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PILES-INDUCED FILTERING ACTION AND ITS EFFECT ON THE SEISMIC RESPONSE OF BUILDINGS

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Abstract. *The inertial interaction analysis of a structure founded on piles is usually performed by taking that the support motion at the foundation level is merely that of the free field, thus neglecting the filtering action exerted by piles. By contrast, the existence of frequency filtering is confirmed through works referring to theoretical studies and experimental evidence, even if this effect has not been so far taken into consideration in design practice. Based on analytical and numerical studies, the importance of the filtering effect is highlighted. This paper focuses on the seismic performance of frame buildings, excited alternatively by the filtered input motion or the free-field input motion. The results of these analyses, expressed in terms of top displacements and base shear, allowed to assess the importance of the beneficial effect coming from the piles on the inertial response of the superstructure.*

1 INTRODUCTION

The analysis of the seismic response of a structure is usually performed assuming that the support motion at the foundation level is merely that of the free-field. Contrarily to this assumption, the superstructure interacts with its foundation and the surrounding soil, creating additional soil deformation, so as the foundation motion can differ substantially from that of the free-field. Assuming a linear soil-foundation-superstructure response, the analysis of the complete system can be performed following the three consecutive steps: (i) calculate the motion of the foundation in the absence of the superstructure, i.e. the so-called foundation input motion; (ii) determine the dynamic impedance functions associated to swaying, vertical, rocking and cross swaying-rocking oscillation of the foundation; (iii) evaluate the response of the superstructure supported on the springs and dashpots and subjected to the motion of the foundation determined at the first step. This method is truly convenient as an alternative to fully 3D analyses involving the complete pile-soil-superstructure that are very complex and rarely performed in engineering practice.

The most attractive application of the substructure method is to assume that the support motion equals the free-field seismic motion. By contrast, the free-field motion is filtered out by the piles, especially in the case of soft soils, where piles are recurrently required to increase the bearing capacity of the foundation and/or to reduce settlements [1, 2]. The importance of the filtering effect has been reported in theoretical studies and works referring to experimental evidence, even if this effect has not been so far taken into consideration in engineering practice. The goal of this paper is threefold: (i) to offer an insight into the filtering effect; (ii) to propose a correction to design spectra that can be of assistance for seismic risk design strategies; (iii) to quantify the beneficial effect coming from the piles on the seismic response of structures. Pertaining to this last point, the study has focused on the response of linear reinforced concrete frame buildings excited by either the filtered input motion or the free-field input motion, to quantify the beneficial effect coming from the piles on the seismic performance of non-dissipative structures. In this respect, the results presented herein can be considered representative of the response to earthquakes that are likely to occur during the life-span of the structure.

2 LITERATURE OVERVIEW

The problem of the filtering action exerted by the piles has been examined in the seminal work by Flores-Berrones and Whitman [3]. By means of a Winkler-type model, the authors expressed the ratio of pile and soil accelerations as function of excitation frequency in a closed form solution, for the case of an infinitely-long pile in homogeneous halfspace. As an outcome, piles were found to reduce seismic motion with increasing excitation frequency and pile diameter, whereas an increase in soil stiffness lead to a decrease in the filtering effect.

Gazetas [4] carried out a parametric analysis with reference to end-bearing single piles embedded in different soil profiles. He concluded that the filtering effect is also affected by the degree of soil inhomogeneity.

Fan et al. [5] studied the kinematic behaviour of single piles and pile groups. They found that group effects, although clearly depending on pile spacing, are not relevant for lateral vibrations. By contrast, they may strongly affect the rotational component of motion which, however, lies beyond the scope of this paper.

All the studies above and further studies on the subject [6-11] demonstrate that for motions that are rich in high frequency components, even practically flexible piles may not be able to follow the wavy movements of the free-field. On the other hand, if low-frequency components of the input motion are predominant, the scattered field is weak, and the support motion can be expected to be approximately equal to that of the free-field [12-14]. There is also some experimental evidence supporting the importance of the frequency content [4, 15-17]. The seismic response of structures founded on piles, however, is a complicated problem and it is difficult to delineate the role of pile-soil-interaction. Kawamura et al. [15] have reported the case history of a 7-storey residential building in Japan (Fig. 1). Acceleration recordings were available since 1971 at two groups of points, the 'building line' and the 'soil line'. Comparing the records at the two lines during 20 earthquakes, they found that the maximum amplification at the ground surface was about 1.5 that recorded at the base slab of the building. They also plotted the Fourier spectral ratio between the building line and the soil line at the level of the base slab pertaining to a particular earthquake event (see again Fig. 1); for structural periods smaller than 0.3 s the ratio of the two accelerations recorded during the event at hand is 0.5 as an average. For increasing structural periods the Fourier spectral ratios have a tendency to approximate unity. It is argued from this case history that the high frequency components of the free-field motion are filtered out by the pile-soil-superstructure interaction.

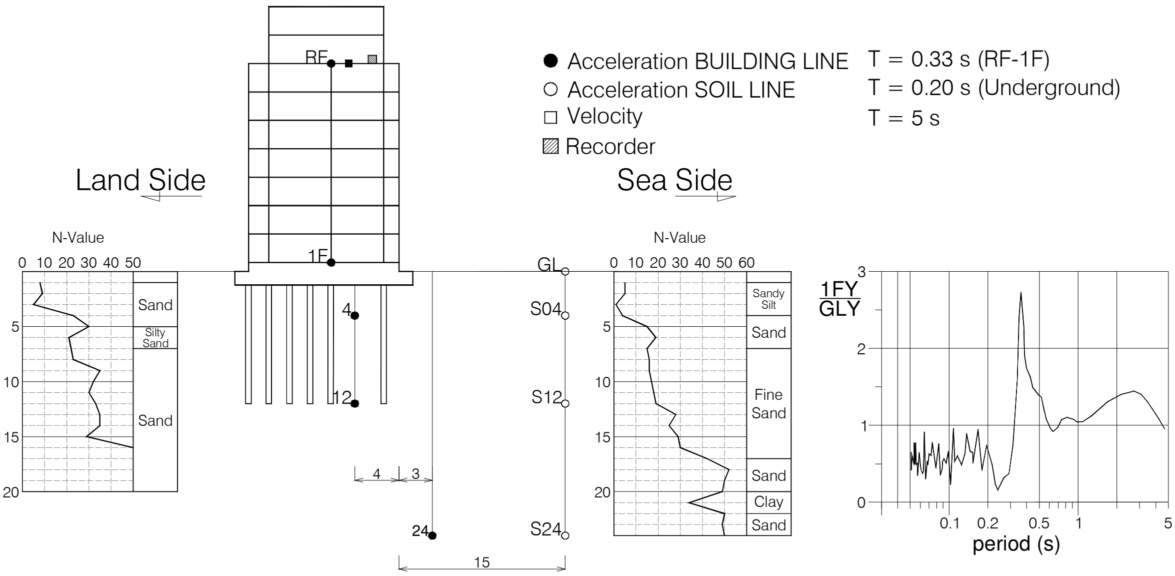

Figure 1. Case history of a 7-storey residential building in Japan (after Kawamura et al. [15])

Gazetas [4] has described an example of (large diameter) bored piles for which acceleration recordings were available at both the pile-cap and at the ground surface on a far-distant axis representing free-field conditions. By comparing the acceleration spectra of the two motions he noticed that the spectrum of the far distant motion included frequency contents higher than those at the pile cap, in agreement with the conclusion of the study by Kawamura et al. [15].

