Evaluation of seismic kinematic and inertial forces in piles

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ABSTRACT
Parametric analyses are carried out by means of nonlinear two-dimensional (2D) finite element (FE) analyses, focusing on normalized seismic forces in piles supporting structures as affected by typical characteristics of structures and piles. The results of the study provide a new interpretation of the interplay between pile kinematic and inertial seismic forces. It is found that for relatively short/stiff piles; the kinematic interaction can be the prime contributor to the seismic forces in the pile provided that the excitation frequency is not close to the natural frequency of the coupled soil-pile-structure system, f_{SSI}. The results show also that maximum kinematic seismic force does not always occur at the fundamental frequency of the deposit. For certain relative soil-pile stiffness and excitation amplitudes, the largest peak of the kinematic seismic forces in piles can be occurring at the second mode.

RÉSUMÉ
Des études paramétriques ont été réalisées avec des analyses numériques non linéaires à deux dimensions (2D) en éléments finis (EF), tout en se focalisant sur les forces sismiques normalisées des pieux qui sont influencées par les caractéristiques typiques des structures et des pieux. Les résultats de l'étude fournissent une nouvelle interprétation de l'interaction entre les forces sismiques du pieu cinématique et inertie. Il a été constaté que pour des pieux relativement courts/rigides; l'interaction cinématique peut être le premier contributeur aux forces sismiques dans le pieu, à condition que la fréquence d'excitation n'est pas proche de la fréquence naturelle du système couplé sol-pieu-structure, f_{SSI}. Les résultats montrent également que la force sismique cinématique maximale ne se produit pas toujours à la fréquence fondamentale du dépôt. Pour certains rigidité sol-pieu et d'amplitudes d'excitation relatives, le plus grand pic des forces sismiques cinématiques dans les pieux peut avoir lieu dans la deuxième mode.

1 INTRODUCTION

It is widely accredited among researchers and design engineers that piles supporting structures built in soft grounds are influenced by both the oscillations of the superstructure (inertial interaction) and that of the surrounding soil (kinematic interaction). Over the past several decades, a substantial research effort, both numerical (e.g., Guin and Banerjee 1998; Dezi et al. 2010; Hussien et al. 2010a, 2011) and experimental (e.g., Meymand 1998; Wilson 1998; Hussien 2010b) has been spent in formulating and studying these two types of soil-structure interactions. Modern seismic regulations, such as Eurocode (2004), also include pile design provisions that account for the combined effect of both soil-structure interaction (SSI) mechanisms.

In fact, there is relatively great geotechnical experience and discussions in characteristics of pile forces induced by earthquakes from the viewpoint of the kinematic and inertial forces based on analyzing soil-pile-structure systems through simplified approaches (e.g., Kagawa and Kraft 1980; Allotey and El nagger 2008) as well as more sophisticated finite element (FE) (e.g., Cai et al. 1995; Rovithis et al. 2009) or boundary element (BE) (e.g., Kattis et al. 1999; Padrón et al. 2007) formulations. However, there is little consistency among researchers on the question of the kinematic-interaction role in the seismic pile design (Kaynia and Mahzooni 1996). This has motivated the present research, which aims to investigate the role of kinematic interaction in pile design more closely. The current paper presents a comprehensive parametric analysis conducted to elucidate the relative contributions of kinematic and inertial interaction on the magnitude of bending moments in piles supporting structures as affected by typical characteristics of structures and piles. The results provide a basis for a realistic appraisal without ambiguity of the kinematic-interaction effect on pile forces. For this purpose, a two-dimensional (2D) FE analysis based on a multi-shear mechanism constitutive relationship, **FLIP** (Iai et al. 1992) was employed. The interaction between the pile and the surrounding soil in three-dimensional (3D) type was idealized in the 2D analysis using soil-pile interaction springs with hysteretic nonlinear load displacement relationships (Ozutsumi et al. 2003). The results of the study are presented in dimensionless graphs, covering a wide range of excitation frequencies and of crucial material and geometric parameters.

2 SOIL-PILE-STRUCTURE SYSTEM STUDIED

The soil-pile-structure system studied refers to an end-bearing pile supporting a single degree of freedom (SDOF) structure and being embedded in a dry sand soil stratum of thickness L_s equal to 30 m, underlain by rigid bedrock (Fig. 1). The seismic excitation is assumed to result from vertically incident S-waves specified at the bedrock level in the form of harmonic horizontal displacement ($U_g(t) = U_{g_0} \exp(i2\pi ft)$), where f being the excitation frequency.

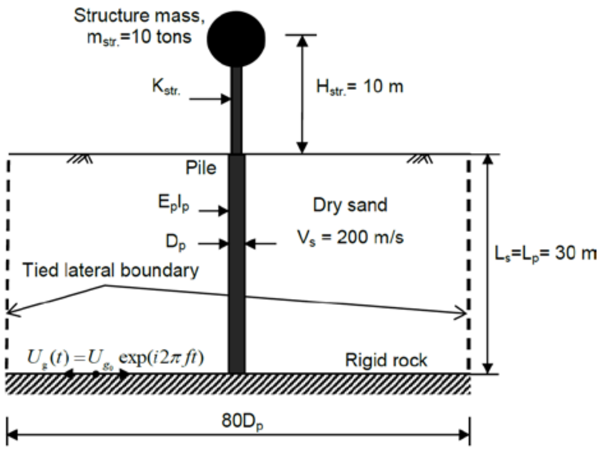

Figure 1. Basic characteristics of the SPS system under investigation and associated boundary conditions.

