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DAMPING MODIFICATION FACTORS INCLUDING SOIL-PILE KINEMATIC INTERACTION

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Abstract

The seismic hazard at a site is usually quantified by means of 5%-damped pseudo-acceleration response spectrum. Thus, for structural damping ratios other than 5%, it is necessary to apply period-dependent Damping Modification Factors, which adjust spectral ordinates to the desirable structural damping ratio. On the other hand, piles, depending on their stiffness, may modify the seismic excitation at the base of a structure with respect to the free-field motion, by filtering the seismic demand imposed by the soil. This phenomenon, which is known as kinematic soil-pile interaction, is also period-dependent and it stems from the inability of piles to follow short wavelengths of the free-field motion. The problem is explored by means of a rigorous Finite Element model of a single, fixed-head pile embedded in a generalized inhomogeneous soil. Average spectral acceleration ratios between the pile-head and the ground surface at free-field conditions are derived for various soil-pile configurations and structural damping ratios. The effect of critical model parameters is discussed, and a new spectral reduction factor is defined which relates the acceleration response spectrum at the pile-head for any structural damping ratio to a 5%-damped acceleration spectrum at the free-field.

Keywords: Piles, Kinematic soil-pile interaction, Damping Modification Factors, Structural damping ratios

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1 INTRODUCTION

Ground Motion Prediction Equations typically provide the 5%-damped pseudo-acceleration response spectrum at free-field conditions to define the seismic demand on a structure, within the framework of a probabilistic seismic hazard analysis. However, for structures with energy dissipation devices [1, 2, 3, 4, 5] or pronounced soil-structure interaction (SSI) effects [6, 7, 8, 9], structural damping ratios other than 5% may be applicable. For example, Cruz and Miranda [5] inferred damping ratios from earthquake records in 14 tall buildings with 20 or more stories and found first-mode damping ratios lower than 2.5%, regardless of the building material, which suggests that higher damping ratios are associated with building and foundation configurations leading to increased energy dissipation due to radiation damping induced by soil-structure interaction (SSI) effects. In a similar vein, Bernal et al. [10] analyzed earthquake records from 81 steel buildings and concluded that damping in low-rise steel structures, when modeled without SSI, can be safely assumed to be larger than the typical 2% used in practice. In such cases, the predicted 5%-damped spectrum should be adjusted accordingly to derive response spectral ordinates for damping ratios other than 5%. Following the pioneering work of Newmark and Hall [11], which highlighted the period-dependent effect of structural damping ratio on the response spectral ordinates, various scaling models have been developed [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23], to define a Damping Modification Factor (DMF). The latter refers to the ratio of a response spectrum parameter (spectral displacement S_d, velocity S_v or acceleration S_a) at the damping ratio ζ of interest over the corresponding spectral ordinate at $\zeta = 5\%$. Calibrated in most cases by real earthquake records, these models provide DMF at free-field conditions, depending on factors such as earthquake magnitude, source-to-site distance, ground motion duration, site conditions, and period of vibration of the Single Degree Of Freedom (SDOF) oscillator. For example, Cameron and Green [17] examined the analytical response of a SDOF elastic oscillator to finite-duration sinusoidal excitations, to show the dependence of the DMF on the frequency content and the duration of ground motion. The scaling of design spectra for different damping ratios has also been addressed in seismic codes (e.g. [25]), which, however, adopt a damping reduction factor η independent of the SDOF period of vibration.

The familiar relationships between spectral displacement S_d, spectral pseudo-velocity PS_v = ($\omega \cdot S_d$) and spectral pseudo-acceleration PS_a (= $\omega^2 \cdot S_d$), where ω is the natural circular frequency of the SDOF, allow alternative definitions of DMF using the above response spectral parameters [14]. In this study, the following form of DMF is employed for free-field conditions [21, 23]:

$$DMF_{ff}(T,\zeta) = \frac{PS_{a,ff}(T,\zeta)}{PS_{a,ff}(T,5\%)} \tag{1}$$

where $PS_{a,ff}(T, \zeta)$ is the pseudo-acceleration spectral ordinate at the desirable ζ and $PS_{a,ff}(T, 5\%)$ refers to the pseudo-acceleration spectral ordinate at 5% damping ratio. Obviously, for $\zeta = 5\%$, DMF_{ff} is equal to unity.

