinite walls under incident SH waves making use of a solution for the interaction among semi-circular semi-infinite cross-sectional foundations. Later, two different finite elements - boundary elements coupling models were used by Wang and Schmid [15] and Lehmann

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and Antes [16] to investigate the dynamic interaction between three-dimensional structures founded on square embedded foundations, for point-loads applied on one of the structural nodes in the first work and for vertical loads on the soil between the two structures in the second. More recently, some work has been done on analyzing the influence of large groups of buildings, as well as that of site effects due to subsoil configuration, on the seismic response of the overall system by means of several experimental and numerical models [17, 18, 19].

In parallel, the dynamic behavior of pile foundations under linear assumptions has been analytically and numerically studied during the past thirty years in a large number of works (*e.g.* [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39]). Dynamic impedances and seismic response of piles and pile groups have been presented for several configurations and load conditions. These results can be used to address soil-structure interaction problems of pile supported structures making use of substructuring approaches as, for instance, in [40, 41, 42], though direct formulations have also been proposed and implemented, for example, for the dynamic analysis of bridge-pier systems, long-span bridges and multi-storey structures supported on piles, taking SSI into account [43, 44, 45]. A review of applications of the boundary element method (BEM) to the solution of both pile foundations and SSI elastodynamic problems, proposed during the period 1986-1996, was presented by Beskos [46].

Indeed, more work needs to be done in order to assess the effects of SSSI on general three-dimensional problems with different kinds of structural and subsoil configurations, and its associated risks. One of the cases that, to the extent of the author's knowledge, has not been addressed to date, is that of the dynamic interaction between two or more pile supported structures, for which the use of a direct methodology is practically mandatory. For this reason, a previously developed BEM-FEM code [47, 48] for the dynamic analysis of piles and pile groups has been enhanced in order to allow for any number of three-dimensionally distributed superstructures composed by any number of vertical piers and horizontal rigid slabs (as depicted in fig. 1), and founded on one or more pile caps. Furthermore, pile groups can be founded on multilayered soils of generic stratigraphy and topography, including deposits and inclusions. This direct model is used herein to study the effects of through-soil interaction between neighbouring pile supported structures. In a first step, however, the problem has been deliberately simplified in order to: first, concentrate on SSSI phenomena; and second, establish a link to previous works on the matter. To this end, all buildings have been considered as one-storey shear structures founded on  $3 \times 3$  similar pile caps in a viscoelastic half-space, and a reduced set of problem configurations has been chosen to perform the analysis, whose intention is not to be a comprehensive study.

In the next sections, the problem is first stated. Then, the used formulation is briefly outlined and the problem parameters and properties are defined. Afterwards, a set of numerical results, in the frequency domain, is presented to assess the effects of structure-soil-structure interaction on the seismic response of buildings in terms of its spectral deflection, fundamental frequency, vertical and rotational response and shear forces at pile heads. Maximum response spectra are also presented for an artificial seismic input.

## 2 Problem definition

The system under investigation is composed of several neighbouring one-storey linear shear structures, three-dimensionally distributed, founded on  $3 \times 3$  fixed-head pile groups embedded on a viscoelastic half-space. A plane sketch of the problem is depicted in fig. 2, where the geometric properties of buildings and piles are labelled. Pile groups are defined by length  $L$  and sectional diameter  $d$  of piles, center-to-center spacing between adjacent piles  $s$  and foundation halfwidth  $b$ , being in this specific case  $b = s$ . The rest of parameters are: center-to-center spacing between adjacent foundations  $D$ , fixed-base fundamental period  $T$  and structural damping ratio  $\zeta$ , cap mass  $m_o$  and moment of inertia  $I_o$ , structure effective height  $h$  and structure effective mass  $m$ .

In this work, as a first approximation and also in order to focus on SSSI, superstructures are modelled as one-degree-of-freedom shear buildings in its fixed-base condition. However, these may represent either one-storey constructions or the fundamental mode of multi-mode structures. Sub-

sequently,  $h$ ,  $m$  and  $\zeta$  must be generally understood as first-mode equivalent height, mass and damping ratio. On the other hand, note that fig. 2 is a two-dimensional representation of the three-dimensional model used herein. This way, eight degrees of freedom are considered on each foundation-superstructure subsystem: two lateral deformations of the structure  $u$  and two foundation translations  $u^c$  along axes  $x$  and  $y$ , one vertical displacement  $u_z$ , two rocking motions  $\varphi$  around horizontal axes and one rotational motion  $\phi$  around the vertical axis. Note that vertical motions of cap and storey have been forced to be identical because buildings are modelled as purely shear structures.

The dynamic behavior of several problems (of which the different relative arrangements of structures are shown in fig. 3) under vertically incident plane S waves (producing motions on the  $y$  axis) or Rayleigh waves (moving along the  $y$  axis from  $y < 0$  to  $y > 0$ ), is analyzed. To this end, the response of each structure in the group is compared to that of the single-structure-soil system in order to find out whether or not structure-soil-structure interaction effects between two or more buildings can be of importance. Note that in all configurations the distance  $D$  between adjacent structures is measured in parallel to  $x$  and  $y$  axes, and is the same between all structures in the same problem.

### 3 BEM-FEM model

A three-dimensional BEM-FEM code [47, 48] previously developed by the authors for the dynamic analysis of pile groups has been enhanced to allow for one or more superstructures (as shear buildings) founded on pile groups. Stratified soils are modelled by BEM, each stratum being considered as a continuum, semi-infinite, isotropic, zoned-homogeneous, linear, viscoelastic medium. The integral equation is written so that pile-soil interface tractions arising from the pile-soil interaction can be regarded as body forces acting within the soil. Fully-bonded contact conditions are assumed between soil and piles, which are modelled as vertical Bernoulli beams using one-dimensional three-node FEM elements, and whose heads can be fixedly connected to a rigid non-ground-contacting cap.

Multi-storey structures, made up of vertical extensible piers and rigid horizontal slabs, can be founded on one or more pile caps. In this work, however, piers sectional area has been assigned an artificially high value in order to analyze the dynamic behavior of purely shear structures. The principal axes of inertia of rigid slabs are assumed to be parallel to the global coordinate axes. Piers have been considered massless elements, being the masses and inertias of structures condensed on slabs and pile caps. Damping of hysteretic type has been considered for both the soil and the structures by defining a complex soil shear modulus  $\mu = Re[\mu](1 + 2i\zeta_s)$  and a complex structural stiffness  $k = Re[k](1 + 2i\zeta)$ , being  $\zeta_s$  and  $\zeta$  the damping coefficients of soil and superstructure.

Tractions, displacements and external loads can be prescribed as boundary conditions. The model can also be subject to incident S, P and Rayleigh seismic waves by considering the displacement and traction fields in the soil as the superposition of incident and scattered fields.

### 4 Problem parameters

The mechanical and geometrical properties of pile foundations and soil are defined by the following parameters: piles separation ratio  $s/d = 5$ , pile-soil modulus ratios  $E_p/E_s = 100$  and  $1000$ , soil-pile density ratio  $\rho_s/\rho_p = 0.7$ , piles aspect ratio  $L/d = 15$ , soil damping coefficient  $\zeta_s = 0.05$  and Poisson ratio  $\nu_s = 0.4$ .

On the other hand, the most important parameters to define the superstructure dynamic behavior are: structural aspect ratios  $h/b = 2, 3$  and  $4$ ; structure-soil stiffness ratio  $h/(Tc_s) = 0.3$ , being  $c_s$  the soil shear wave velocity; and structural damping ratio  $\zeta = 0.05$ . The choice of the structure-soil stiffness ratio is justified below. Other parameters are: foundation mass moment of inertia  $I_o = 5\%$ ,  $2.2\%$  and  $1.25\%$  of  $mh^2$  for  $h/b = 2, 3$  and  $4$ , respectively; structure-soil mass ratio  $m/4\rho_sb^2h = 0.20$ ; and foundation-structure mass ratio  $m_o/m = 0.25$ . The values chosen for

these three last parameters are considered to be representative for typical constructions, and similar values have been used by other authors before [5, 6, 9]. In any case, SSI and SSSI results are not significantly sensitive to its variation.

Soil-structure interaction effects on a single building can be measured by parameters  $\tilde{T}/T$  and  $\tilde{\zeta}$ , where  $\tilde{T}$  is the fundamental period of the soil-structure system and  $\tilde{\zeta}$  its equivalent structural damping (see, *e.g.*, [5, 9]). The first parameter accounts for the shifting in the system fundamental frequency, while the effective damping is related to the absolute maximum value of the pseudo-acceleration in the structure, *i.e.* if  $\tilde{\zeta} > \zeta$ , the maximum structural response of the soil-structure system is smaller than the fixed-base response, and viceversa. In order to be able to relate the SSSI effects that are studied herein with the specific level of SSI effects of the isolated soil-structure system, fig. 4 shows the evolution of  $\tilde{T}/T$  and  $\tilde{\zeta}$  with the structure-soil stiffness ratio  $h/(Tc_s)$ , being  $c_s$  the soil shear wave velocity, for the problem defined above with  $E_p/E_s = 1000$ . Since this is the case of a single structure founded on only one pile group with a rigid cap, this kind of study can be performed by a substructure method, which requires less computational effort in comparison to the direct approach. Therefore, fig. 4 has been obtained through the substructure method and making use of complex impedance functions and kinematic factors, obtained from the same model used in this work, as explained in [47, 48]. As said above, the present study has been performed for  $h/(Tc_s) = 0.3$ , which is within the range of realistic values and yet soil-structure interaction effects become apparent. Obviously, for  $h/(Tc_s) \rightarrow 0$  (relatively stiff soil or soft/tall structure), the structure behavior is that of the fixed-base system, and consequently, no SSSI effects would appear.

## 5 Numerical results

### 5.1 Steady-state response

The influence of structure-soil-structure interaction on the dynamic response of piled structures is addressed in this section. Here, the horizontal seismic behavior of buildings is analyzed in terms of its lateral deformation response spectra (also called dynamic magnification factor [49]), defined as  $\text{Abs}[\Omega^2 u/\omega^2 u_{ff}]$ , where  $\Omega$  is the fundamental frequency of the fixed-base structure,  $\omega$  is the excitation frequency and  $u_{ff}$  is the horizontal free-field motion at the ground surface. The product of this value with the structural mass and the corresponding free-field horizontal acceleration at ground surface level yields the amplitude of the shear force at the base of the structure. On the other hand, the harmonic vertical motion of structures  $u_z$  is obtained in terms of transfer functions defined as  $\text{Abs}[u_z/u_{ff}]$  or  $\text{Abs}[u_z/u_{zff}]$  when the system is impinged by S or Rayleigh waves, respectively, and where  $u_{zff}$  is the vertical free-field motion at the ground surface for Rayleigh waves. The harmonic rotational motion of structures  $\phi$  around its vertical axis is also analyzed in terms of transfer functions defined as  $\text{Abs}[\phi \cdot b/u_{ff}]$ . All figures in this section are plotted against the dimensionless frequency  $a_o = \omega d/c_s$ .