The limited amount of experimental evidence demonstrates that the frequency content of the input signal might exert a remarkable influence on the support motion.

3 THE MECHANISM OF FILTERING EFFECT

Flores-Berrones and Whitman [3] showed that in the homogenous halfspace the ratio between the acceleration atop a fixed-head infinitely long pile, a_p, and that at the soil surface, a_s, is given by:

$$I_u = \frac{a_p}{a_s} = \Gamma \tag{1}$$

where Γ is an interaction factor which may be approximately expressed as:

$$\Gamma = \frac{4\lambda^4}{4\lambda^4 + q^4} \tag{2}$$

in which q ($=\omega/V_s$) is the wave number of the harmonic SH wave travelling in the soil, and λ is the well-known Winkler parameter:

$$\lambda = \left(\frac{k + i\omega c}{4E_p I_p} \right) \tag{3}$$

The stiffness of the springs k may be taken as proportional to soil stiffness E_s by a coefficient δ, which typically assumes values close to unity [18], whereas the dashpot coefficient is expressed as [19]:

$$c = 6\omega^{-\frac{1}{4}} \rho_s V_s^{\frac{5}{4}} d^{\frac{3}{4}} + 2\beta_s k / \omega \tag{4}$$

Compared to the original formulation, the above derivations neglect the inertia contribution due to the pile mass. Eq. (2) is plotted in Fig. 2a against the traditional dimensionless parameter $a_0 = \omega d/V_s$, accounting for excitation frequency, for different values of stiffness ratio E_p/E_s. Pile-to-soil acceleration ratio is always smaller than unity (i.e. piles play always a beneficial role in reducing the seismic motion that excites the superstructure) and decreases with frequency. This effect is physically due to the resistance that the pile offers in adapting to the short wavelengths of the soil, as the dimensionless frequency a_0 may be interpreted as the ratio of pile diameter d and soil wavelength λ_s ($=V_s/\omega$). Moreover, at a given frequency pile-soil acceleration ratio is progressively smaller as pile-soil stiffness ratio increases. The physical interpretation of this phenomenon deserves special discussion as reported below.

The ability of the pile to follow soil displacements is well represented by the characteristic wavelength:

$$\lambda_p = d \left(\frac{E_p}{E_s} \right)^{\frac{1}{4}} \tag{5}$$

which encompasses both diameter and pile-soil stiffness ratio. Eq. (5) can be substituted into Eq. (2), to express λ as a function of E_s. Finally, assuming $\delta = 1$, the amplitude of Γ can be expressed as:

$$\Gamma = \left[1 + \frac{1}{20} \left(\frac{\omega \lambda_p}{V_s} \right) \right]^2 \tag{6}$$

The new dimensionless parameter $\omega\lambda_p/V_s$ can be viewed as the ratio of pile characteristic wavelength and soil wavelength. Eq. (6) is plotted in Fig. 2b against such parameter. It can be seen that the larger is the characteristic wavelength of the pile compared to the soil wavelength, the greater is the amount of the filtering effect. For comparison, results from Fan et al. [5] are plotted in the graph, according to the new normalization. Results undertaken from finite elements carried out in the frequency domain have been also added for comparison.

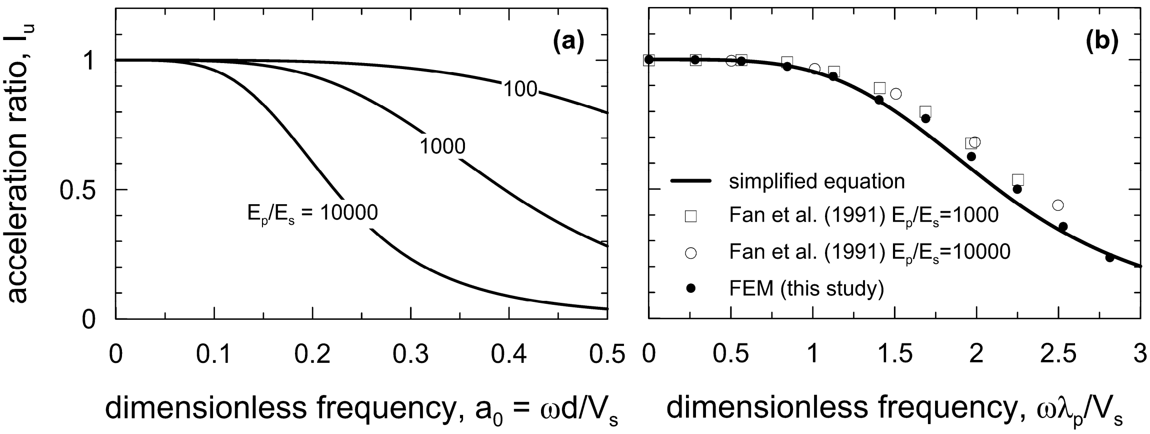

Figure 2. Pile-soil acceleration ratio as function of different dimensionless frequency parameters

4 PARAMETRIC ANALYSIS FOR FILTERING EFFECT

To investigate quantitatively the filtering effect exerted on the Foundation Input Motion by a piled foundation, a comprehensive set of Finite Element analyses has been performed. Owing to the second-order influence of group effects for lateral vibration [5], a single pile embedded in a two-layer soil has been considered, as shown in Fig. 3a. Harmonic S-waves applied at the bedrock level and propagating up and down constitute the seismic excitation.

The total height of the soil deposit, H, is set equal to 30 m, whereas the pile has diameter d = 1 m, length L = 20 m and Young's modulus Ep = 30 GPa. Soil and pile density are set to 1.75 and 2.5 Mg/m^3, respectively, whereas the value of soil Poisson's ratio is 0.4.

