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FILTERING EFFECT FOR A PILE IN TWO-LAYER SOIL

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Abstract

The aim of this work is to investigate the kinematic response of fixed-head vertical floating piles embedded in two layer soils with shallow interfaces and subjected to upward-propagating seismic waves. The problem is explored numerically by means of a rigorous finite element analysis, to quantify the kinematically-induced reduction of the horizontal free-field spectral acceleration. Insight about the beneficial role of the stiffer layer is provided.

Keywords: Kinematic pile interaction, earthquakes, finite element analysis, seismic design.

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1 INTRODUCTION

It is widely recognized that the passage of seismic waves through the ground induces deformations in the soil mass. Piles embedded in the soil are not always able to follow the deformations of the surrounding soil, given their large flexural stiffness. Such inhability is more and more pronounced with increasing excitation frequency, i.e. with decreasing soil wavelength (λ_s) compared to the characteristic pile wavelength (λ_p) as highlighted by Di Laora & de Sanctis (2013). Therefore, piles can filter out the high-frequency components of the free-field motion, producing generally a beneficial effect on the Foundation Input Motion (FIM) which excites the structure (Fig. 1).

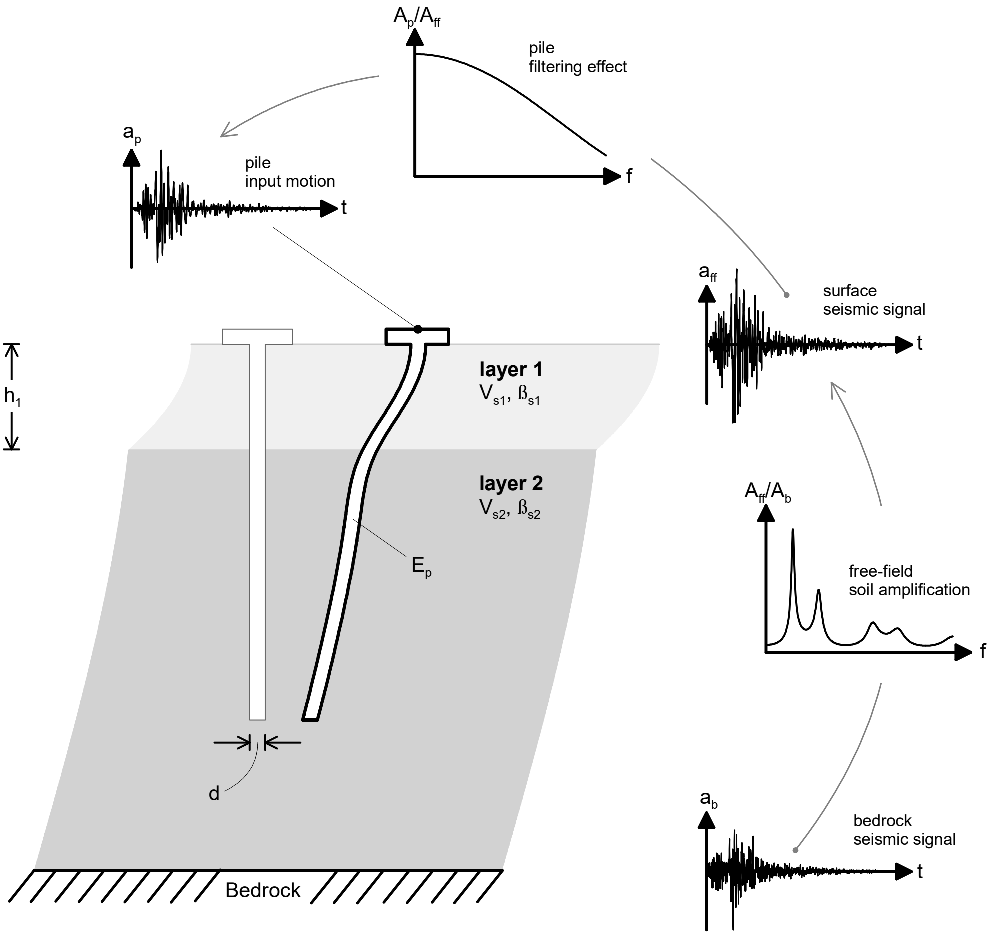

Figure 1: Problem under investigation.