Distance  $D$  between adjacent foundations is expressed either proportionally to the foundation halfwidth  $b$  or as a fraction of the soil wave length at the soil-structure fundamental frequency  $\lambda = c_s \tilde{T}$ . The goal of relating  $D$  and  $\lambda$  is linking the separation between dynamically similar structures to one of the system's main dynamic properties.

Fig. 5 shows the dynamic response of single soil-structure systems (solid lines) together with the response of groups of three identical buildings (non-solid lines) under vertically incident S waves in terms of their lateral deformation response spectra for  $E_p/E_s = 1000$ . Three different structural aspect ratios ( $h/b = 2, 3$  and  $4$ ) and distances between adjacent buildings ( $D = \lambda/2, 3\lambda/4$  and  $\lambda/4$ ) are considered. Shaking direction is assumed to be either parallel or perpendicular to the direction of alignment of the structures (as shown in figs. 3b and c, respectively). It can be seen that the lateral response of a structure may vary significantly due to the presence of neighbouring buildings. A slight shift in the fundamental period of the system takes place, but the peak value of the lateral shear force at the base of the structure can be considerably amplified. For instance, when  $D = \lambda/2$ , the lateral response of the central building of three aligned along the direction of shaking is increased by 40, 35 and 25 per cent for  $h/b = 2, 3$  and  $4$ , respectively. The influence

of SSSI varies from one position to another, as well as for different distances between structures and for different aspect ratios, and the response may even increase or decrease depending on the configuration. However, it appears that the central construction is usually subject to the strongest shaking. It is also worth noting that even though problems with different  $h/b$  and the same  $D$  are not dimensionally equivalent, the same trends can be observed when  $D$  remains constant, in terms of  $\lambda$ .

The relation between the seismic response of different structures in a group configuration and the single soil-structure problem is also approximately the same for different pile-soil modulus ratios  $E_p/E_s$ . To show this, fig. 6 presents the dynamic response of single soil-structure systems (solid lines) together with the response of groups of three identical buildings (non-solid lines) under vertically incident S waves, now for  $E_p/E_s = 100$ . Only results for  $h/b = 4$  and distances between adjacent buildings  $D = \lambda/2$  and  $\lambda/4$  are presented. Indeed, comparing these plots with those of fig. 5 for the same structural aspect ratio, it is observed that the system behavior is qualitatively equivalent for both  $E_p/E_s$  values.

Also in fig. 6, and in some other figures below, it is apparent that the curves corresponding to the response of the central building, when  $D = \lambda/4$ , tend to zero at some frequency around  $\tilde{T}$ . This behavior responds to the fact that the displacements of the soil around the structures, particularly at that distance, tend to zero at that frequency. The phenomenon can be understood by analogy with a lumped-mass two-degree-of-freedom linear system subjected to support motion, where the displacements of the mass attached to the support tend to zero when the other mass suffers the maximum relative displacements, i.e., at the fundamental frequency of the one-degree-of-freedom spring-mass system formed by the second mass. The effect is apparent mainly for  $D = \lambda/4$  because, at this distance, the influence of the two extreme structures on the location of the central building tend to prevent it from moving at the same time. Also, the phenomenon is more noticeable for  $E_p/E_s = 100$  because when  $E_p/E_s = 1000$  the foundation is even less compliant to the soil movement and, therefore, disturbs more the behavior explained above.

The influence of distance on the interaction between identical structures of aspect ratio  $h/b = 4$  is investigated in fig. 7 for  $E_p/E_s = 100$ . The structures are aligned along the direction of shaking, produced by vertically incident S waves. Results for the central and lateral buildings are presented for  $D = \lambda/4$ ,  $\lambda/3$ ,  $\lambda/2$  and  $\lambda$ . Once again it is observed that the central structure is the most influenced one by the presence of neighbouring constructions, and that, for the properties used in this work,  $D = \lambda/2$  yields the highest lateral deformations, up to 65 per cent larger than those of the single soil-structure system. On the contrary,  $D = \lambda/4$  and  $\lambda$  produce an attenuation of the response of 25 per cent.

Figs. 8 and 9 show the dynamic response of single soil-structure systems (solid lines) together with the response of groups of three dissimilar buildings (non-solid lines) under vertically incident S waves producing motions parallel or perpendicularly to the direction of alignment of the structures, respectively. In this case, adjacent buildings are considered to have different structural aspect ratios ( $h/b = 2$  and  $4$ ) and, regarding the rest of constraints, their fixed-based fundamental period differ by a factor of 2. Two distances between adjacent buildings ( $D = 4b$  and  $6b$ ) are considered, and  $E_p/E_s = 100$ . It is observed that, under these assumptions, SSSI effects appear to be generally negligible, though when a short-period building is placed among two identical long-period structures, the response of both types of constructions increases by 20 and 30 per cent, respectively.

The dynamic response of a group of five structures under vertically incident S waves is presented and compared to that of a group of three in fig. 10 for  $E_p/E_s = 100$  and two values of  $D$ :  $\lambda/4$  and  $\lambda/2$ . Buildings are aligned along the direction of shaking (arranged as shown in figs. 3b and c), and both cases are compared according to their position in the row. It becomes apparent how the dynamic behavior of the structures is significantly similar when compared by pairs starting by the end positions. However, the responses of the respective central constructions are considerably different. Besides, the configuration of five structures appears to be slightly more favorable than that of three.

Now, a case of nine similar  $h/b = 4$  structures arranged as shown in fig. 3d is analyzed. To this end, fig. 11 shows the dynamic response of the single soil-structure system (solid lines), together with

the response of similar buildings in a group of nine (non-solid lines), under vertically incident S waves in terms of their lateral deformation response spectra for  $E_p/E_s = 100$ . Two different distances between adjacent buildings ( $D = \lambda/2$  and  $\lambda/4$ ) are considered. This plot can be compared with fig. 6, where the same problem but with only three structures is presented. It can be seen that, again, the general trend remains, *i.e.*, that the  $D = \lambda/2$  configuration is much more unfavorable than the  $D = \lambda/4$  situation, and that structures in central positions show significantly larger maximum response values. In this case, the central building increases its response by 130 per cent with respect to the response of the isolated soil-structure system.

The next three figures show the response of several groups of structures subject to incident Rayleigh waves. Fig. 12 presents the dynamic response of the single soil-structure system together with the response of groups of three similar  $h/b = 2$  buildings in terms of their lateral deformation response spectra, for  $D = \lambda/2$ . Fig. 13 presents the same information for three identical  $h/b = 4$  buildings and two distances ( $D = \lambda/2$  and  $\lambda/4$ ). Results for  $E_p/E_s = 100$  and 1000 are presented for Rayleigh waves impinging parallel or perpendicularly to the direction of alignment of the structures. Firstly, it is worth noting that, when the system is impinged by Rayleigh waves, the most unfavorable separation, for the properties used in this work and among the considered distances, is  $D = \lambda/4$ , contrary to what happened with the vertically incident S waves. In fact, in this case, the grouping of the structures at distance  $D = \lambda/2$  makes the seismic response smaller. Secondly, when seismic waves impinge in the direction of alignment of structures, a slight shifting in the fundamental period of the overall system is observed: up to 8 per cent smaller than that corresponding to the single soil-structure system. Also, shielding effects become apparent in this case. Around the overall system fundamental frequency, seismic response of the first structure to be impinged by the incident Rayleigh waves (labelled “a” in the figures) is significantly above the seismic response of the other two. The last structure (labelled “c”) is usually the weakest excited by the impinging waves, being its seismic response up to a 50 per cent smaller. Finally, both figures show that the overall behavior of the system is independent of  $E_p/E_s$  (though, obviously, magnitudes change from one to another). The last of this set is fig. 14, where the response of three different structures  $h/b = 2$  and 4 is presented for  $E_p/E_s = 1000$  and  $D = 4b$ . In this case, similarly to what happened for the S waves, the interaction effects are negligible, except for the existent shielding effects.

Vertical and rotational behavior of adjacent pile supported structures is presented in terms of transfer functions in figs. 15 and 16 for vertically incident S waves, and in fig. 17 for incident Rayleigh waves. All results correspond to parameters  $E_p/E_s = 100$  and  $h/b = 4$ . For incident S waves, results for groups of three and nine piled structures are shown, while for Rayleigh waves, only the response of three adjacent buildings is presented. In all cases, only the positions and configurations whose transfer functions are not zero are specified. Vertical displacements, measured at the caps’ center of gravity, are normalized by the free-field horizontal or vertical motion for incident S or Rayleigh waves, respectively, while rotation is multiplied to the foundation halfwidth and normalized by the free-field horizontal motion, so that the magnitude is indicative of the horizontal displacements at the external pile heads due to rotation. Fig. 15 shows that vertical displacements under incident S waves are greater for the shortest of the tested distances between adjacent buildings. For  $D = \lambda/4$ , vertical motions arising from structure-soil-structure interaction effects are above 35 per cent of horizontal motions at free-field ground level produced by the incident S waves, and for  $D = \lambda/2$  they reach values between 20 and 30 per cent. The rotational response, shown in fig. 16, seems to be also of importance, as it produces horizontal displacements on piles of the order of 5 to 10 per cent of horizontal motions at free-field ground level. The system exhibits similar trends under the action of incident Rayleigh waves. In this case (fig. 17), SSSI can produce vertical motions up to 70 per cent greater than those presented by a single structure. At the same time, horizontal displacements on piles due to rotational response of buildings are above 20 per cent of horizontal motions at free-field ground level.