Although the problem is 3D, the geometry is axisymmetric whereas the load is antisymmetric. To simplify the analysis, stresses and displacements are expanded into a Fourier series in the circumferential direction, according to the technique introduced by Wilson [20]. For the example at hand, only the first-order term of the series is needed. Owing to this procedure, the original three-dimensional problem is conveniently reduced to a 2D one, as shown in Fig. 3b.

Numerical analyses were conducted using the commercial FE code ANSYS. Four-noded axisymmetric 2D elements are used to mesh soil and pile. The assumption of a line of antisymmetry implicitly implies the use of 'periodic' or 'tied' boundaries. As a consequence, the model under examination does not allow for the transmission of outgoing waves generated at the pile-soil interface, which remains trapped inside the model. A common procedure to check the amount of inaccuracy coming from this choice is that originally suggested by Zienckiewicz et al. [21] for both linear and non linear models. It consists of comparing the results of the complete model with those predicted by the free-field conditions at the location of the boundary. For the problem under examination, Di Laora et al. [22] have shown that the assumption of tied boundaries provides sufficient accuracy, provided that the width of the entire model is large enough. To this aim, the lateral boundary of the model was set at 400 d from the pile axis. Vertical displacements are restrained along the lateral boundary of the mesh, while nodes at the base of the model are restrained to both horizontal and vertical directions to represent a rigid bedrock. The vertical size of the elements is constant and set to 0.5

diameters, whereas the horizontal size is 1/8 pile diameters at pile-soil interface, thereby increasing with radial distance up to 1.5 diameters at the free-field. The analyses performed in the parametric study were carried out in the frequency domain, first extracting vibrational modes with frequency up to 25 Hz, each having a pre-specified level of viscous damping. In this way the drawbacks stemming from use of common energy loss formulations such as Rayleigh damping were avoided. An FFT algorithm was employed to transfer responses from the frequency to the time domain and vice versa. Transient response is investigated by using real signals, selected from an Italian database [23] and the European database by Ambraseyes et al. [24]. Time histories and Fourier spectra of the above events are reported in Di Laora and de Sanctis [25].

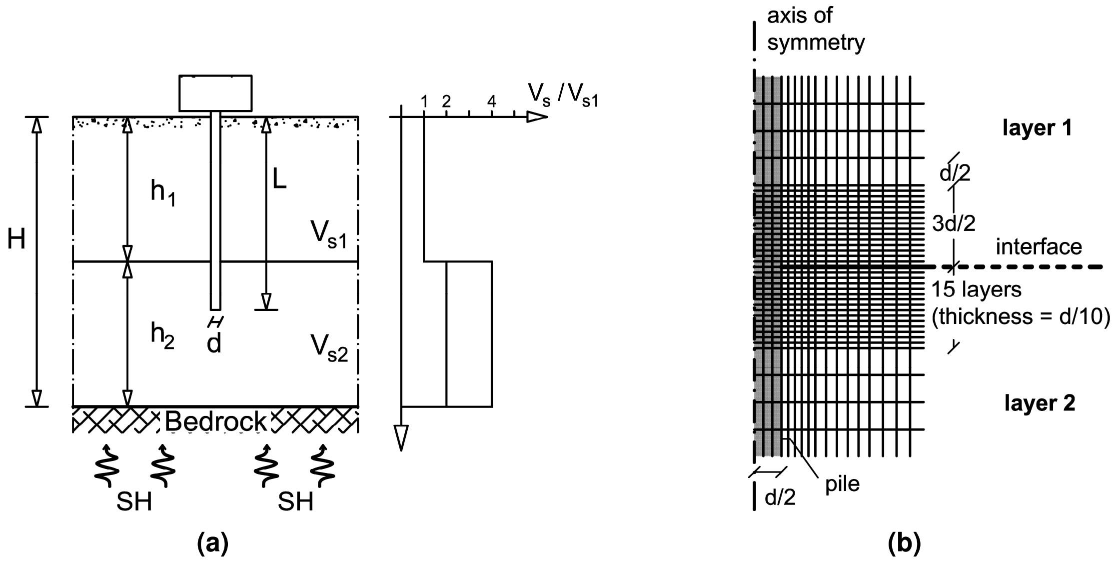

Figure 3. (a) Problem under consideration and (b) Finite Element mesh employed in the analyses.

Some results of the parametric analysis are illustrated in Fig. 5, where the ratio ξ of the spectral acceleration of the filtered motion, $S_{a,p}$, over that of the free field, $S_{a,s}$, is plotted against the structural period. For a given subsoil profile and any particular earthquake event it is possible to recognize two critical points: (i) that corresponding to the minimum value of the spectral acceleration ($T_{\min}$, $\xi_{\min}$); (ii) that pertaining to the structural period after which the filtering effect becomes negligible (T_{crit}, ξ_{crit}). The second point can be identified with the point of maximum curvature of the spectral ratio function, whose ordinate can be considered nearly coincident with unity, so that the coordinates of the second point can be assumed to be (T_{crit}, 1). The most interesting result is that for any subsoil the structural periods T_{crit} and $T_{\min}$ are practically unaffected by the earthquake event. On the other hand, the $\xi_{\min}$ is clearly dependent on the frequency content of the input signal. The spectral acceleration ratio at $T = 0$, ξ_0, is a purely kinematic interaction factor and is also strongly affected by the frequency content.

The result of the parametric analysis can be conveniently condensed in the form of mean spectral acceleration ratios, as shown in Fig. 6. It is worthy to note that for both V_{s1} = 50m/s and V_{s1} = 100 m/s, the mean spectral ratios have un upper bound, corresponding to the homogeneous soil deposit. In this case, in fact, the contribution to the filtering effect due to the kinematical restraint exerted by the lower stiffer vanishes. At the same time, the impedance contrast has only a weak effect on the structural periods $T_{\min}$ and T_{crit}. As a result, Fig. 6 can be further synthesized by referring only the upper bound represented by the homogenous subsoil.