The soil is idealized by a hyperbolic-type multi-shear mechanism constitutive relationship (Iai et al. 1992). The model is formulated based on the concept of contact forces in granular media. In this model, contact forces between soil particles are idealized by evenly distributed multiple springs, whose property is characterized by a nonlinear load-deformation relationship. In addition to the conventional assumption of hyperbolic relationship assigned for each shear spring for monotonic initial loading, the model uses the extended Masing rule to reproduce more realistic hysteresis loop for cyclic loading (Towhata and Ishihara 1985; Ishihara et al. 1985; Iai et al. 1990). The core of the multi-shear mechanism soil model could be found in (Iai et al. 1992; Hussien et al. 2010c; 2012; 2014).

The pile is a cylindrical steel solid beam of cross-section diameter D_p, total length L_p equal to the soil thickness L_s, Poisson's ratio υ_p of 0.29, mass density ρ_p =7.9 t/m^3, and initial shear modulus G_p of 77.5 GPa. The moment curvature relationship of the pile is idealized as a bilinear curve, whose parameters are obtained from standard sectional analysis given the pile material and sectional properties. The structure is modeled as a SDOF (shear type) oscillator with mass $m_{str.}$ of 100Mg, initial flexural rigidity EI_0, lateral stiffness $k_{str.}$, and height of the mass above ground level $H_{str.}$ of 10 m. The fixed-base natural frequency of the structure is denoted by $f_{str.fixed}$ and is given by $\sqrt{k_{str.} / m_{str.}} / 2\pi$. To investigate kinematic interaction, only the soil-pile subsystem (without the superstructure) was considered.

Due to the abundant number of parameters involved and to reduce the required number of analyses (without loss of insight), only the following crucial dimensionless parameters are varied (Veletsos and Meek 1974; Dobry et al. 1982; Rovithis et al. 2009):

(i) The wave parameter ($\frac{1}{\sigma}$):

$$\frac{1}{\sigma} = \frac{f_{str.fixed} . H_{str.}}{V_s} \quad [1]$$

where V_s is the shear wave velocity of the soil medium in elastic condition, V_s is selected at 200 m/s;

(ii) The foundation flexibility (S_H)

$$S_H = (L_p / D_p)(E_p / E_s)^{-0.25} \quad [2]$$

where E_s and E_p are the elastic modulus of soil and pile, respectively.

A total of 32 cases of coupled systems were analyzed considering a suite of SDOF structures characterized by their fixed-base frequencies ($\frac{1}{\sigma}$ = 0.04 to 0.42), piles of different rigidities (S_H = 1.78 to 6.32), and two amplitudes of harmonic excitations (i.e. A= 0.001 and 1.0 m/s^2).

The quantity of interest in this study is the maximum absolute value of the seismic bending moment M of the pile. This seismic force was normalized to the amplitude of bedrock acceleration following (Kavvadas and Gazetas 1993):

$$M_{nor} = \frac{M}{\rho_p D_p^4 \ddot{U}_{g0}} \quad [3]$$

where $\ddot{U}_{g0} = \omega^2 U_{g0}$ is the amplitude of the harmonic input motion introduced at the base of the soil profile. Results are presented for normalized bending moments, together with their kinematic-interaction counterparts in dimensionless graphs.

3 FINITE ELEMENT MODEL AND BOUNDARY CONDITIONS

A series of effective stress parametric analyses is carried out with the computer code **FLIP** (Iai et al. 1992), by implementing a 2D FE model of the coupled soil-pile-structure system. A 30 (m) thick soil stratum was meshed with quad plane elements. The total mesh size of soil was extended to a horizontal distance of 80-pile diameter to prevent spurious wave reflections at the boundaries (Seed and Lysmer 1978). Moreover, tied lateral boundary approach (a simpler alternative to the boundary approach suggested by Zienkiewicz et al. (1988) was used in the analyses. In this approach, the values of displacements, stresses, etc. are set to be identical on both side boundaries. This condition is explicitly imposed in **FLIP** by an equivalent node concept, namely Multi-Point Constrain (MPC). These kinematic constraints at the lateral edges of the model allowed it to move as the free field. The dimension of the soil element limits the value of the highest frequency, which is transferable. For this reason, the vertical dimension of a soil element (h) follows (Matthees and Magiera 1982):

$$h \leq \frac{1}{5}\left(\frac{V_s'}{f_{max}}\right) \quad [4]$$

where f_{max} is the highest excitation frequency used in the analyses, f_{max} = 10.5 Hz and V_s' is the shear wave velocity expected after the decline of the shear modulus due to soil nonlinearity and can be related to the initial shear wave velocity V_s by:

$$\left(\frac{V_s'}{V_s}\right) = \frac{1}{10} \quad [5]$$

1/10 is a typical reduction factor of the shear modulus in a range of 1–10% on the strain dependent shear modulus curve.