Flores-Berrones and Whitman (1982) proposed the first closed-form analytical solution for the kinematic interaction factor for an infinitely long fixed-head pile, embedded in a homogeneous half space, based on the beam-on-dynamic-Winkler-foundation (BDWF) approach. With the same approach Nikolaou et al. (2001) provided the analytical solution for the case of a free-head pile; Anoyatis et al. (2013) proposed analytical solutions for the kinematic response of a single pile of finite length in homogeneous layer with different boundary conditions at its ends. Iovino et al. (2019) provided a simplified expression for the case of soil with stiffness varying continuously with depth according to a generalized power law function.

As regards the pile groups Fan et al. (1991) studied the kinematic behaviour of groups of vertical floating piles connected by a rigid massless cap, showing that the number of piles and the group geometry have a negligible effect in terms of lateral displacements, while they affect significantly the rotation of the pile cap. Di Laora et al. (2017) proposed a simplified closed-form solution for the horizontal motion and rotation of a capped pile group generated by kinematic interaction.

Nevertheless, the case of a pile embedded in a two-layer soil with shallow interface, i.e. with interface depth lower than the active pile length, has been less investigated, despite it is a very common geotechnical scenario, for example in presence of made ground, when piles are required to transfer loads to a deeper, more competent soil layer.

In this work the kinematic response of a single fixed-head pile embedded in a two-layer soil is investigated through rigorous finite element analysis carried out in frequency domain, with the commercial FE code ANSYS. Adopting the kinematic interaction coefficient obtained through the finite element analysis, the transient response is studied evaluating the reduction of the design spectra for some cases employing 9 selected real accelerograms.

2 FE MODEL

Numerical analyses are performed using the commercial FE code ANSYS. The analyses were carried out in the frequency domain, pile is assumed to be a linear elastic medium, while soil possesses a complex shear modulus $G^* = G(1+2i\beta)$, with β the constant hysteretic damping ratio. 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 (1965).

So the original three-dimensional problem is reduced to a 2D one. Four-noded axisymmetric elements were used to mesh soil and pile. After a thorough sensitivity analysis, the vertical size of the elements is set to 0.1 diameters for a width of 3 diameters close to layers interface and 0.5 diameters elsewhere. On the other hand, 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 (Fig. 2). The nodes at the base of the model are restrained to both horizontal and vertical directions to represent a rigid bedrock. The lateral boundary, where vertical displacements are restrained, is placed at 400 m, a sufficiently large distance from the pile, thus allowing diffracted waves from pile-soil interface to attenuate because of the soil damping before being reflected at the boundary (Di Laora et al., 2012; Iovino et al. 2019; Iovino et al. 2022).