On the other hand, earthquake records from instrumented pile-supported structures provide evidence that piles filter the high-frequency components of the free–field motion at ground surface [26, 27]. This behavior, often referred to as the *filtering effect* [28], stems from the *kinematic interaction* between the pile and the surrounding soil during the passage of seismic waves. From a physical point of view, this phenomenon is related to the reluctance of piles, due to their large flexural stiffness, to follow the wavelength of the soil motion, which becomes progressively shorter with increasing frequency of excitation. However, this aspect is often overlooked in design practice, although it may be particularly pronounced for large-diameter piles in soft soils, where piles are the most common foundation design option. The filtering effect is usually quantified in the dynamic regime by the ratio I_u [= u_p/u_{ff} = a_{ph}/a_{ff}], which represents pile-head response over free-field response at ground surface in terms of horizontal displacement (u_p and u_{ff}) or acceleration (u_{ph} and u_{ff}). A series of solutions published in the literature [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38] since the original work of Flores-Berrones and Whitman [39], which presented the first closed-form analytical expression of I_u for fixed-head piles, allow the assessment of the filtering effect for a wide range of soil-pile configurations. The practical importance of I_u is that it can be readily employed to obtain pile-head response in time domain for a given free-field motion at ground surface and, accordingly, to derive the corresponding pseudo-acceleration response spectrum at the pile head for a prescribed damping ratio of the pile-supported structure. In this manner, one can obtain kinematic-induced spectral reduction factors between pile-head and ground surface under free-field conditions. With reference to a structural damping ratio at 5%, this concept was originally followed by Di Laora and de Sanctis [33], who proposed period-dependent spectral reduction factors for fixed-head piles embedded in a subsoil with a thick homogeneous surface layer and was later extended by Iovino et al. [38] to the case of generalized inhomogeneous soils.

This paper builds on the above two studies and employs a validated Finite Element (FE) model of a fixed-head pile in a generalized inhomogeneous soil, to obtain period-dependent spectral reduction factors between pile-head and free-field motion, for different soil-pile configurations. These FE-based spectral ratios account for both the kinematic-induced filtering action of the piles and the structural damping ratio effect, and they allow the derivation of the acceleration response spectrum at the pile-head for any structural damping ratio when a 5%-damped spectrum at the free-field is known, by means of a novel kinematic-induced Damping Modification Factor.

2 PROBLEM STATEMENT AND PARAMETERS EXPLORED

The problem at hand involves a long fixed-head pile in a viscoelastic soil layer, with shear stiffness varying continuously with depth over a rigid base (Figure 1). The pile is modeled as a linearly elastic cylindrical solid beam of diameter d, length L, Young's modulus of elasticity E_p, and mass density ρ_p. The distribution of the shear modulus of the soil with depth is described by the generalized power law function:

$$G_s = G_{sd}\left[a + (1-a)\frac{z}{d}\right]^n \tag{2}$$

where z represents the depth measured from the soil surface, $a = (G_{s0}/G_{sd})^{1/n}$ and n are dimensionless inhomogeneity factors, while G_{s0} and G_{sd} stand for the shear modulus of soil at ground surface (z = 0) and at the depth of one pile diameter ($z = d$), respectively. The above equation allows for modelling a wide range of stiffness profiles. Two cases are explored herein: a constant profile (n = 0) and a proportional (a = 0, n = 1) profile of soil stiffness. The average low-strain shear wave velocity $V_{S0,30}$ was set at 100 and 200 m/s, corresponding to soil type D and C according to EC8 [25], which yields an average $V_{s,5d}$ over a depth of five pile diameters from ground surface close to the value specified by the latest (under publication) version of EC8 as critical for checking kinematic interaction effects on piles. The pile diameter d and Young's modulus E_p were set at 1.0 m and 30 GPa, respectively, while the hysteretic damping ratio of the soil was considered equal to 10%. The nonlinear behavior of soil was considered by means of an equivalent linear approach, in line with relevant recommendations of EC8. Further details may be found in Iovino et al. [38]. Such an approach has been established to be rather accurate to describe solely soil-pile interaction effects even in the presence of strong soil nonlinearities in free field conditions [40]. Given that the difference between acceleration response spectrum