Finally, figs. 18 and 19 compare shear forces at pile heads due to vertically incident S waves under  $h/b = 4$  structures alone or when three identical buildings are separated  $D = \lambda/3$  and aligned either perpendicularly or parallel to shaking direction. Shear forces are normalized by the static horizontal stiffness of a single pile and the free-field horizontal motion due to the incident seismic

waves. When structures are aligned perpendicularly to shaking direction, shear forces at pile heads of lateral buildings are almost identical to those corresponding to a single building, while at the central cap, shear forces decrease with respect to the single building case. On the contrary, when structures are aligned parallel to shaking direction, shear forces increase both under lateral and central buildings. More precisely, in this case corner piles are subject to forces up to 16 per cent greater.

## 5.2 Earthquake response

In this section, selected acceleration response spectra are presented in order to measure the influence of SSSI on the seismic response of structures. Results in the time domain are obtained by Fourier transformation, using the fast Fourier transform (FFT) algorithm. An artificial accelerogram, compatible with AFPS-90 [50] chapter 5.7 normalized response spectrum (shown in fig. 20), has been produced making use of SIMQKE [51]. Signal's total length and peak acceleration are 18 seconds and  $0.17 g$ , respectively. Five per cent damped peak spectral response acceleration of artificial signal and target spectrum are  $0.463 g$  and  $0.425 g$ , respectively. The reason why a synthetic accelerogram has been used instead of a recorded one is the greater smoothness of the target response spectra, which clarifies the results. Properties of soil and piles used to compute these results, only as an example, are summarized in table 1, being  $h/b = 4$ . It is worth saying that the soil-structure system fundamental period is  $\tilde{T} \simeq 0.40 s$ .

Soil	Piles	Structures
$c_s = 239 m/s$	$E_p = 2.76 \cdot 10^{10} N/m^2$	$T = 0.28 s$
$\rho_s = 1750 kg/m^3$	$\rho_p = 2500 kg/m^3$	$m = 7 \cdot 10^5 kg$
$\nu_s = 0.4$	$d = 1 m$	$h = 20 m$
$\zeta_s = 0.05$	$L = 15 m$	$\zeta = 0.05$

Table 1: Soil, piles and structures properties.

Five per cent damped acceleration response spectra, corresponding to an isolated structure and to the central building of three adjacent constructions separated either  $D = \lambda/4$  or  $D = \lambda/2$ , and aligned along the direction of shaking, are presented. They have been obtained assuming that the system is subject to the input accelerogram that was described above, prescribed at free-field surface, and that the seismic motion is caused by vertically incident S waves. The system transfer functions are part of those used to compute the results shown in fig.7.

Fig. 20 shows the system response measured at pile caps together with the free-field and target response spectra, while fig. 21 shows the response measured at slabs at height  $h$ . Obviously, peak spectral response acceleration at pile caps is highly influenced by the presence of the superstructure at periods around soil-structure system fundamental frequency. On the contrary, in this range, it is little influenced by the presence of other structures in the neighbourhood, being the variation not larger than 5.6 per cent. However, for periods around 0.32 seconds, differences due to SSSI reach 20 per cent. On the other hand, peak spectral response acceleration measured at height  $h$  is significantly influenced by the presence of nearby structures. In comparison to the peak response of a single structure, the one corresponding to the central building of a group is 15 per cent lower for  $D = \lambda/4$  and 38 per cent higher for  $D = \lambda/2$ . Consequently, neighbouring pile supported structures can significantly increase the seismic response of a structure.

## 6 Conclusions

A 3D numerical procedure for the dynamic analysis of pile supported linear structures was used in this work to address the problem of through-soil interaction between neighbouring one-storey shear buildings. The code, based on a previously presented harmonic three-dimensional boundary elements - finite elements coupling method, allows for the rigorous 3D modelling of pile foundations

under linear assumptions. Several shear multi-storey structures, composed of vertical piers and horizontal rigid slabs, and founded on one or more rigid non-ground-contacting pile caps, can be considered. This way, structure-soil-structure interaction phenomena are implicitly included in the model, as it represents a direct approach to the problem, yet with an affordable number of degrees of freedom.

A particular set of parameters and problem configurations was chosen to perform the analysis, which obviously does not intend to be a comprehensive study. One-storey shear buildings, founded on  $3 \times 3$  pile groups in a viscoelastic half-space, with different aspect ratios and separations between adjacent structures, were considered. Lateral spectral deformation, vertical and rotational transfer functions, harmonic shear forces at pile heads, and maximum response spectra are presented in order to assess the influence of structure-soil-structure interaction phenomena on the structural seismic response of neighbouring buildings subject to incident S or Rayleigh waves.

In the case of groups of structures with similar dynamic characteristics, SSSI effects have been found to be of importance, mainly around the overall system fundamental frequency. Depending on the distance between adjacent buildings, which is expressed in terms of the soil wave length  $\lambda = c_s \tilde{T}$  at the soil-structure fundamental period  $\tilde{T}$ , the seismic response of each member of the group can increase or decrease. For vertically incident S waves, and for the set of properties and configurations selected for this work, the most unfavorable distance appears to be  $D = \lambda/2$ . For this separation between adjacent buildings, large amplifications have been observed in the response of groups of three and five aligned structures, and even larger motions for a square group of nine similar constructions. The highest amplifications occur at central constructions and when the impinging waves produce motions in the direction of alignment of the structures. On the other hand, in the case of groups of dissimilar structures, SSSI effects are not so important, being the situation of short-period buildings placed among long-period constructions the most unfavorable configuration.

On the other hand, when Rayleigh waves impinge in the same direction of alignment of the structures, the first building to be hit suffers the largest displacements and, at the same time, shielding effects become apparent. In this case, contrary to what happened for S waves, the most unfavorable of the tested distances is  $D = \lambda/4$ . For Rayleigh waves impinging perpendicularly to the direction of alignment of the structures, the overall response is usually attenuated.

Vertical and rotational motions induced by SSSI have been found to be also of importance for both S and Rayleigh waves. For instance, vertical displacement amplitudes of lateral structures of groups impinged by S waves can reach values of 35 per cent of horizontal motions at free-field ground level. In addition, shear forces at pile heads can also be amplified due to SSSI.

In view of the results, it is apparent that further studies about structure-soil-structure interaction phenomena and their influence on structural seismic risk are mandatory, as it has been shown that nearby buildings can significantly increase the seismic response of a structure. Therefore, studies of the magnitude of this coupling phenomena on the dynamic behavior of existing important buildings in presence of other close structures, or of existing groups of special buildings, should be carried out. Also, the influence on the system response of foundation characteristics, structural configuration and design, relationships between dynamic properties of neighbouring structures, sub-soil properties, stratigraphy, type, angle and direction of incident seismic waves and input motion, should be addressed.

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## References

- [1] Parmelee RA. Building-Foundation Interaction Effects. J Eng Mech Div ASCE 1967;93(EM2):131-152.
- [2] Perelman DS, Parmelee RA, Lee SL. Seismic Response of Single-Storey Interaction Systems. J Struct Div ASCE 1968;94(ST11):2597-2608.
- [3] Parmelee RA, Perelman DS and Lee SL. Seismic Response of Multiple-Storey Structures on Flexible Foundation. Bul Seism Soc Ame 1969;59(3):1061-1070.
- [4] Sarrazin MA, Roesset JM, Whitman RV. Dynamic Soil-Structure Interaction. J Struct Div ASCE 1972;98(ST7):1525-1544.
- [5] Veletsos AS, Meek JW. Dynamic behaviour of building-foundation systems. Earthquake Eng Struct Dyn 1974;3:121-138.
- [6] Bielak J. Dynamic Behavior of Structures with Embedded Foundations. Earthquake Eng Struct Dyn 1975;3:259-274.
- [7] Wolf JP. Dynamic soil-structure interaction. Prentice-Hall, Englewood Cliffs, NJ, 1985.
- [8] Todorovska MI. Effects of the depth of the embedment on the system response during building-soil interaction. Soil Dyn Earthquake Eng 1992;11:111-123.
- [9] Avilés J, Pérez-Rocha LE. Evaluation of interaction effects on the system period and the system damping due to foundation embedment and layer depth. Soil Dyn Earthquake Eng 1996;15:11-27.
- [10] Avilés J, Pérez-Rocha LE. Effects of foundation embedment during building-soil interaction. Earthquake Eng Struct Dyn 1998;27:1523-1540.
- [11] Avilés J, Suárez M. Effective periods and dampings of building-foundation systems including seismic wave effects. Eng Struct 2002;24:553-562.
- [12] Lee TH, Wesley DA. Soil-structure interaction of nuclear reactor structures considering through-soil coupling between adjacent structures. Nuclear Eng Design, 1973;24:374-387.
- [13] Luco JE, Contesse L. Dynamic structure-soil-structure interaction. Bul Seism Soc Ame 1973;63:1289-1303.
- [14] Wong HL, Trifunac MD. Two-dimensional, antiplane, building-soil-building interaction for two or more buildings and for incident plane SH waves. Bul Seism Soc Ame 1975;65(6):1863-1885.
- [15] Wang S, Schmid G. Dynamic structure-soil-structure interaction by FEM and BEM. Comput Mech 1992;9:347-357.
- [16] Lehmann L, Antes H. Dynamic structure-soil-structure interaction applying the Symmetric Galerkin Boundary Method (SGBEM). Mechanics Research Communications, 2001;3:297-304.
- [17] Clouteau D, Aubry D. Modifications of the ground motion in dense urban areas. J Comput Acoustics, 2001;9:1659-1675.
- [18] Tsogka C, Wirgin A. Simulation of seismic response in an idealized city. Soil Dyn Earthquake Eng 2003;23:391-402.
- [19] Kham M, Semblat JF, Bard PY, Dangla P. Seismic site-city interaction: main governing phenomena through simplified numerical models. Bul Seism Soc Ame 2006;96(5):1934-1951.