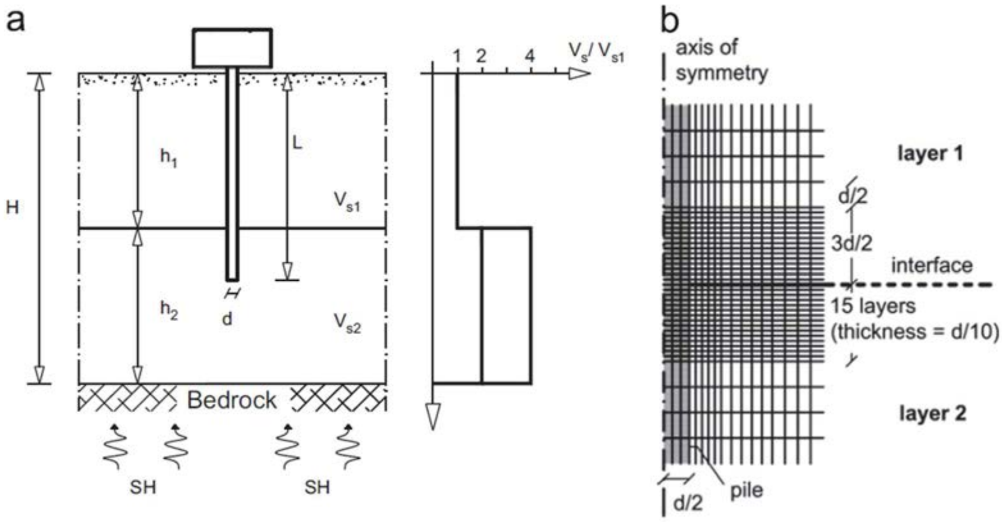

Figure 2: (a) problem considered; (b) finite element mesh employed in the analyses.

3 HARMONIC RESPONSE

Some FEM analysis results are depicted in Figure 3, in terms of pile-to-soil acceleration ratio I_u, against the dimensionless frequency as defined by Anoyatis et al. (2013), $\omega/\lambda_1 V_{s1}$, where λ_1 is the Winkler wavenumber of the soil-pile system, equal to:

$$\lambda_1 \approx \left(\frac{k_1}{4E_p I_p} \right)^{1/4} \tag{1}$$

The spring stiffness k_1 could be considered to be frequency-independent and expressed as a multiple of the soil Young's modulus E_s (Gazetas & Dobry, 1984):

$$k_1 \approx \delta E_{s1} \tag{2}$$

where δ is a proportionality coefficient, which for the problem at hand varies in the range 1.5 to 2.5.
It can be observed that, when the interface depth becomes deep enough the kinematic interaction coefficient obtained converges with that related an infinitely long pile in homogeneous half space, that can be expressed as proposed by Flores-Berrones & Whitman (1982):

$$I_u = \Gamma_1 = \frac{4\lambda_1^4}{4\lambda_1^4 + q_1^4} \tag{3}$$

where $q_1 = \omega/V_{s1}*$ is the complex wavenumber of the soil.

In particular, pile response is not affected by the presence of the second layer if the interface depth is greater than the active pile length which is typically equal to about 10 pile diameters (Poulos and Davis, 1980; Randolph, 1981).
For a fixed-head pile the pile-to-soil acceleration ratio is, even for the two layer case, always lower then unity and diminishes with increasing frequency (Fig. 3).
The presence of the second layer, stiffer than the first, may be beneficial since would act as a partial fixity for the embedded portion of the pile (Di Laora & de Sanctis, 2013). Indeed for a fixed interface depth the filtering effect increases (i.e. I_u decreases) with the stiffness contrast between the two layers, as can be observed in Fig. 3a, 3c and 3e.
Nevertheless, this is not always the case. The effect of a stiffer second layer is beneficial only for an "intermediate" interface depth. This is because on one hand, as expected, if the interface depth is too deep the pile behaviour is unaffected by the presence of the second layer. On the other hand, if the interface is too shallow the pile response becomes close to that of a pile embedded in an homogeneous half space with the characteristics of the second layer, thus the overall pile-to-soil stiffness contrast decreases and so does the filtering effect for a given excitation frequency (Fig. 3).