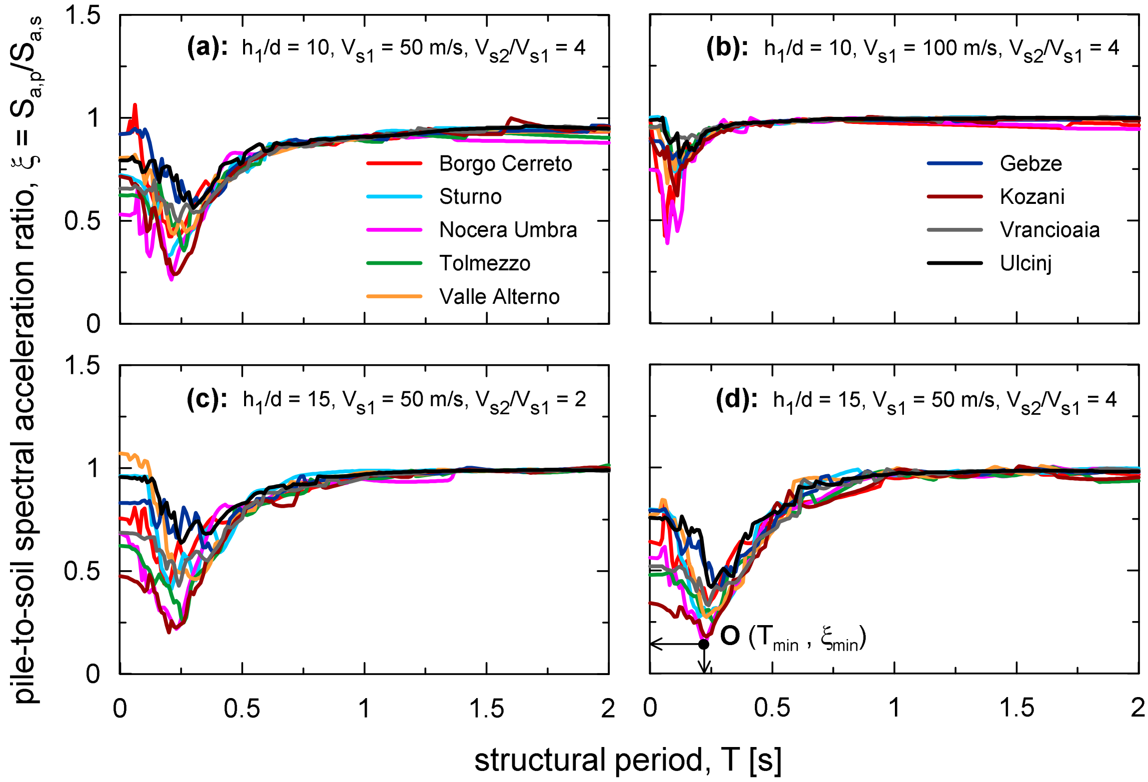

Figure 5. Pile-head spectral acceleration over that of the free-field.

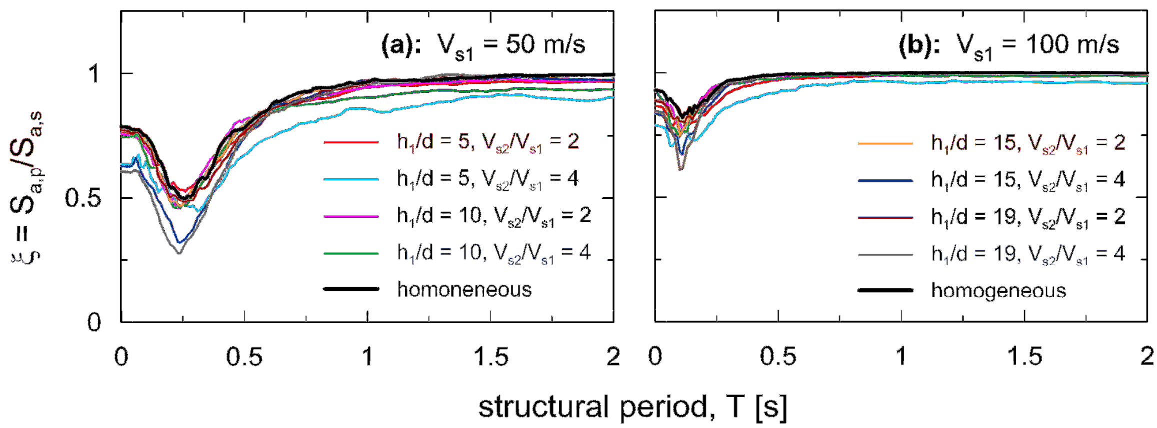

Figure 6. Mean spectral ratios for the subsoils considered in the parametric study.

It is straightforward to recognize that the structural periods T_{min} and T_{crit} can be expressed through the linear correlations:

$$T_{min} = 12\frac{d}{V_s} \tag{7}$$

$$T_{crit} = 3.5\, T_{min} \tag{8}$$

It is also easy to verify that the reduction parameters ξ_0 and ξ_{min} pertaining to the ratio between the mean spectral functions satisfy the equations:

$$\xi_0 = \left(1 + 0.15 \frac{\lambda_p}{V_{s1}} \cdot 10 rad/s\right)^{-1} \tag{9}$$

$$\xi_{min} = 2.5\, \xi_0 - 1.5 \tag{10}$$

For further details about Eqs (9, 10) the reader can refer to Di Laora & de Sanctis [25]. All the ingredients are now available to define reduced design spectra. It is suggest to adopt the reduction factor for acceleration spectra defined by the following equations:

$$\begin{cases} \xi(T) = \xi_0 - \dfrac{(\xi_0 - \xi_{min})}{T_{min}^2} T^2 = \xi_0 - (\xi_0 - \xi_{min}) \left(\dfrac{T}{T_{min}}\right)^2; & T \le T_{min} \\ \xi(T) = 1 - (1 - \xi_{min}) \left(\dfrac{T_{crit} - T}{T_{crit} - T_{min}}\right)^2; & T_{min} \le T \le T_{crit} \end{cases} \tag{11a,b}$$

Eqs (11a,b), also plotted in Fig. 6 for two different values of the shear wave velocity V_{s1}, may be conveniently adopted to evaluate the seismic vulnerability of existing structures or to evaluate efficiently the seismic response of a structure from the design standpoint. The same criterion can be also adopted within the framework of the substructure method, whatever the structure be modeled as a dissipative or a non dissipative system, to evaluate the opportunity of carrying out the computational cost associated to the pile-soil kinematic interaction analysis.

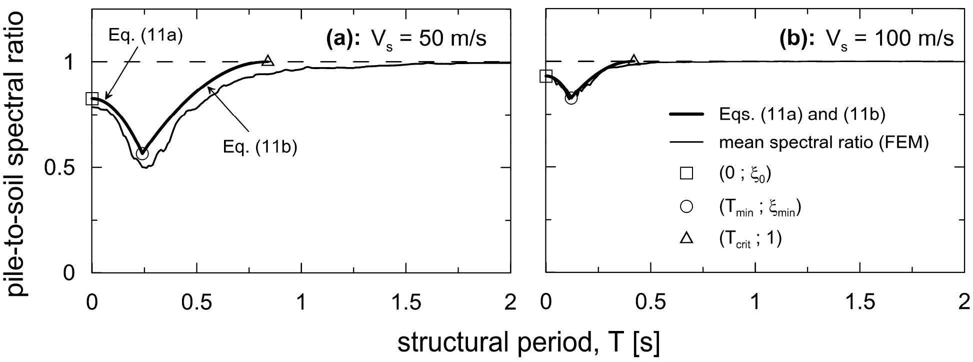

Figure 7. Mean spectral ratios for homogeneous soil conditions and corresponding proposed spectral reduction.