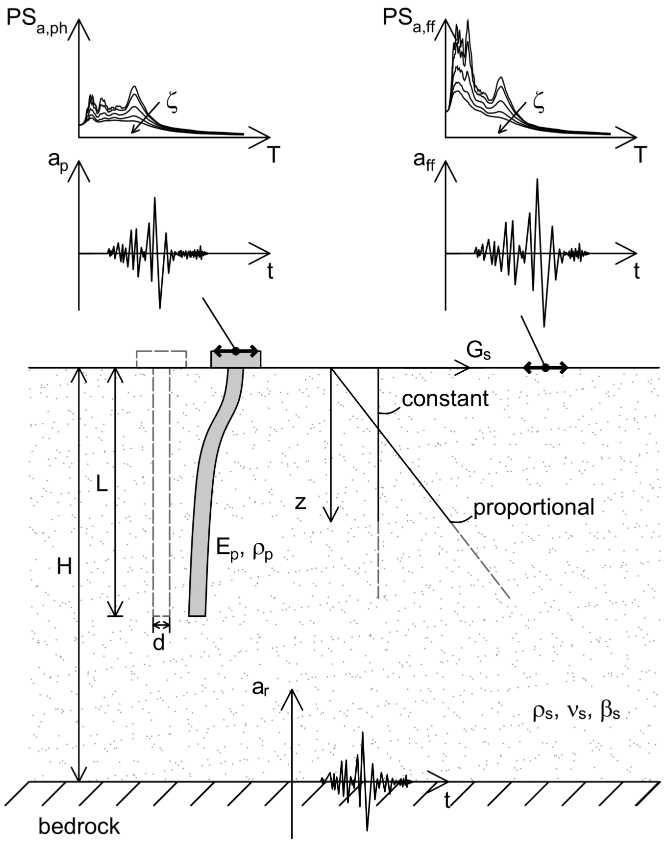

Figure 1: Single elastic fixed-head pile in a soil layer with continuous variation of stiffness over rigid rock.

(S_a) and pseudo-acceleration response spectrum (PS_a) increases with damping, five values of structural damping ratios ζ up to 15% [i.e. 1%, 2%, 5%, 10% and 15%] were considered, which provide similar spectral performance between PS_a and S_a [14].

3 FE ANALYSIS OF THE SOIL-PILE SYSTEM

The rigorous Finite Element model described in Iovino et al. [38] was employed to analyze each soil-pile system under seismic excitation. To this end, nine earthquake recordings were specified as input motions at the base of the soil profile. The pseudo-acceleration response spectra of the selected motions are plotted in Figure 2. Further details on the specific set of recordings can be found in Di Laora and de Sanctis [33].

3.1 Effect of structural damping ratio on pseudo-acceleration response spectra

The analysis was performed for each input motion, and an average pseudo-acceleration response spectrum was derived from the nine spectra at the pile-head and the free-field. The above averaging procedure was applied for each structural damping ratio. The effect of ζ on the average pseudo-acceleration response spectra is shown in Figure 3 for the homogeneous (Figure 3a and 3b) and the proportional (Figure 3c and 3d) profiles when $V_{S0,30}$ = 100 m/s, d = 1.0 m and E_p = 30 GPa. The left plots refer to the spectral response at the free-field, while the right plots refer to the pile-head response. A strong filtering effect is observed, especially for the inhomogeneous case (Figure 3d), as has already been demonstrated in Iovino et al. [38]. Clearly, the effect of damping is not the same over the entire period range, which supports the period-dependent nature of the associated Damping Modification Factor [11].

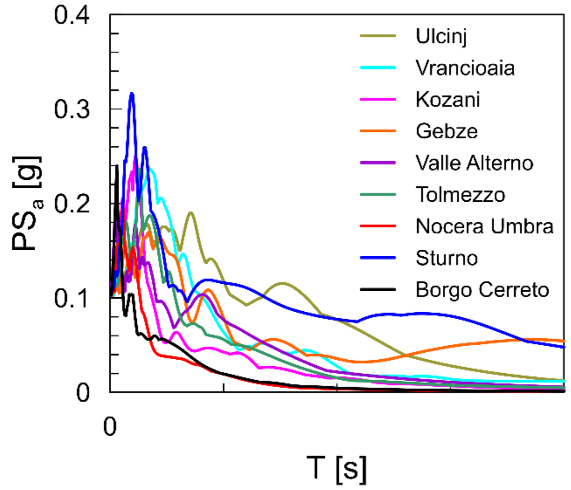

Figure 2: Response spectra of the selected input motions normalized by the peak rock acceleration.