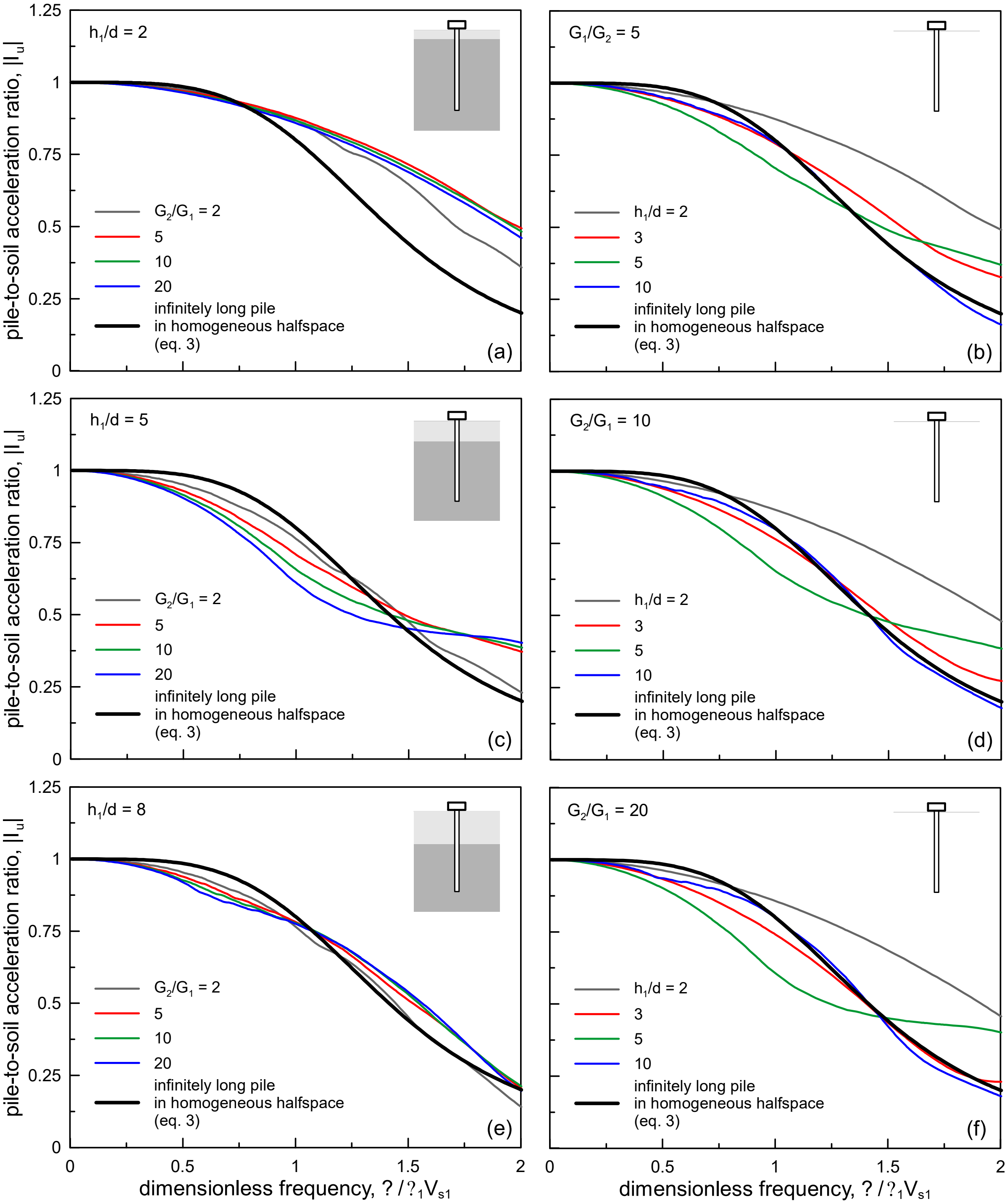

Figure 3: Numerical results for $E_p/E_1 = 1000$, $\delta = 1.5$ and $\beta = 0.05$.

4 TRANSIENT RESPONSE

Transient response is investigated by using real acceleration time-histories selected from the Engineering Strong Motion Database (Luzi et al., 2020). In Fig. 4 and Fig. 5 time histories and Fourier spectra of the signals are depicted. Furthermore in Fig. 5 the mean frequency f_m as defined by Rathje et al. (1998) is reported for each accelerogram.