- [20] Kuhlemeyer RL. Static and dynamic laterally loaded floating piles. J Geotech Eng ASCE 1979;105:289-304.
- [21] Dobry R, O'Rourke MJ, Roesset JM, Vicente E. Horizontal stiffness and damping of single piles. J Geotech Eng Div ASCE 1982;108(GT3):439-459.
- [22] Sen R, Davies TG, Banerjee PK. Dynamic analysis of piles and pile groups embedded in homogeneous soils. Earthquake Eng Struct Dyn 1985;13:53-65.
- [23] Pak RSY, Jennings PC. Elastodynamic response of the pile under transverse excitation. J Eng Mech, ASCE 1987;113(7):1101-16.
- [24] Rajapakse RKND, Shah AH. On the lateral harmonic motion of an elastic bar embedded in an elastic half-space. Int J Solids Struct 1987;23(2):287-303.
- [25] Mamoon SM, Kaynia AM, Banerjee PK. Frequency domain dynamic analysis of piles and pile groups. J Eng Mech ASCE 1990;116(10):2237-57.
- [26] Mamoon SM, Ahmad S. Seismic response of piles to obliquely incident SH, SV, and P waves. J Geotech Eng ASCE 1990;116(2):186-204.
- [27] Fan K, Gazetas G, Kaynia A, Kausel E, Ahmad S. Kinematic seismic response of single piles and pile groups. J Geotech Eng ASCE 1991;117(12):1860-1879.
- [28] Kaynia AM, Kausel E. Dynamics of piles and pile groups in layered soil media. Soil Dyn Earthquake Eng 1991;10:386-401
- [29] Gazetas G, Fan K, Kaynia AM, Kausel E. Dynamic interaction factors for floating pile groups. J Geotech Eng ASCE 1991;117:1531-48.
- [30] Novak M. Piles under dynamic loads. 2nd Int Conf Recent Adv Geotech Earthquake Eng Soil Dyn, Vol 3, St Louis, Missouri, 250-273, 1991.
- [31] Gazetas G, Makris N. Dynamic pile-soil-pile interaction. Part I: Analysis of axial vibration. Earthquake Eng Struct Dyn 1991;20:115-132.
- [32] Makris N, Gazetas G. Dynamic pile-soil-pile interaction. Part II: Lateral and seismic response. Earthquake Eng Struct Dyn 1992;21:145-162.
- [33] Kaynia A, Novak M. Response of pile foundations to Rayleigh waves and obliquely incident body waves. Earthquake Eng Struct Dyn 1992;21:303-318.
- [34] Gazetas G, Fan K, Tazoh T, Shimizu K, Kavvadas M, Makris N. Seismic pile-group-structure interaction. Geotechnical Special Publication NO.34, ASCE 1992;56-93.
- [35] Mylonakis G, Gazetas G. Lateral vibration and internal forces of grouped piles in layered soil. J Geotech and Geoenvironmental Eng ASCE 1999;125(1):16-25.
- [36] Kattis SE, Polyzos D, Beskos DE. Vibration isolation by a row of piles using a 3-D Frequency domain BEM. Int J Numer Meth Eng 1999;46:713-28.
- [37] Zeng X, Rajapakse RKND. Dynamic axial load transfer from elastic bar to poroelastic medium. J Eng Mech ASCE 1999;125(9):1048-55.
- [38] Wang JH, Zhou XL, Lu JF. Dynamic response of pile groups embedded in a poroelastic medium. Soil Dyn Earthquake Eng 2003;23:235-42.
- [39] Maeso O, Aznárez JJ, García F. Dynamic impedances of piles and groups of piles in saturated soils. Comput Struct 2005;83:769-82.

- [40] Wolf JP, von Arx GA, de Barros FCP, Kakubo M. Seismic analysis of the pile foundation of the reactor building of the NPP Angra 2. *Nuclear Eng Design*, 1981;65:329-341.
- [41] Kaynia AM, Mahzooni S. Forces in pile foundations under seismic loading. *J Eng Mech*, 1996;122(1):46-53.
- [42] Mylonakis G, Nikolaou A. Soil-pile-bridge seismic interaction: kinematic and inertial effects. Part I: Soft soil. *Earthquake Eng Struct Dyn* 1997;26:337-359.
- [43] Guin J, Banerjee PK. Coupled soil-pile-structure interaction analysis under seismic excitation. *J Struct Eng* 1998;124(4):434-444.
- [44] Koo KK, Chau KT, Yang X, Lam SS, Wong YL. Soil-pile-structure interaction under SH wave excitation. *Earthquake Eng Struct Dyn* 2003;32:395-415.
- [45] Millán MA, Domínguez J. Simplified BEM/FEM model for dynamic analysis of structures on piles and pile groups in viscoelastic and poroelastic soils. *Eng Anal Bound Elem* 2008, doi:10.1016/j.enganabound.2008.04.003
- [46] Beskos DE. Boundary element methods in dynamic analysis: Part II (1986-1996). *Appl Mech Rev* 1997;50:149-97.
- [47] Padrón LA, Aznárez JJ, Maeso O. BEM-FEM coupling model for the dynamic analysis of piles and pile groups. *Eng Anal Bound Elem* 2007;31:473-484.
- [48] Padrón LA, Aznárez JJ, Maeso O. Dynamic analysis of piled foundations in stratified soils by a BEM-FEM model. *Soil Dyn Earthquake Eng* 2008;28:333-346.
- [49] Clough RW, Penzien J. *Dynamics of structures*. McGraw-Hill, 1993.
- [50] Comité Scientifique et Technique de l'AFPS. *Récommandations AFPS 90*. Presses des Ponts et Chaussées, Paris, France. 1990.
- [51] Vanmarcke EH. *SIMQKE: A program for artificial motion generation*, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA, 1976.



Figure 1: Group of neighbouring pile supported buildings.

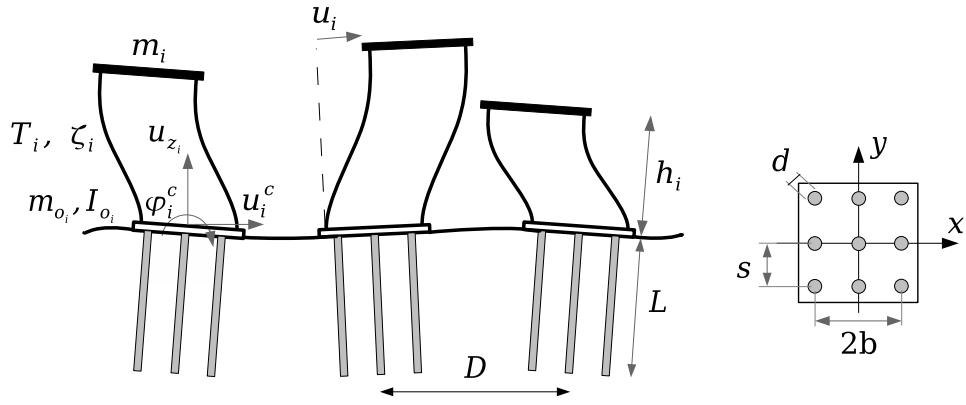


Figure 2: Geometric definition of the problem.

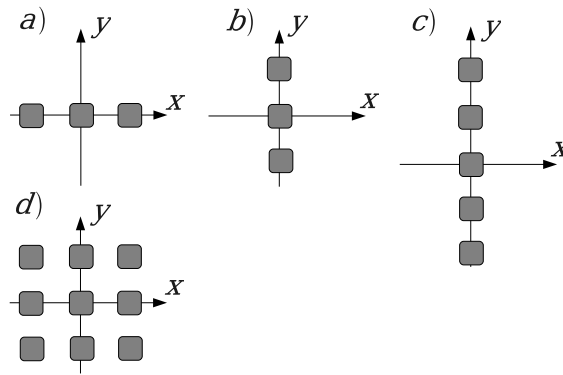


Figure 3: Different relative arrangements of structures considered in this work.

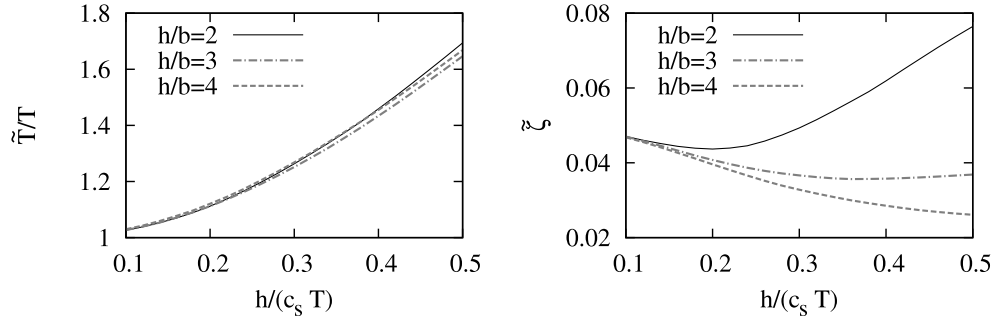


Figure 4: SSI effects measurement for shear structures founded on  $s/d = 5$ ,  $L/d = 15$ ,  $3 \times 3$  pile groups.  $E_p/E_s = 1000$ .