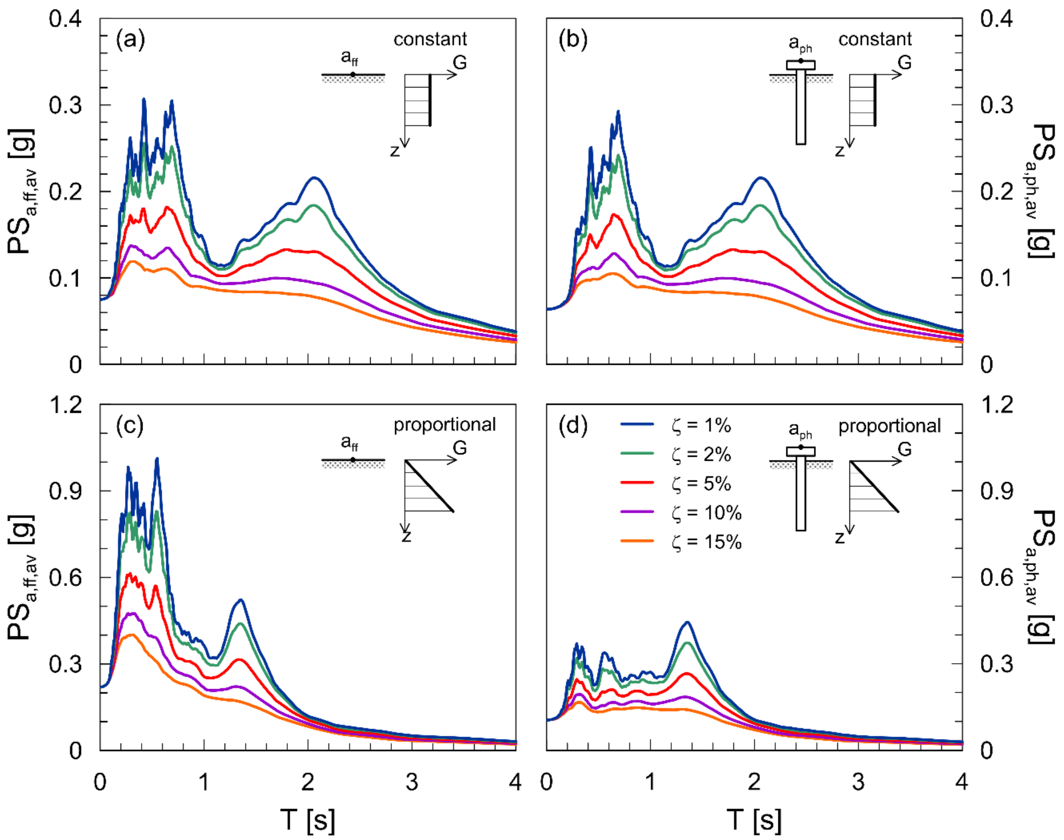

Figure 3: Effect of structural damping ratio on average pseudo-acceleration response spectra for the homogeneous (a-b) and proportional (c-d) stiffness profiles. The left plots refer to free-field motion, and the right plots refer to the pile-head motion. In all plots, E_p = 30 GPa, $V_{s0,30}$ = 100 m/s, d = 1 m and β_s = 10%.

3.2 Kinematic-induced Damping Modification Factor

Having computed the average response spectra for each soil-pile configuration, a FE-based kinematic-induced Damping Modification Factor (DMF_{ph}) is defined at the pile-head in the same manner as the DMF_{ff} in Equation 1:

$$DMF_{ph}(T,\zeta) = \frac{PS_{a,ph,av}(T,\zeta)}{PS_{a,ff,av}(T,5\%)} \tag{3}$$

where $PS_{a,ph,av}$ (T, ζ) is the average pseudo-acceleration response spectrum at the pile-head for damping ratio ζ and $PS_{a,ff,av}$ (T, 5%) refers to the acceleration spectral ordinates at free-field for 5% damping ratio. Equations (1) and (3) are plotted in Figure 4 for the homogeneous and the proportional case. The structural period on the *x*-axes of the graphs in Figure 4 is normalized by the fundamental period (T_1) of the soil layer, corresponding to the mobilized stiffness profile.