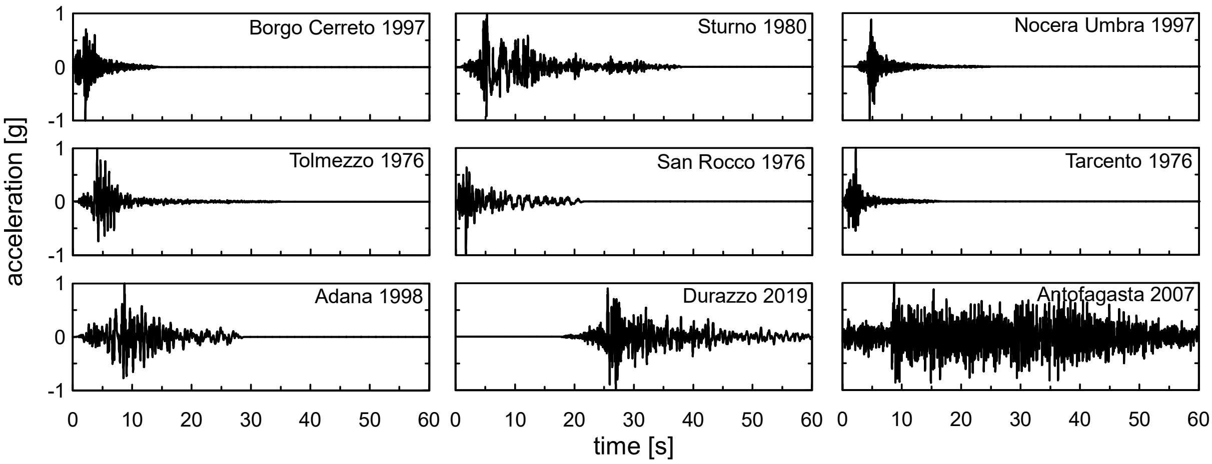

Figure 4: Acceleration time-histories.

Pile to soil acceleration spectral ratios were obtained deriving the transient response at the pile-head and free-field surface, then the corresponding acceleration response spectra were computed for each of the 9 accelerograms (Fig. 6).
The spectral acceleration rations ξ were calculated as the mean response spectrum at the pile head over the mean response spectrum of the free-field motion.
Figure 6a shows the outcropping bedrock to soil surface amplification function for a dimensionless interface depth $h_1/d = 5$, layers stiffness contrast $G_2/G_1 = 10$ and total height of the soil medium $H = 30$ m. In the same figure the outcropping-bedrock to pile amplification function is also reported. Figure 6b shows the surface response spectra for each selected accelerogram, the pile response spectra, the outcropping-bedrock mean response spectrum, the surface mean response spectrum and the pile mean response spectrum. From inspection of the two graphs, it is evident that piles may provide a significant filtering effect within the frequency range of the selected signals, resulting in a reduction of seismic demand for structures having a fundamental period up to 0.5 s.

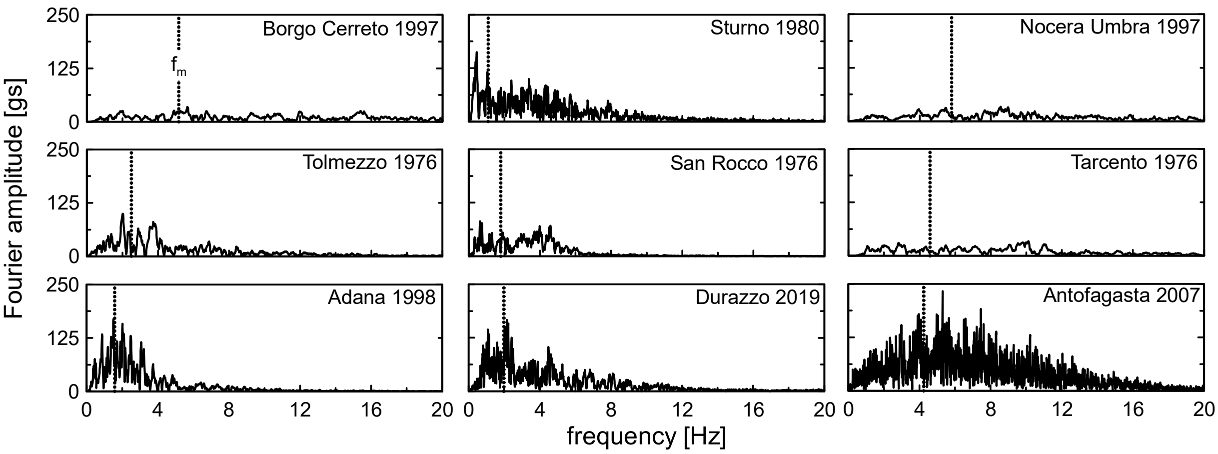

Figure 5: Fourier spectra of the acceleration time-histories.