5 INERTIAL INTERACTION ANALYSIS

The study discussed in section 4 has been focused on linear elastic soil behavior and an ideal subsoil consisting of a two layer deposit underlain by a rigid layer. It is therefore believed that further investigations are needed, particularly for subsoil conditions other than those considered in this work, to confirm the general validity of the equations for design spectrum reduction. Before anything else, however, the potential coming from the piles in reducing the seismic demand has to be verified against real structures, i.e. Multi Degree Of Freedom (MDOF) systems, that can behave quite differently from the Single Degree Of Freedom (SDOF) systems. To address this point, the study has been focused on the response of linear frame buildings excited by either the filtered input motion or the free-field input motion, to quantify the beneficial effect coming from the piles on the seismic performance of non-dissipative structures.

Five planar reinforced concrete (RC) frames have been considered for such analyses (Fig. 7), each of these assumed to be representative of a 3D structure having identical 2D frames 4 meters spanned one each other. Concrete having characteristic compressive cylinder strength f_{ck} equal to 25 MPa and steel reinforcement with characteristic yield strength f_{yk} equal to 450 MPa have been considered.

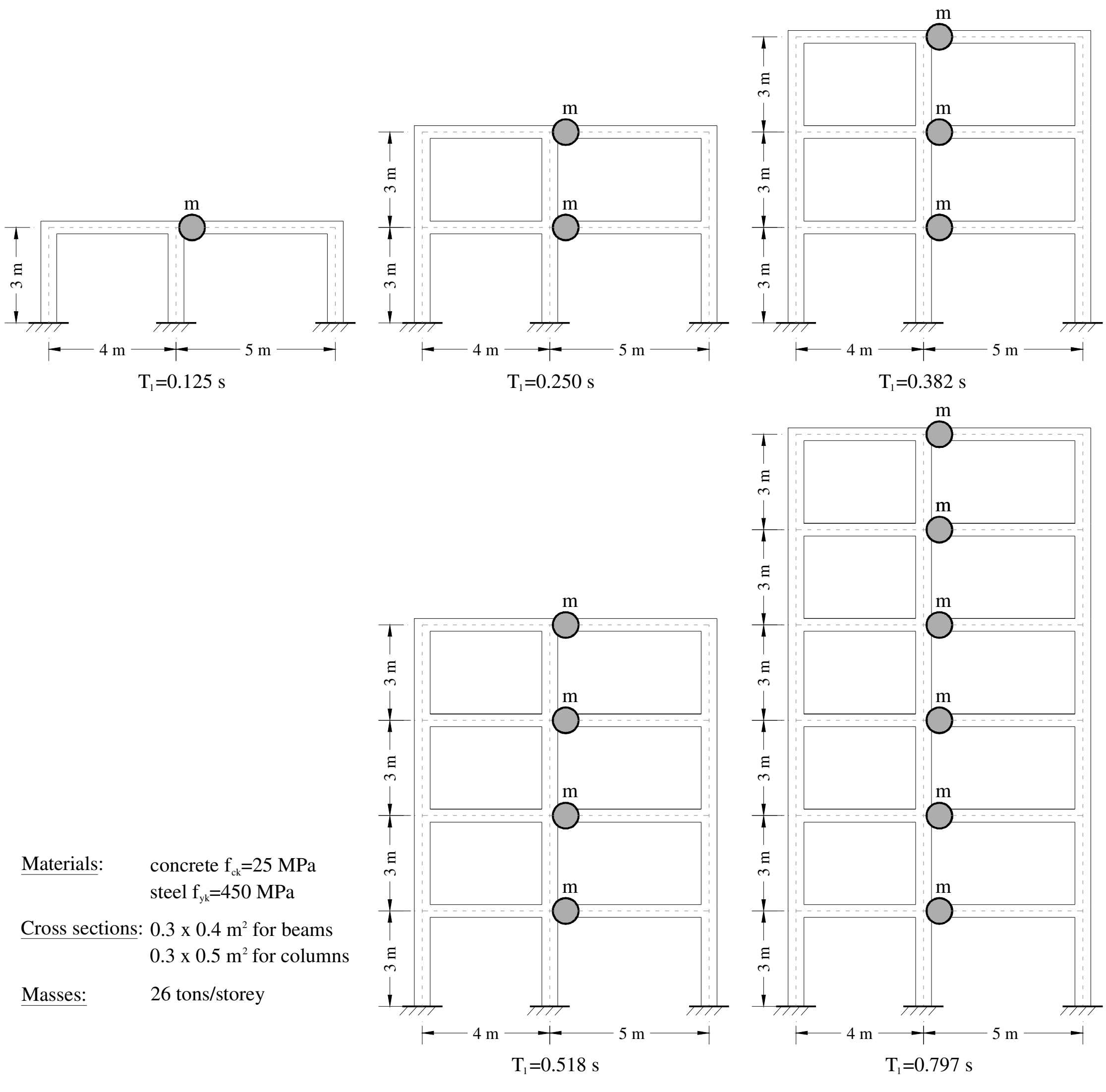

Figure 8. The five RC frame structures considered as case-studies for the dynamic analyses.

The structural design has been performed according to Eurocodes 2 and 8 [26, 27], using the lateral force method of analysis and assuming the following input data: (i) residential use of the buildings; (ii) structures located in L'Aquila (central Italy); (iii) ductility class DCM (medium); (iv) 50 years of lifetime; (v) ground type C; (vi) one way RC slabs subjected to characteristic permanent structural, permanent non-structural and variable actions equal to 1.8 kN/m^2, 2.0 kN/m^2 and 2.0 kN/m^2 respectively; (vii) storey masses (related to both self-weight of elements and above additional loads) of 26 tons.

Frames differ in terms of number of storeys (1, 2, 3, 4 and 6), whereas they have the same interstorey height (3 m) and cross sections' dimensions (0.3x0.4 m^2 and 0.3x0.5 m^2 for beams and columns, respectively). A lumped mass model has been built for each frame. Masses are ideally concentrated in the corresponding center of masses of each storey. The fundamental periods of vibration are indicated in Fig. 8, falling in the range [0.13, 0.80 s].