As expected, the DMF at free field is above and below unity for damping ratios above and below 5%, respectively. It asymptotically approaches unity as the structural period tends to zero, since the peak relative displacement of the oscillator tends also to zero, regardless of the damping ratio. The same applies when the structural period tends theoretically to infinite, as in this case the peak relative displacement of the oscillator approaches the peak ground displacement for any structural damping [23]. It is also noteworthy that the DMF_{ff} is amplified not only when the structural period becomes equal to the fundamental period of the soil layer (i.e. when T/T_1 = 1), but also at lower normalized periods (around 0.3), which reflects the contribution of higher resonances. Similar observations on the period variation of DMF have been reported by Davalos et al. [23].

On the other hand, the small deviation of the DMF at free-field between the homogeneous (Figure 4a) and the inhomogeneous profiles (Figure 4c) indicates a minor effect of the subsoil conditions on DMF_{ff}, in agreement with earlier findings by Hatzigeorgiou [19]. With reference to DMF_{ph}, it is observed that as the structural period tends to zero, it attains a value lower than 1, depending on the amount of the fixed-head pile's filtering on the free-field motion. This value is again independent of the structural damping ratio in a similar fashion as the DMF_{ff}. For large structural periods, the behaviour of DMF_{ph} becomes identical to that of the $DMF_{ff,}$ as the filtering effect becomes zero with increasing period. It is also interesting to observe that the effect

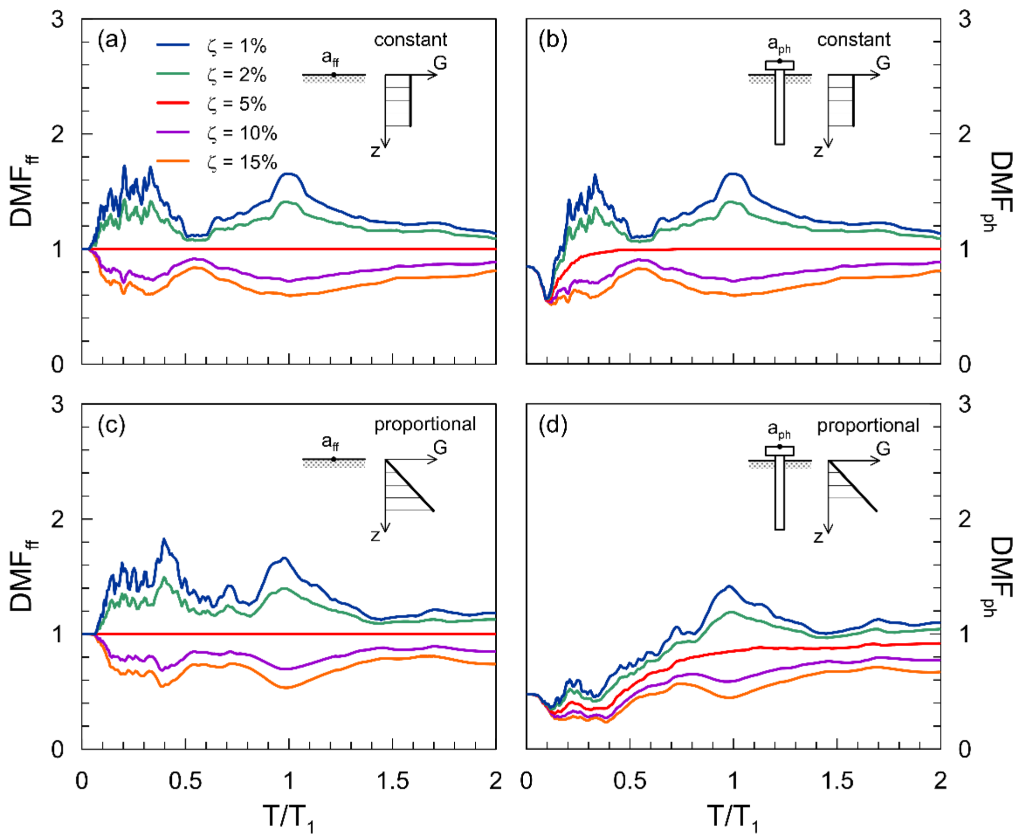

Figure 4: DMF_{ff} (left plots) and DMF_{ph} (right plots) against the period normalized by the fundamental natural frequency of the soil layer for the homogeneous (a-b) and the proportional (c-d) stiffness profiles. In all plots, E_p = 30 GPa, $V_{s0,30}$ = 100 m/s, d = 1 m and β_s = 10%.

of structural damping on DMF_{ph} is less pronounced compared to DMF_{ff} in the period range of strong filtering (i.e. the period range where DMF_{ph} is quite lower than 1).