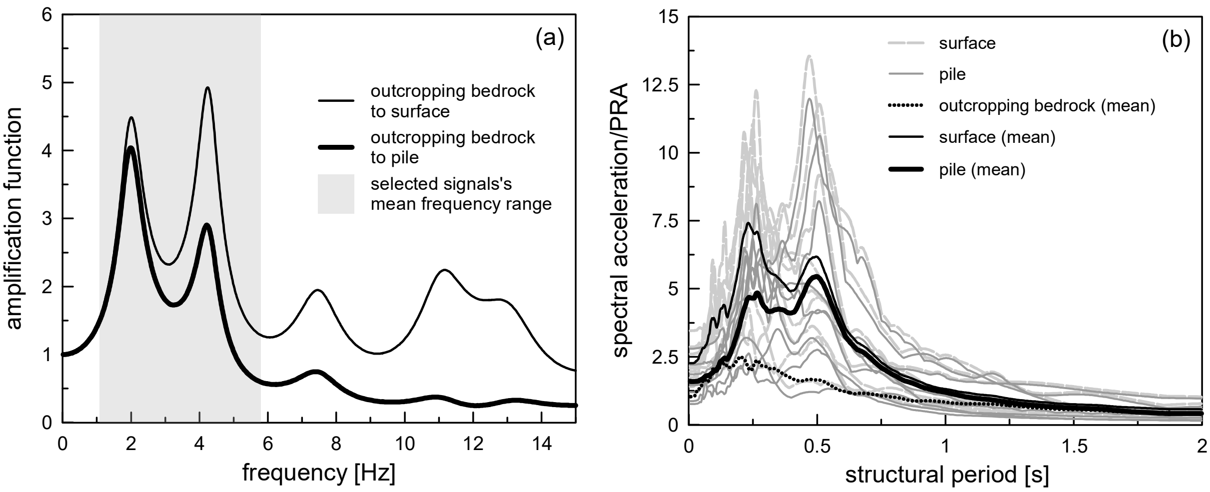

Figure 6: Amplification function (a) and spectral acceleration (b) for d = 1 m, E_p/E_{s1} = 1000, h_1/d = 5, G_2/G_1 = 10 β = 0.05, H = 30 m.

The spectral acceleration ratio is shown in Fig. 7 for selected cases. A noteworthy point is that time-domain response seems more sensitive to the presence of a second layer as compared to the frequency domain, since even deep interfaces may affect spectral ratios in a significant manner. This is because the time-domain results reflect also the frequency content of the signal at soil surface, which is shifted to higher frequencies in presence of a stiffer second layer, rendering the filtering action more pronounced. For the same reason, a large layers' stiffness contrast has a double beneficial role. This is evident in Fig. 7(b,d): for an interface depth equal to 10 pile diameters, which in the frequency domain returns the same interaction factor as a homogeneous soil, the filtering effect is more pronounced than for a homogeneous halfspace with the proprieties of the first layer, and for some structural periods could be even more beneficial compared to an "intermediate" interface depth.