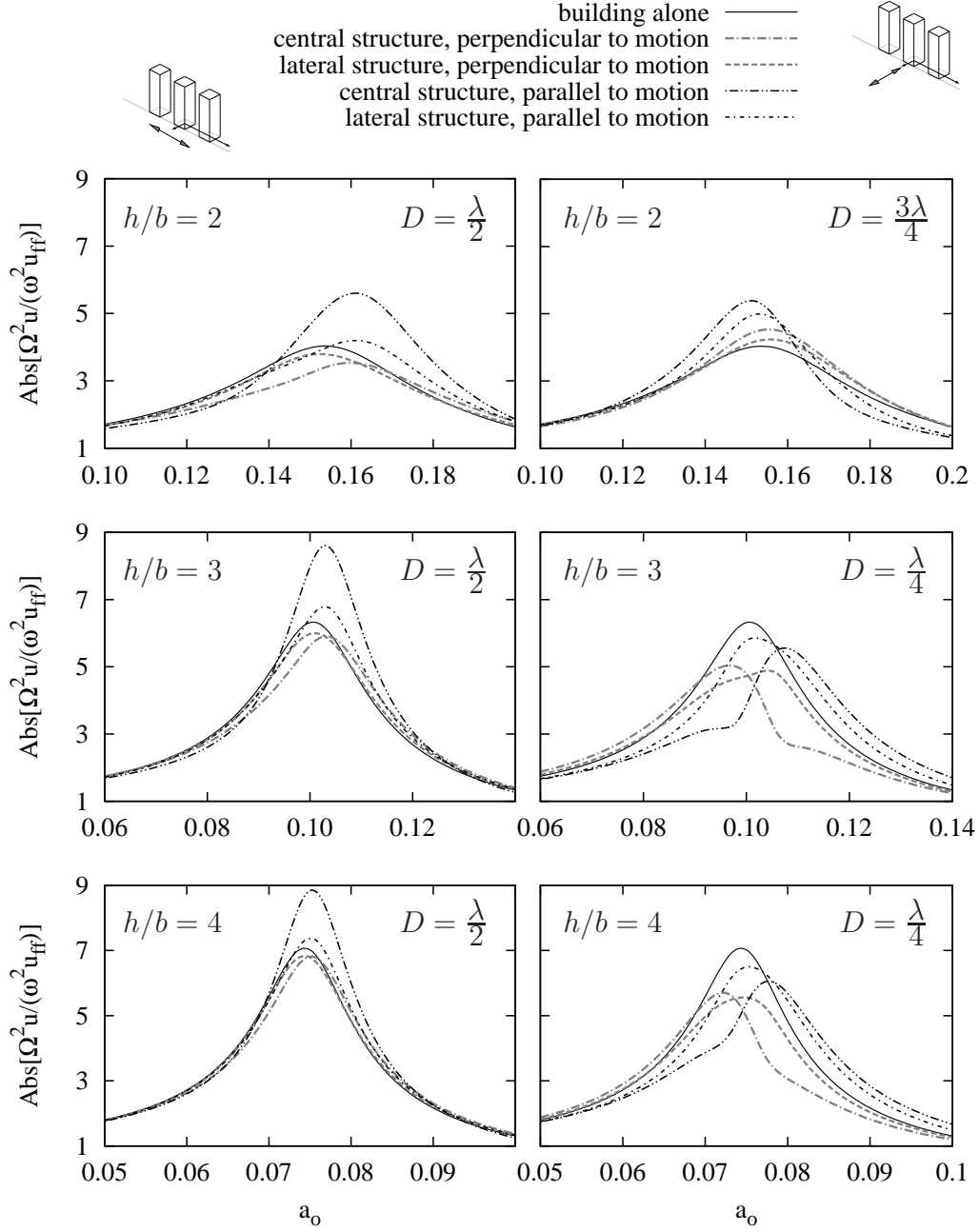


Figure 5: Interaction between three structures of identical fundamental frequencies in terms of their harmonic response spectra for different configurations under S waves.  $E_p/E_s = 1000$

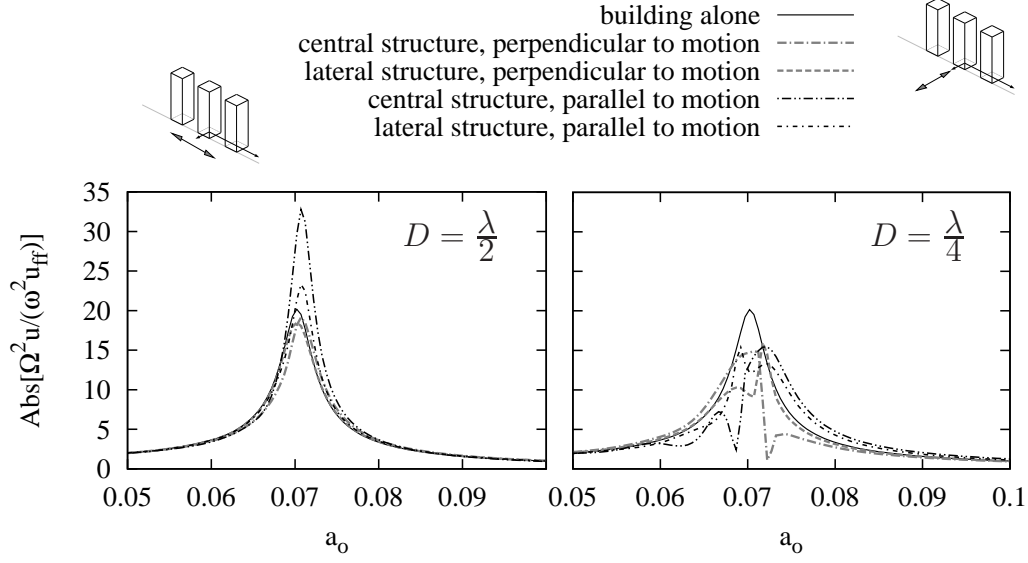


Figure 6: Interaction between three structures of similar fundamental frequencies in terms of their harmonic response spectra under S waves.  $E_p/E_s = 100$ .  $h/b = 4$ . To be compared with bottom plots of fig. 5.

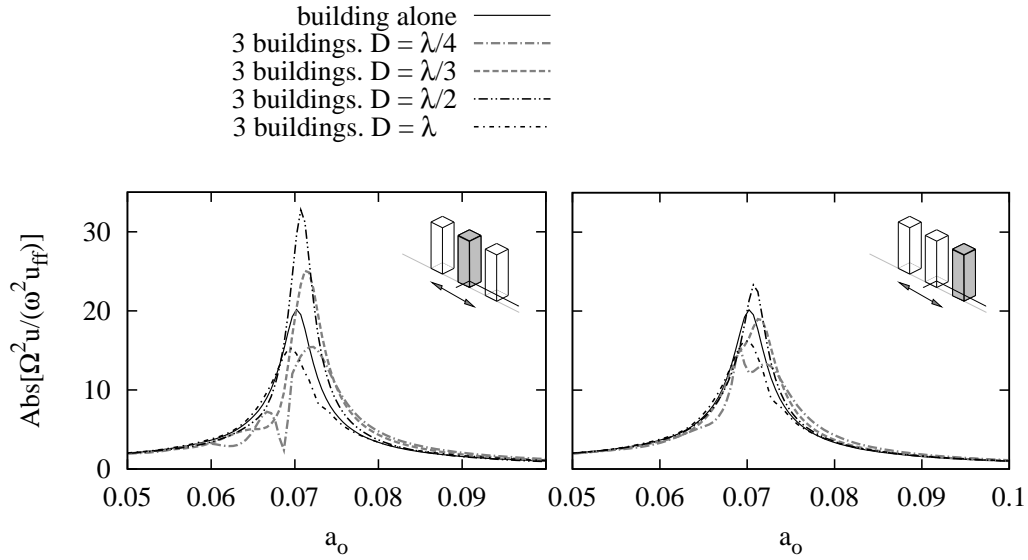


Figure 7: Influence of distance on the interaction between three structures of identical fundamental frequencies under S waves.  $h/b = 4$ ,  $E_p/E_s = 100$

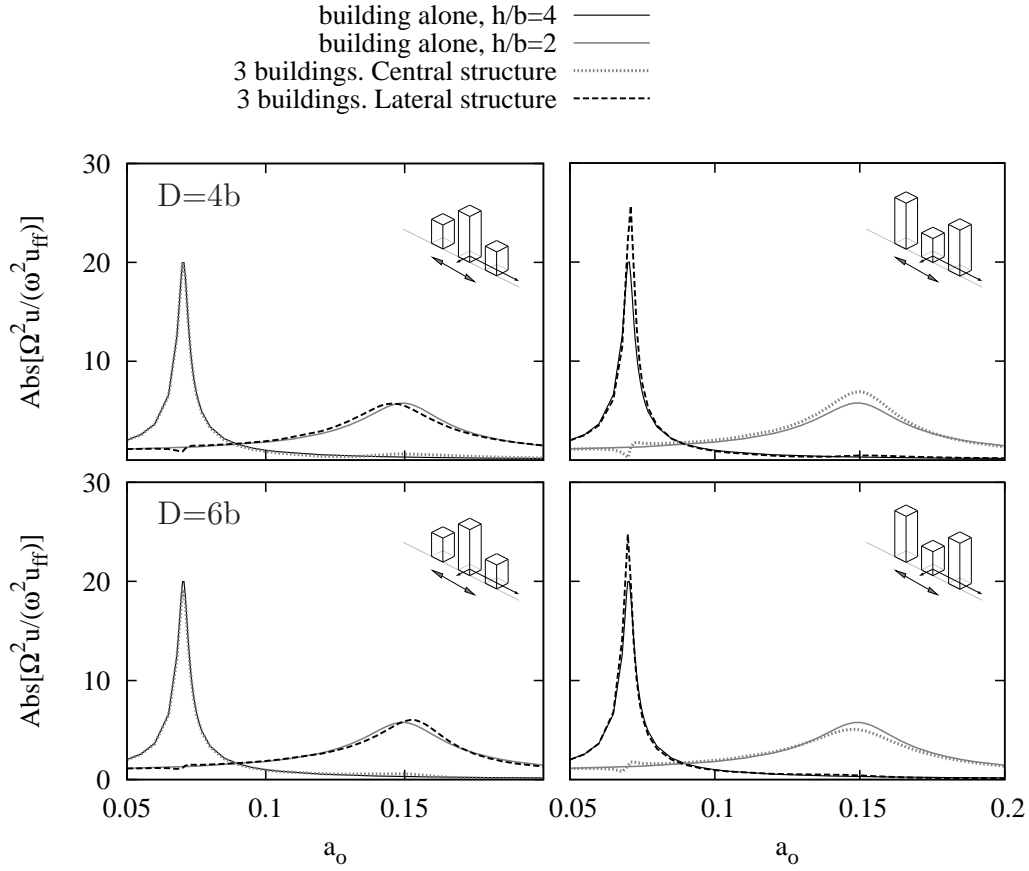


Figure 8: Interaction between three structures of dissimilar fundamental frequencies in terms of their harmonic response spectra for different configurations under S waves. Structures aligned along direction of shaking.  $h/b = 2$  and  $4$ .  $E_p/E_s = 100$ .