3.3 Generalized Spectral Reduction Factor

The spectral reduction factor employed originally by Di Laora and de Sanctis [33] for a homogeneous soil and later by Iovino et al. [38] for an inhomogeneous layer, both referring to 5%-damped spectral response, is extended here to structural damping ratios other than 5%, leading to the definition of a generalized spectral reduction factor $\chi(T, \zeta)$. The latter is defined as the ratio of the average pseudo-acceleration spectrum at the pile-head [$PS_{\mathrm{a,ph,av}}(T, \zeta)$] over the average pseudo-acceleration spectrum at free-field for any damping ratio ζ [$PS_{\mathrm{a,ff,av}}(T, \zeta)$]:

$$\chi(T,\zeta) = \frac{PS_{\mathrm{a},ph,av}(T,\zeta)}{PS_{\mathrm{a},ff,av}(T,\zeta)} \tag{4}$$

Upon normalizing both the numerator and the denominator of Equation (4) by the average 5%-damped spectrum at free-field [i.e. $PS_{\mathrm{a,ff,av}}(T, 5\%)$] and recalling the definitions of damping modifications factors in Equations (1) and (3), the generalized spectral reduction factor may also be written as:

$$\chi(T,\zeta) = \frac{DMF_{ph}(T,\zeta)}{DMF_{ff}(T,\zeta)} \tag{5}$$

The above expressions allow a direct assessment of the acceleration response spectrum at the pile-head for any structural damping ratio, when a 5%-damped acceleration spectrum at free-field conditions is known, using the following formula expansion:

$$PS_{a,ph,av}(T,\zeta) = \chi(T,\zeta)\cdot DMF_{ff}(T,\zeta)\cdot PS_{a,ff,av}(T,5\%) \tag{6}$$

Thus, the generalized spectral reduction factor $\chi(T, \zeta)$ may be viewed as an additional spectral modifier, which accounts for the filtering action of piles, in complement to the classical damping modification factor DMF_{ff}. The latter may be defined by any appropriate model that is available in the literature, without affecting the consideration of $\chi(T, \zeta)$. Two points are noteworthy by inspection of Equation (6). First, for negligible kinematic interaction effects, $\chi(T, \zeta)$ becomes equal to1, independent of the damping ratio of the structure. Second, for structural damping ratio at $\zeta = 5\%$, $\chi(T, 5\%)$ degenerates to the spectral reduction $\xi(T, 5\%)$ introduced by Di Laora and de Sanctis [33].

The numerically obtained damping modification factors at the pile-head and the free-field (Figure 4) can now be employed to provide $\chi(T, \zeta)$ for different damping ratios by means of Equation (5), as shown in Figure 5. Each plot in Figure 5 corresponds to a different soil-pile configuration. More specifically, Figures 5a and 5c refer to the homogeneous and inhomogeneous case, respectively, with $V_{\mathrm{s0,30}} = 100$ m/s, while Figures 5b and 5d show the corresponding results for $V_{\mathrm{s0,30}} = 200$ m/s. It is observed that the spectral reduction factor $\chi(T, \zeta)$ attains progressively higher values with increasing damping ratio of the structure, indicating less filtering action. This effect seems particularly evident in the soft homogeneous case (Figure 5a) compared to the inhomogeneous profiles (Figures 5c and 5d).

Overall, the variation of $\chi(T, \zeta)$ with structural period follows the trends described in Iovino et al. [38] for $\xi(T, 5\%)$. The spectral ratio shows a single minimum for the constant stiffness profile, while a double minimum of the spectral ratio appears in the proportional case. These minima, which correspond to maximum filtering, are observed at specific periods, as identified in the above reference, regardless of the structural damping ratio.