Linear time-history analyses have been performed with SAP2000 [28] for each of the above frame structures under the action of the 9 natural earthquakes previously discussed. For any particular earthquake event, the structure has been excited by considering the free-field input motion and then by using the filtered signal. This has been done with reference to 3 subsoil configurations (i.e. respectively h_1/d=5, V_{s1}=50 m/s, V_{s2}/V_{s1}=4; h_1/d=10, V_{s1}=50 m/s, V_{s2}/V_{s1}=4 and h_1/d=10, V_{s1}=100 m/s, V_{s2}/V_{s1}=2) for a total of 9x2x3=54 analyses. Roof displacement and base shear time-histories have been recorded for each analysis as output results. Then the structural demand reduction due to the pile filtering effect has been evaluated assessing: (i) the absolute value of the ratio between maximum roof displacements corresponding to pile filtered and free-field conditions respectively; (ii) the similar ratio expressed in terms of base shear.

It is worth noting that these indexes are such that the smaller value corresponds to a higher reduction of the seismic demand on the superstructure due to the beneficial presence of the piles. All the values resulted from the analyses have been graphically synthesized in Fig. 9 as a function of the previously cited dimensionless parameter $\omega_s d/V_{s1}$, ω_s being an average circular frequency defined as:

$$\omega_s = \frac{2\pi f_m + 2\pi f_p}{2} \tag{12}$$

where f_m is the mean frequency as defined by Rathje et al. [29] and f_p the predominant frequency (corresponding to the maximum spectral acceleration).

Different indicators (circle, rhombus, square) refer the data to the three different subsoil conditions. The following comments can be drawn:

a. the values of response reduction in terms of base shear and top displacement are very close to each other; actually they derive from linear time-history analyses of regular, first-mode dominated structures, therefore such similarity was expected;
b. all the ratios resulted to be less than or equal to 1, demonstrating that the way in which piles alter the seismic demand imposed to the superstructure is never harmful for the latter, indeed is beneficial in most cases;
c. the general trend is that the demand reduction remains almost constant or increases with the dimensionless frequency $\omega_s d/V_{s1}$, consistently with Fig. 2(a);
d. the first subsoil condition (see circles) generally resulted in the largest response reduction, physically due to the lower value of the soil stiffness and the shallower position of the layer interface;
e. the second (rhombuses) subsoil type also corresponds to a significant reduction of structural demand for all the cases analyzed;
f. for both first (circles) and second (rhombuses) subsoil conditions, the highest reduction occurs for the two-storey frame (T_1=0.250 s), as expected from Fig. 7(a);
g. the third subsoil condition (h_1/d=10, V_{s1}=100 m/s, V_{s2}/V_{s1} = 2; see squares) resulted in a significant reduction of displacements and forces demand only for the one-storey building (T_1 = 0.125 s). This is consistent with Fig. 7(b) where, with reference to a homogeneous subsoil having V_s = 100 m/s, it is shown that appreciable reduction of the spectral demand occurs for vibration periods around 0.125 s, quickly going to be negligible when the period gets longer.

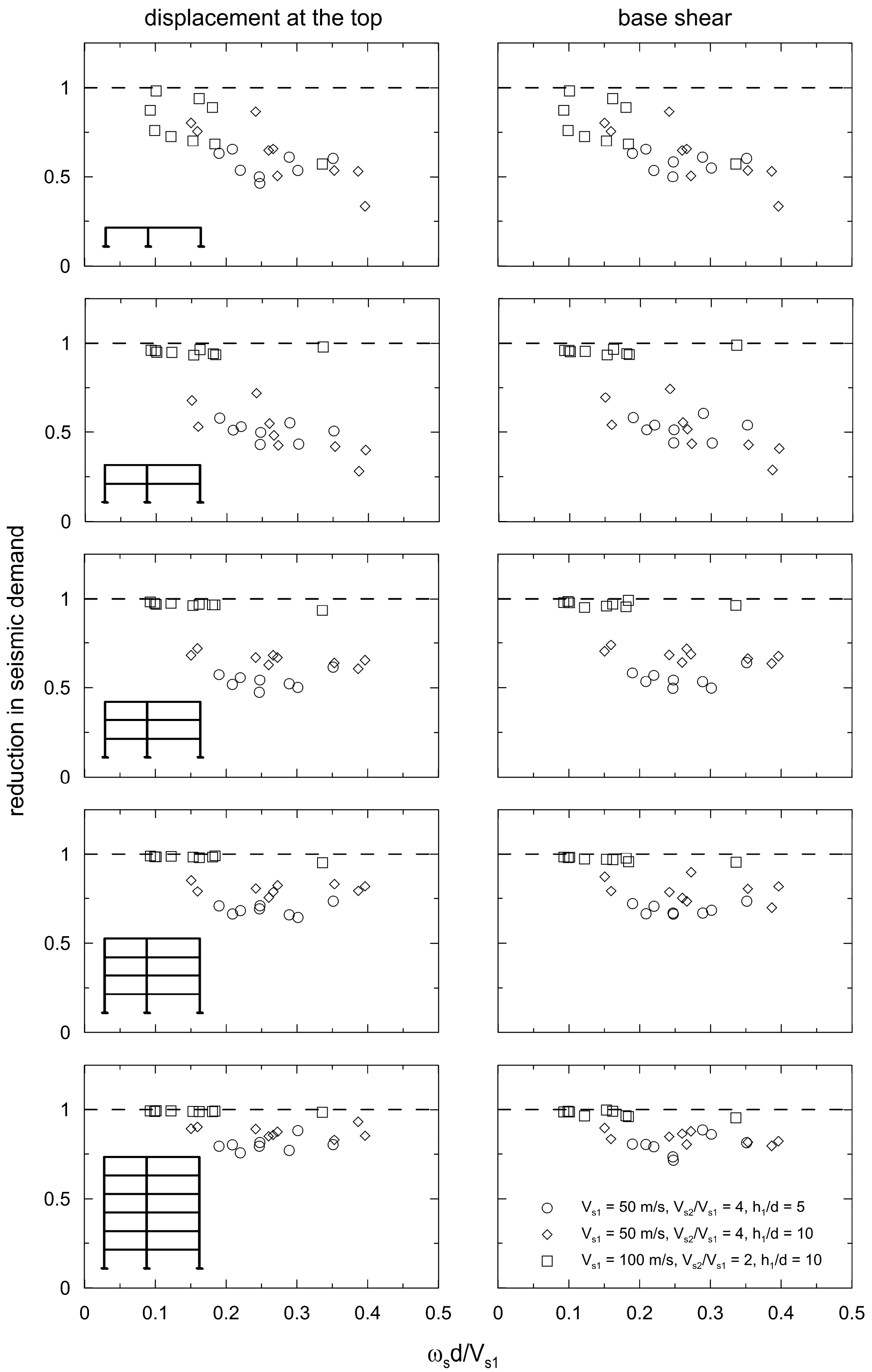

Figure 9. Reduction in top displacement and base shear demand for the five case-study structures.