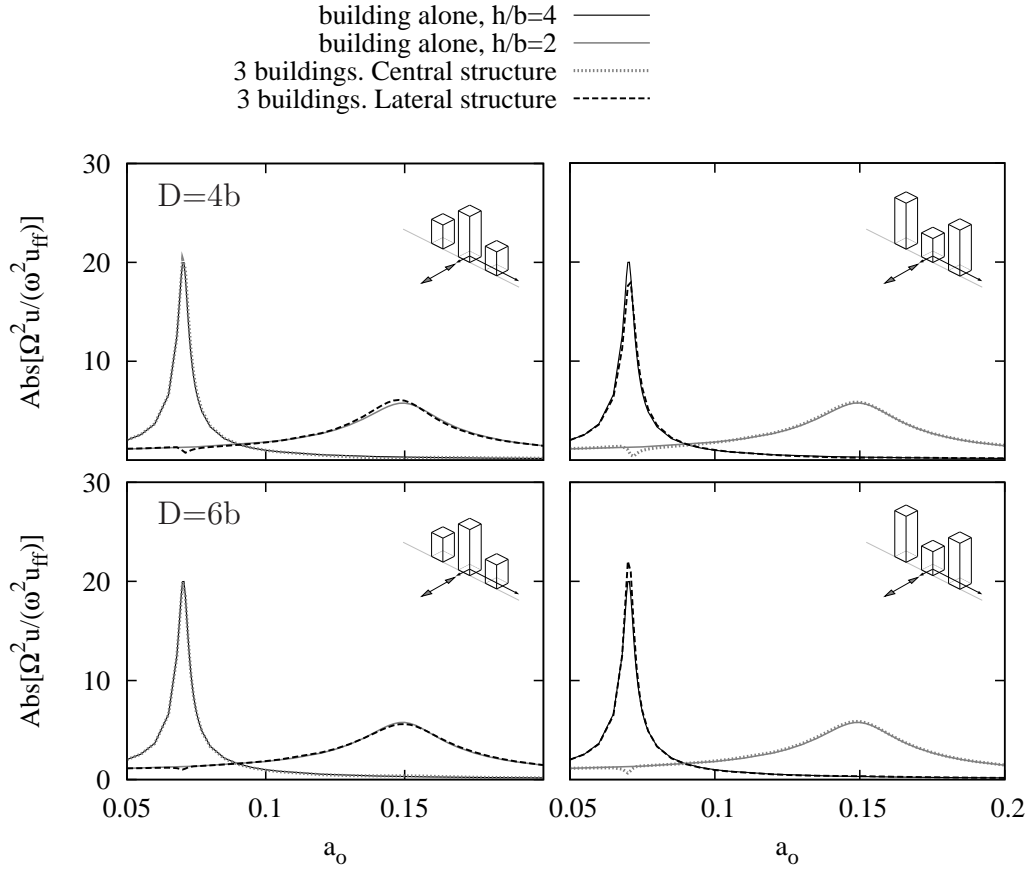


Figure 9: Interaction between three structures of dissimilar fundamental frequencies in terms of their harmonic response spectra for different configurations under S waves. Structures aligned perpendicularly to the direction of shaking.  $h/b = 2$  and  $4$ .  $E_p/E_s = 100$ .

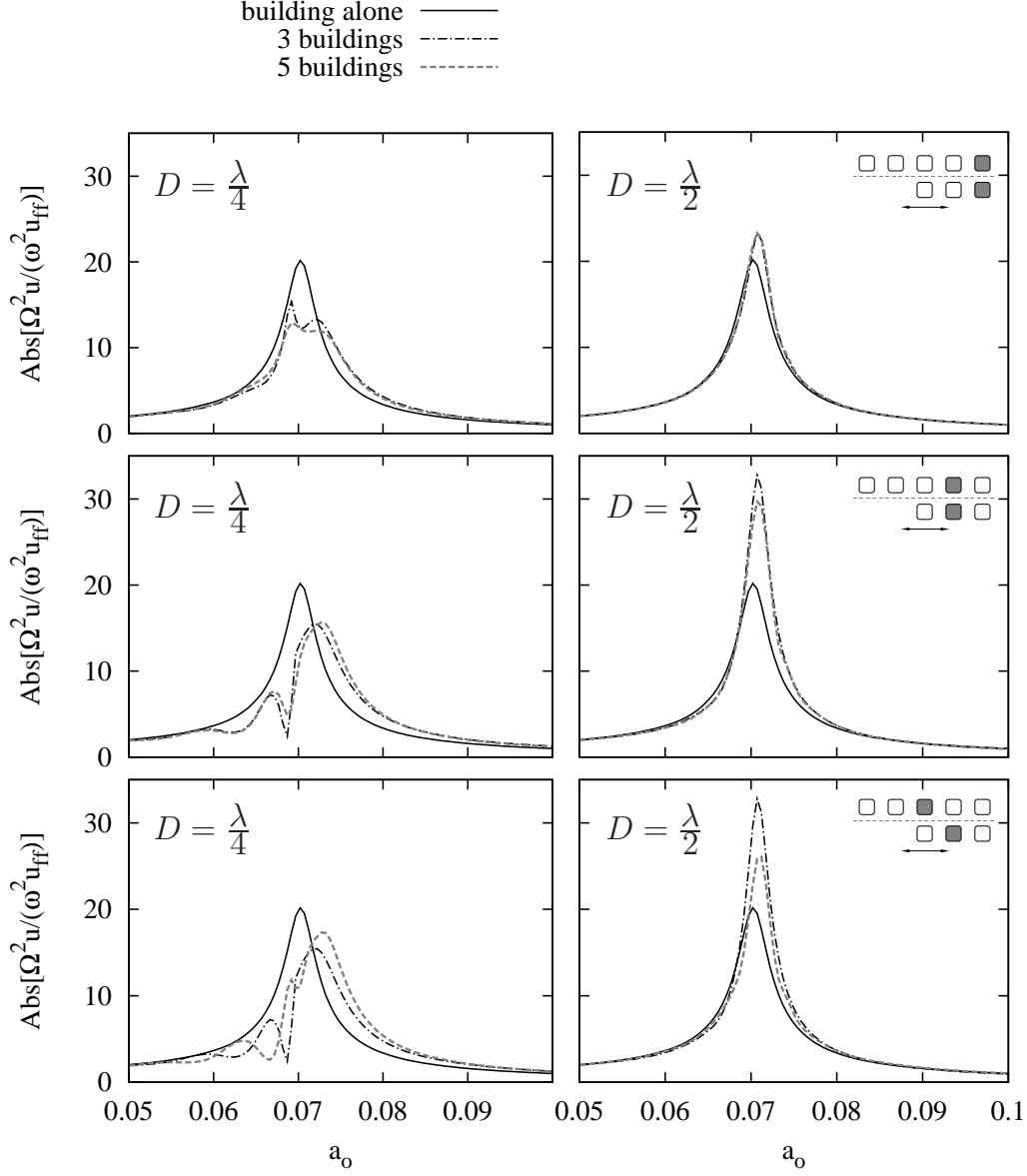


Figure 10: Interaction between three or five structures of similar fundamental frequencies in terms of their harmonic response spectra under S waves. Structures aligned along direction of shaking. Comparison of behavior of structures according to their position in the row.  $h/b = 4$ .  $E_p/E_s = 100$ .

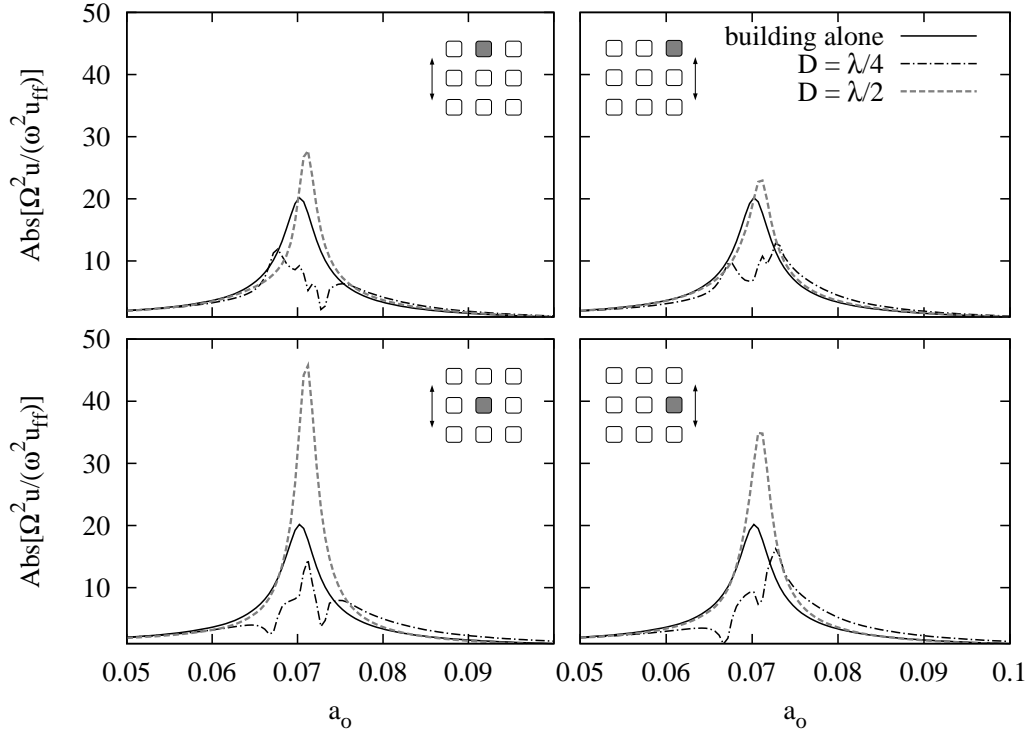


Figure 11: Interaction between nine structures of similar fundamental frequencies in terms of their harmonic response spectra under S waves.  $h/b = 4$ .  $E_p/E_s = 100$ .

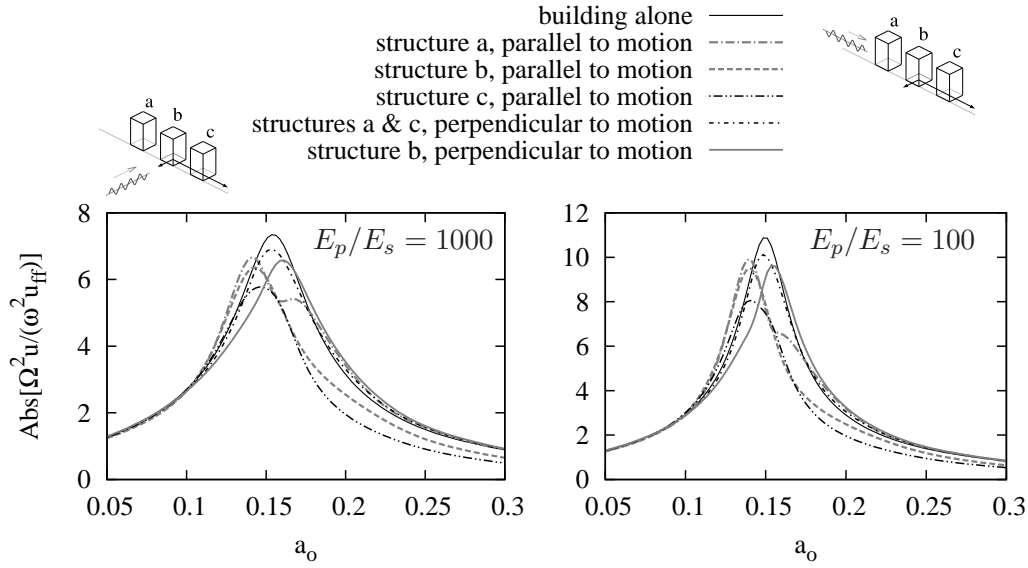


Figure 12: Interaction between three structures of similar fundamental frequencies in terms of their harmonic response spectra under Rayleigh waves.  $h/b = 2$ .  $D = \lambda/2$ .