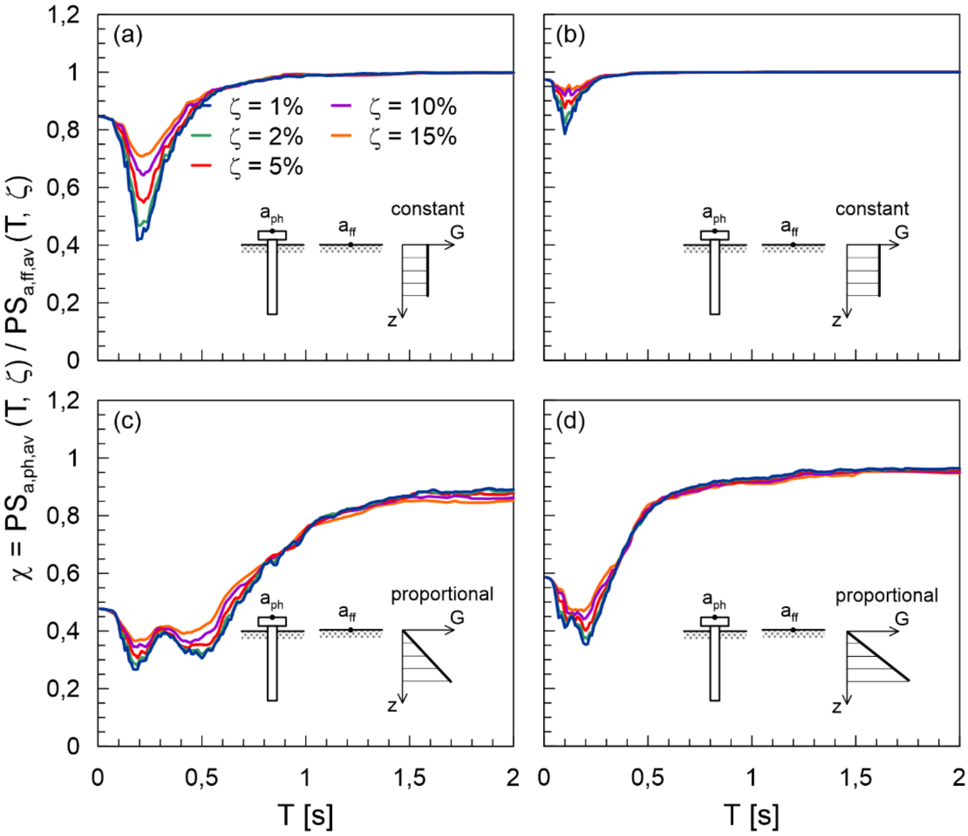

Figure 5: Spectral reduction factor $\chi(T, \zeta)$ computed from FE analysis for the homogeneous (a-b) and proportional (c-d) stiffness profiles. The left plots refer to $V_{s0,30}$ = 100 m/s, and the right plots refer to the $V_{s0,30}$ = 200 m/s. In all plots E_p = 30 GPa, d = 1 m and β_s = 10%.

4 CONCLUSIONS

Building upon earlier contributions of the Authors [33, 38], this work introduces the novel concept of a Damping Modification Factor (DMF_{ph}) at the top of a fixed-head pile to explore the effect of structural damping ratio on the filtering action of piles, thereby including kinematic soil-pile interaction. Two cases of soil stiffness were explored, referring to a constant and a proportional variation of shear modulus with depth. Period-dependent spectral ratios between pile-head and free-field motion were derived by means of a validated FE model. The main conclusions of the study may be summarized as follows:

- The new definition of DMF_{ph} allows a transition from the 5%-damped response spectrum at the free-field to the acceleration response spectrum at the pile-head for any structural damping ratio. This may be of importance in the seismic design of pile-supported structures with a damping ratio other than 5% either due to the type of structure itself or due to the incorporation of soil-structure interaction effects.
- The filtering action of piles, which was quantified herein in terms of a new generalized period- and damping-dependent spectral reduction factor $\chi(T, \zeta)$ [Equation (4) or (5)], becomes smoother and less pronounced with increasing structural damping ratio, as reflected in higher values of $\chi(T, \zeta)$.
- With reference to the period range of strong filtering action, the effect of structural damping on DMF_{ph} is less pronounced compared to the classical DMF_{ff}, regardless of the subsoil conditions.

- Minimum spectral reduction factors, which refer to maximum filtering, were identified at the same structural periods for all the structural damping ratios. This indicates that the filtering effect of piles exhibits the same period-dependent pattern for any damping ratio of the structure.

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