Such results can be further discussed from a different perspective, i.e. observing the trend of the reduction in seismic demand as a function of the fundamental structural period, taking the average of the values corresponding to each earthquake. This representation (Fig. 10) allows to include, for comparison, the mean spectral ratios for the examined subsoil (thinner line) and the proposed spectral reduction for homogeneous soil conditions (thicker line), described in the previous section. Fig. 10 refers separately to the three subsoil cases (see parts (a), (b) and (c) respectively). Circles correspond to mean ratios of maximum base shear whereas rhombuses to mean ratios of maximum top displacements. It can be observed that: (i) the values of ratios in terms of base shear and top displacement are very close to each other as already observed with reference to the disaggregated data in Fig. 9; (ii) all the response reduction indicators result to be almost aligned on the thin lines representing mean spectral ratios; this indicates that the filtering effect due to the presence of the piles measured on SDOF does not change dramatically when referred to MDOF systems.

Nonlinear behavior of materials [30] and stiffness/strength irregularities of structures in plan [31] and in elevation could affect these results. Further analyses in such direction have been planned by authors, being the subject of a future paper. With reference to the same above case-study buildings, authors are also working on the comparison, via decision making procedures already applied to civil engineering problems [32], of the two alternative design strategies addressed to the adoption of shallow and deep foundations respectively. Finally the effect of pile filtering on the seismic response of a benchmark bridge [33, 34] is currently under investigation, to evaluate the results with reference to a MDOF very different from buildings for dynamic characteristics.

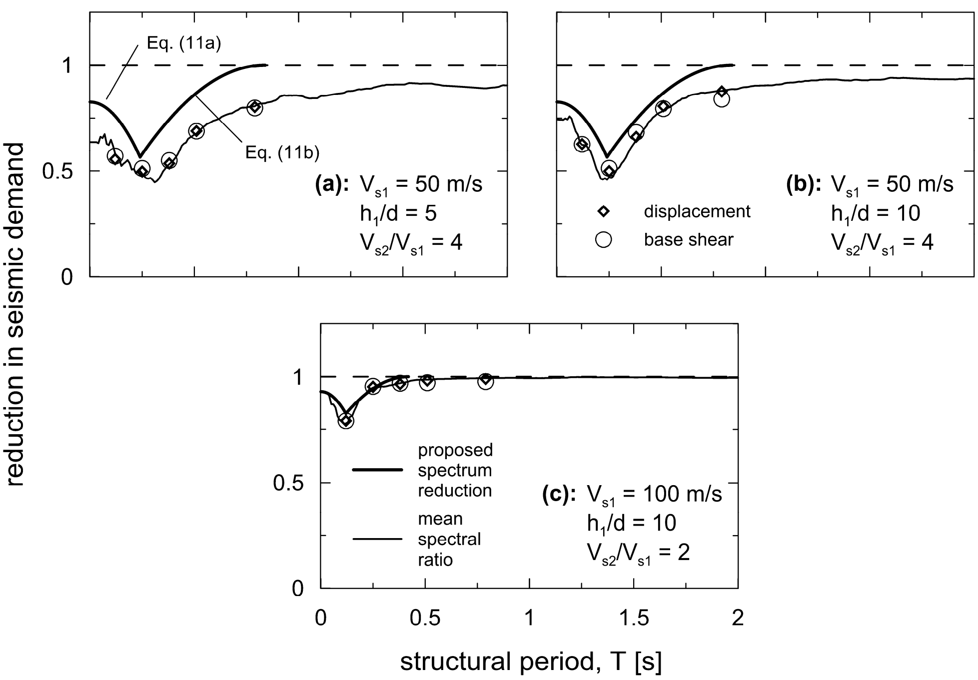

Figura 10. Mean response reduction in terms of top displacement and base shear. Mean spectral ratios. Proposed spectral reduction for homogeneous soil conditions.

6 CONCLUSIONS

The inertial interaction analysis of the superstructure is usually performed by assuming that the foundation input motion is merely that of the free field, thus neglecting the filtering action exerted by the piles. In this work, the concept of piles as seismic demand reducers has been introduced and discussed.

First, emphasis has been placed on the mechanism of the filtering effect. From results undertaken by FE analyses carried out in the frequency domain the following conclusion can be drawn: (i) the phenomenon of the filtering action is governed by soil stiffness, pile diameter and excitation frequency; (ii) the amount of the filtering action is lowered by the spectral ratio function pertaining to the homogenous soil deposit; (iii) the ratio of the spectral accelerations between the filtered motion over that of the free field has a somewhat 'root' shape, characterized by a critical structural period, after which the filtering effect becomes negligible.

Based on the above results, a coefficient for the reduction of design spectra has been suggested. This can be conveniently adopted within strategies for seismic risk reduction to assess the seismic vulnerability of existing structures founded on piles. It can be also employed within the framework of the substructure method to evaluate the convenience to carry out the computational cost associated to the analysis of pile-soil kinematic interaction.

Moreover, the potential coming from the piles in reducing the seismic demand has been verified against real structures, i.e. MDOF systems. The performance of structures with gradually increasing vibration period has been analyzed performing linear time-history analyses to quantify the beneficial effect coming from the piles for earthquake that are likely to occur during the life span of the structure. Five reinforced concrete frame structures have been designed according to Eurocode 8 so as to make their fundamental vibration periods range in the interval [0.13, 0.80 s]. Measures of response reduction due to the piles expressed in terms of base shear and top displacement resulted to be very close to each other, as expected from linear analysis of first-mode dominated structures. On average, the percentage reduction in seismic demand (in some cases even equal to about 50%) resulted to be similar to that measured in terms of spectral ratios, so confirming also for MDOF the beneficial effect that a pile foundation may lead to, acting as a mechanical filter between soil and superstructure.

Nonlinear behavior of materials and stiffness/strength irregularities of structures along the height could affect these results. Further analyses addressed to investigate in such direction have been planned by authors and will be the object of a future paper.

REFERENCES

[1] L. de Sanctis, G. Russo, Analysis and performance of piled rafts designed using innovative criteria. *Journal of Geotechnical and Geoenvironmental Engineering*, **134**(8), 1118-1128, 2008.

[2] G. Russo, C. Viggiani, L. de Sanctis. *Piles as settlement reducers: a case history. Proc. of the Skempton Conference 'Advances in Geotechnical Engineering: The Skempton conference. Proc. of a three day conference on advances in Geotechnical Engineering, organized by the Institution of Civil Engineers.* London, Thomas Telford, 1143-1154, 2012.

[3] R. Flores-Berrones, R.V. Whitman, Seismic response of end bearing piles. *Journal of the Geotechnical Engineering Division,* **108**(4), 554-569, 1982.