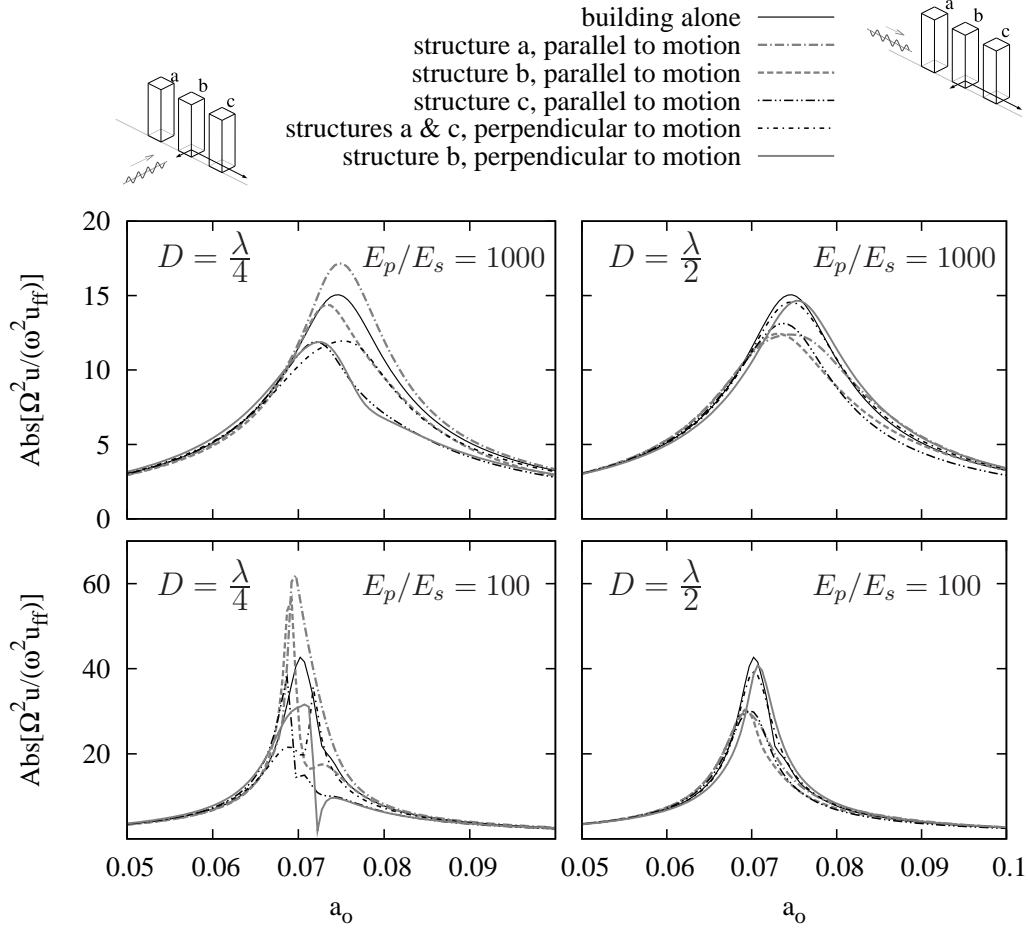


Figure 13: Interaction between three structures of similar fundamental frequencies in terms of their harmonic response spectra under Rayleigh waves.  $h/b = 4$ .

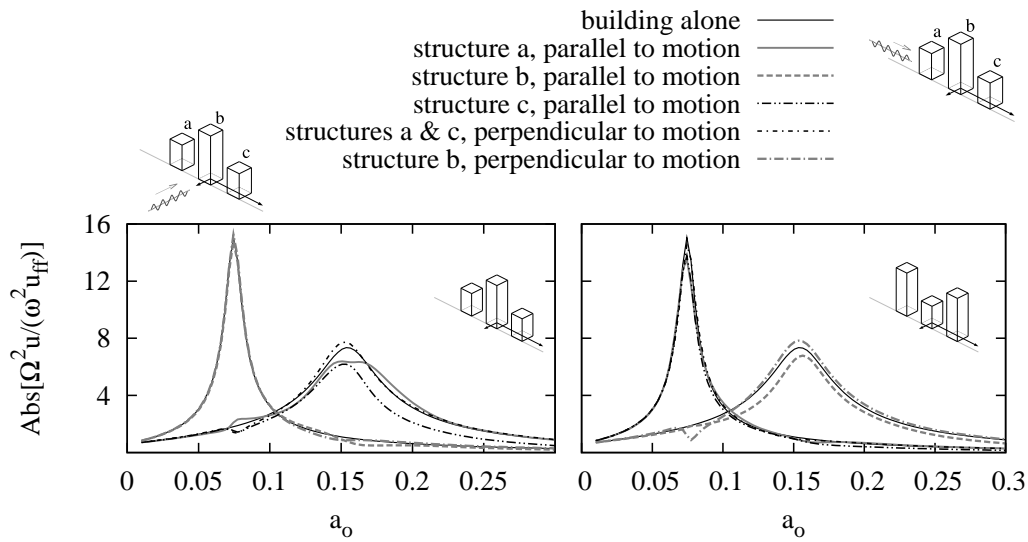


Figure 14: Interaction between three structures of dissimilar fundamental frequencies in terms of their harmonic response spectra under Rayleigh waves.  $h/b = 2$  and  $4$ .  $E_p/E_s = 1000$ .  $D = 4b$ .

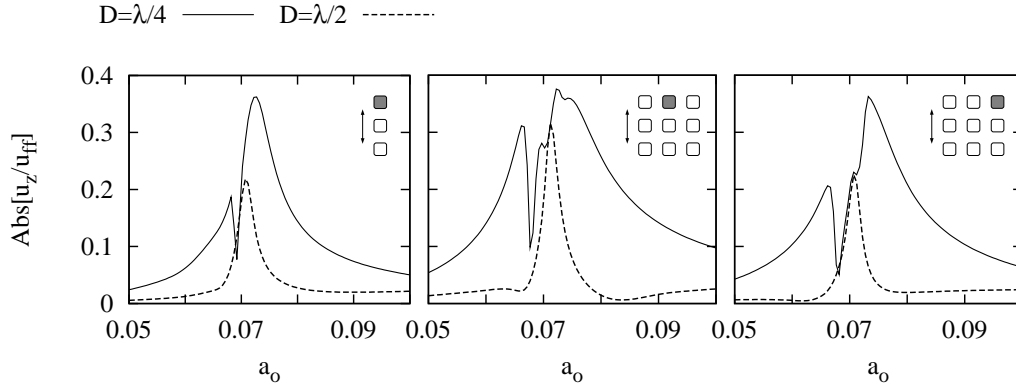


Figure 15: Vertical displacement transfer functions of piled structures under vertically incident S waves due to SSSI.  $h/b = 4$ .  $E_p/E_s = 100$ .

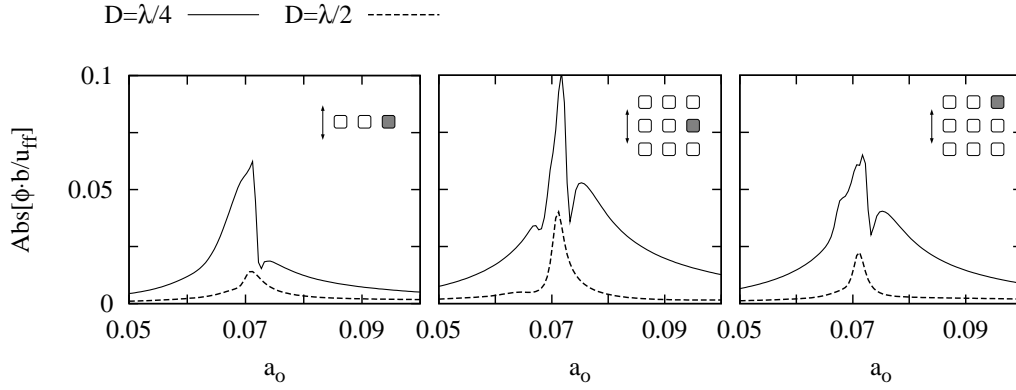


Figure 16: Rotation transfer functions of piled structures under vertically incident S waves due to SSSI.  $h/b = 4$ .  $E_p/E_s = 100$ .

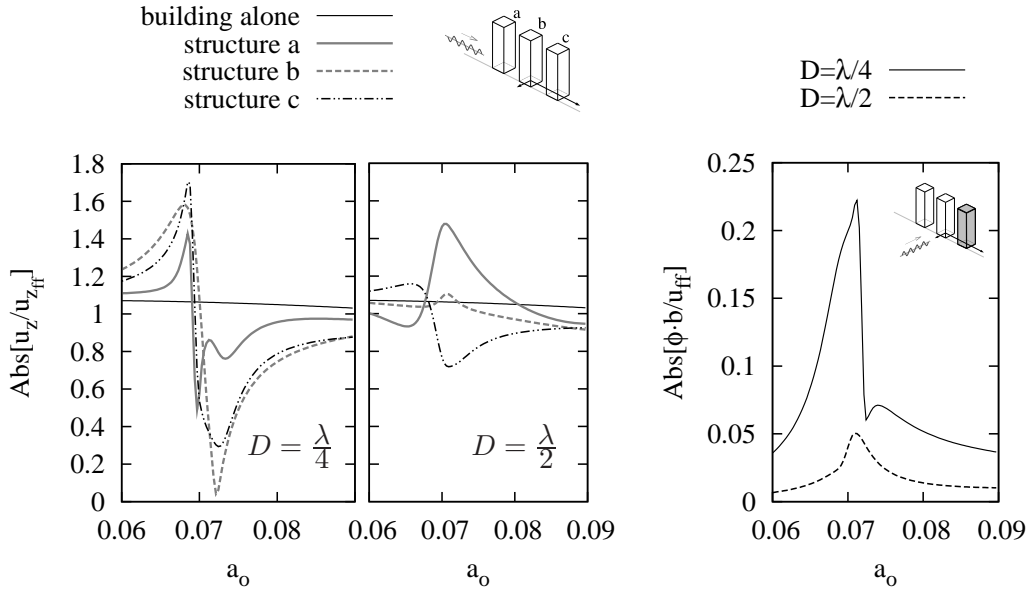


Figure 17: Vertical motion and rotation transfer functions of piled structures under Rayleigh waves due to SSSI.  $h/b = 4$ .  $E_p/E_s = 100$ .