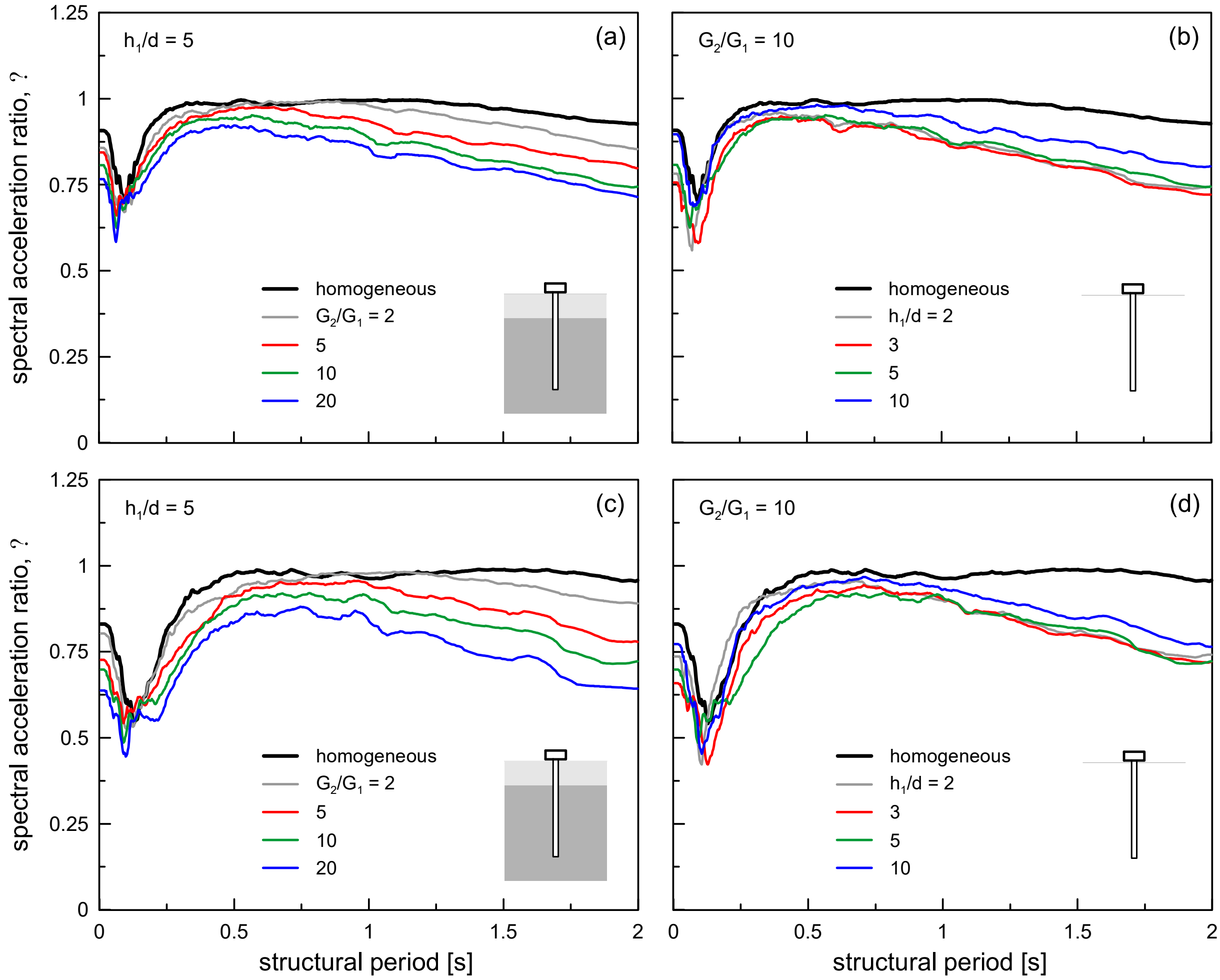

Figure 7: Spectral acceleration ratio for d = 1 m, β = 0.05, H = 30 m; E_p/E_{s1} = 500 for (a) and (b); E_p/E_{s1} = 1000 for (c) and d.

5 CONCLUSIONS

This work investigates the pile-induced filtering effect due to kinematic interaction in two-layer soil with shallow interfaces, i.e. when the first layer thickness is lower than the active pile length. A wide set of rigorous Finite Element (equivalent) linear analyses was carried out in the frequency domain using the commercial FE code ANSYS. Transient response has been analyzed with reference to 9 selected real acceleration time-histories. The beneficial role of the second layer, stiffer than the first, has been highlighted. It is shown that while the pile-to-soil acceleration ratio in the frequency domain is significant only for intermediate interface depths, the transient response shows that filtering effect may be very important also for deep interfaces. This is because the presence of a stiff layer shifts the frequency content of the signal at surface towards higher frequencies. From a general standpoint, a stiffer underlying layer is usually beneficial for pile filtering.

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