[4] G. Gazetas, Seismic response of end-bearing single piles. *International Journal of Soil Dynamics and Earthquake Engineering*, **3**(2), 82-93, 1984.

[5] K. Fan, G. Gazetas, A. Kaynia, E. Kausel, S. Ahmad, Kinematic seismic response analysis of single piles and pile groups. *Journal of the Geotechnical Engineering Division*, **117**(12), 1860-1879, 1991.

[6] G. Anoyatis, R. Di Laora, A. Mandolini, G. Mylonakis, Kinematic response of single piles for different boundary conditions: analytical solutions and normalization schemes. *Soil Dynamics and Earthquake Engineering*, **44**, 183-195, 2013.

[7] A.S. Nikolaou, G. Mylonakis, G. Gazetas, T. Tazoh, Kinematic pile bending during earthquakes analysis and field measurements. *Géotechnique*, **51**(5), 425-440, 2001.

[8] R.M.S. Maiorano, L. de Sanctis, S. Aversa, A. Mandolini, Kinematic response analysis of piled foundations under seismic excitations. *Canadian Geotechnical Journal*, **46**(5), 571-584, 2009.

[9] L. de Sanctis, R.M.S. Maiorano, S. Aversa, A method for assessing kinematic bending moments at the pile head. *Earthquake Engineering and Structural Dynamics*, **39**(10), 1133-1154, 2010.

[10] S. Sica, G. Mylonakis, A.L. Simonelli, Transient kinematic pile bending in two-layer soil. *Soil Dynamics and Earthquake Engineering*, **31**(7), 891-905, 2011.

[11] R. Di Laora, G. Mylonakis, A. Mandolini, Pile-head kinematic bending in layered soil. *Earthquake Engineering and Structural Dynamics,* **42***,* 319-337, 2013.

[12] S.M. Mamoon, P.K. Banerjee, Response of piles and pile groups to travelling SH waves. *Earthquake Engineering & Structural Dynamics*, **19**(4), 597-610, 1990.

[13] A. Kaynia, E. Kausel. Dynamics of piles and pile groups in layered soil media. *Soil Dynamics and Earthquake Engineering*, **10**(8), 386-401, 1991.

[14] K. Fan, G. Gazetas, A. Kaynia, E. Kausel, S. Ahmad, Kinematic seismic response analysis of single piles and pile groups. *Journal of the Geotechnical Engineering Division,* **117**(12), 1860-1879, 1991.

[15] S. Kawamura, H. Umemura, Y. Osawa, Earthquake motion measurement of a pile-supported building on reclaimed ground. *Proc. 6th WCEE*, India, 1977.

[16] H. Tajimi, Seismic effects on piles. *State-of-the-Art-Report. Spec. Session Proc. 9th Int. Conf. Soil Mech.*, Tokyo, 1977.

[17] T. Ohta, S. Uchiyama, M. Niwa, K. Ueno, Earthquake response characteristics of structure with pile foundation on soft subsoil layer and its simulation analysis. *7th World conf. on earthquake engineering*. Vol. 3. Istanbul, Turkey, 1980.

[18] J.M. Roesset. The use of simple models in soil-structure interaction. *ASCE specialty conference*, Knoxville, TN, Civil Engineering and Nuclear Power, vol. 2, 1980.

[19] N. Makris, G. Gazetas, Dynamic pile-soil-pile interaction. Part II: Lateral and seismic response. *Earthquake Engineering & Structural Dynamics* , **21**(2), 145-162, 1992.

[20] E.L. Wilson, Structural analysis of axisymmetric solids. *American Institute of Aeronautics and Astronautics Journal AIAA*, **3**, 2269-2274, 1965.

[21] O.C. Zienckiewicz, N. Bicanic, F.Q. Shen, Earthquake input definition and the transmitting boundary conditions. *Conf. Advances in computational non-linear mechanics*, 109-130. Editor St. Doltnis I, 1988

[22] R. Di Laora, A. Mandolini, G. Mylonakis, Insight on kinematic bending of flexible piles in layered soil. *Soil Dynamics and Earthquake Engineering,* **43**, 309-322, 2012.

[23] G. Scasserra, G. Lanzo, J.P. Stewart, B. D' Elia. SISMA (Site of Italian Strong Motion Accelerograms): a web-database of ground motion recordings for engineering applications. *Seismic Engineering Conference commemorating the 1908 Messina and Reggio Calabria Earthquake*, Reggio Calabria, Italy, Vol. 2, 1649-1656, 2008.

[24] N. Ambraseys, P. Smit, R. Sigbjornsson, P. Suhadolc, B. Margaris. Internet-Site for European Strong-Motion Data. European Commission; Research-Directorate General, Environment and Climate Programme, 2002.

[25] R. Di Laora, L. de Sanctis, Piles-induced filtering effect on the Foundation Input Motion. Soil Dynamics and Earthquake Engineering, **46**, 52-63, 2013.

[26] Eurocode 2, Design of concrete structures - Part 1-1: General rules and rules for buildings, 2004.

[27] Eurocode 8, Design for Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings, 2003.

[28] SAP2000, Static and Dynamic Finite Element Analysis of Structures, release 15.0, Computers and Structures Inc., Berkeley, CA, 2011.

[29] M. Rathje, N.A. Abrahamson, J.D. Bray. Simplified frequency content estimates of earthquake ground motions. *Journal of Geotechnical and Geoenvironmental Engineering,* **124**(2), 150-159, 1998.

[30] G. Maddaloni, G. Magliulo, E. Cosenza. *Effect of the seismic input on non-linear response of R/C building structures*. Advances in Structural Engineering, **15**(10), 1861-1877, 2012.

[31] G. Magliulo, G. Maddaloni, E. Cosenza. Extension of N2 method to plan irregular buildings considering accidental eccentricity. *Soil Dynamics and Earthquake Engineering*. **43**, 69-84, 2012.

[32] N. Caterino, I. Iervolino, G. Manfredi, E. Cosenza, Multi-Criteria Decision Making for Seismic Retrofitting of RC Structure, *Journal of Earthquake Engineering*, **12**, 1-29, 2008.

[33] G. Maddaloni, N. Caterino, A. Occhiuzzi, Semi-active control of the benchmark highway bridge based on seismic early warning systems. *Bulletin of Earthquake Engineering,* **9**(5), 1703-1715, 2011.

[34] G. Maddaloni, N. Caterino, G. Nestovito, A. Occhiuzzi, Use of seismic early warning information to calibrate variable dampers for structural control of a highway bridge: evaluation of the system robustness. *Bulletin of Earthquake Engineering* (in press).