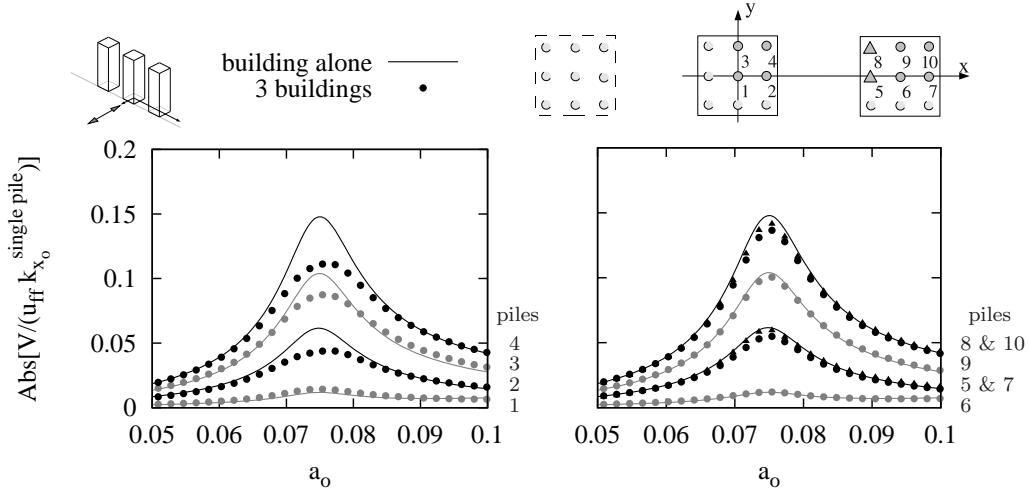


Figure 18: Shear forces on pile heads under S waves. Three buildings aligned perpendicularly to shaking direction.  $h/b = 4$ .  $E_p/E_s = 1000$ .  $D = \lambda/3$ .

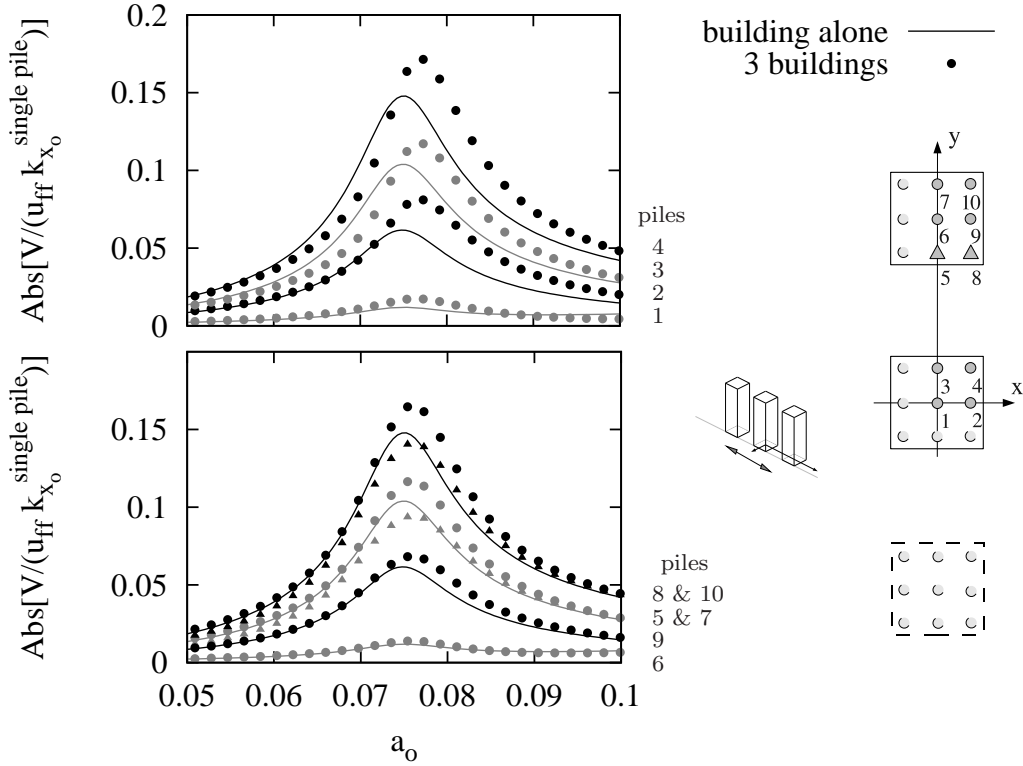


Figure 19: Shear forces on pile heads under S waves. Three buildings aligned parallel to shaking direction.  $h/b = 4$ .  $E_p/E_s = 1000$ .  $D = \lambda/3$ .

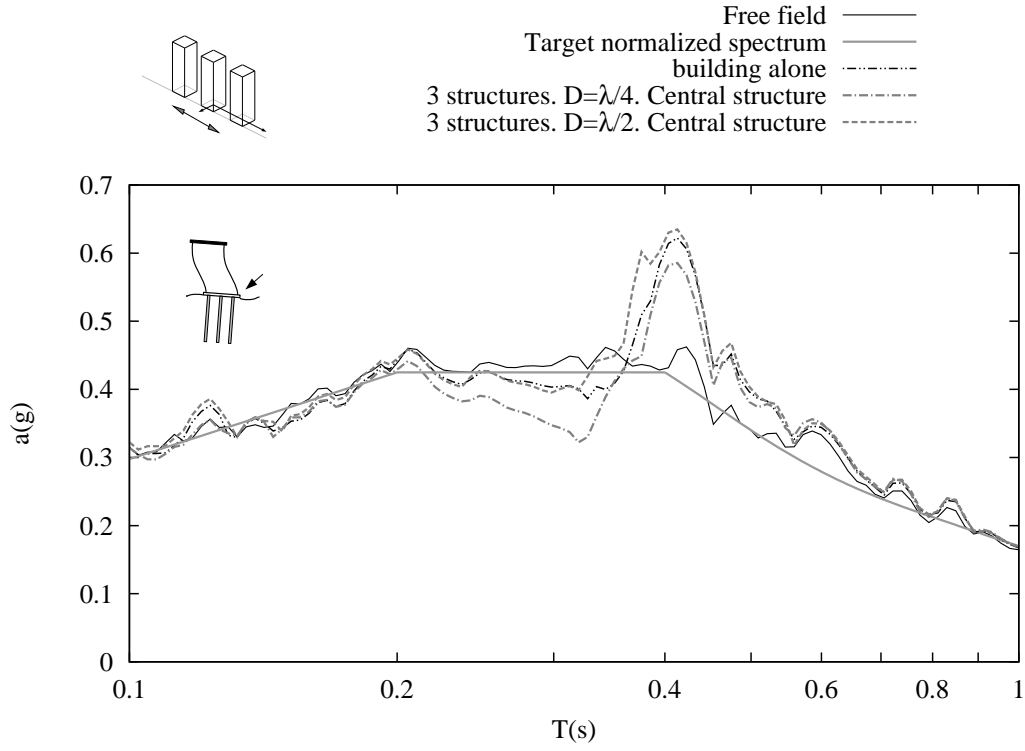


Figure 20: Five per cent-damped acceleration response spectra. Three  $h/b = 4$  structures under S waves. Influence of structure-soil-structure interaction and separation between adjacent structures. Response at pile cap.

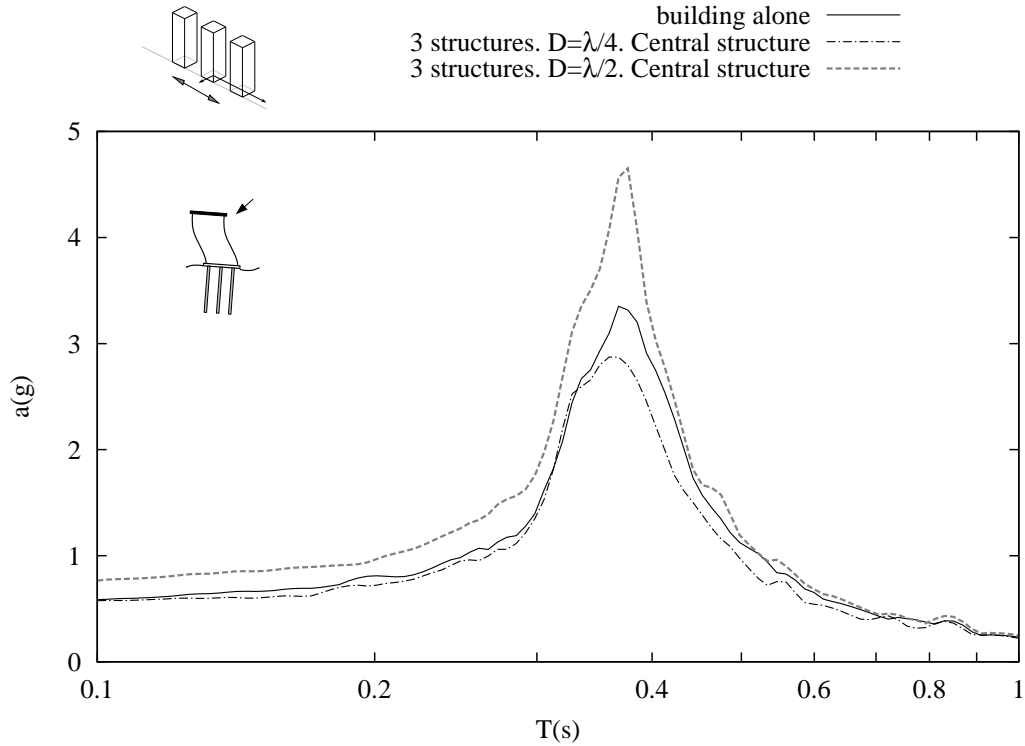


Figure 21: Five per cent-damped acceleration response spectra. Three  $h/b = 4$  structures under S waves. Influence of structure-soil-structure interaction and separation between adjacent structures. Response at slab at height  $h$ .