Hussien et al. (2015) verified the multiple shear mechanism model for the analysis of soil-pile-structure systems under both static and dynamic loading. They have performed linear and nonlinear analyses and have compared the results against available experimental and analytical solutions.

4 PARAMETRIC RESULTS

The spectrum of maximum-along-the-pile normalized bending moment amplitudes for all studied soil-pile-structure cases together with their kinematic interaction counterparts were plotted against normalized excitation frequency in Figs. 2a-d for 1/σ of 0.42-0.04, respectively. Each plot in Fig. 2 corresponds to one value of S_H. In the two horizontal axes, the frequency of excitation, f is normalized by the soil fundamental frequency, f_{1soil}, and $f_{str.fixed}$, respectively. The results in Fig. 2 exhibit some features that warrant explanation:

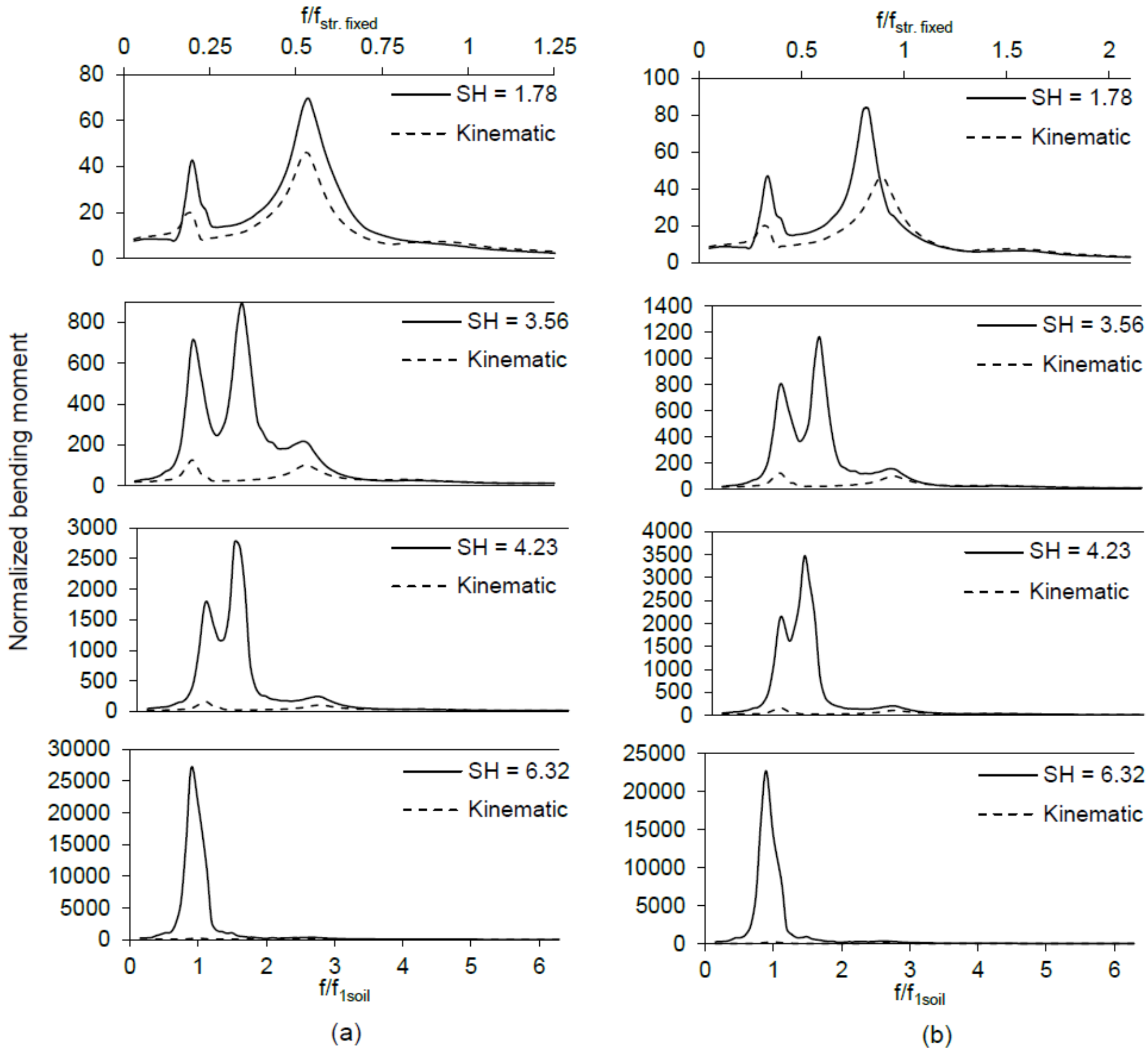

Figure 2. Maximum normalized bending moment amplitude (at the most adverse location along the pile) for homogeneous soil layer (A =0.001m/s2) and: (a) (1/σ) = 0.42 and (b) (1/σ) = 0.25.

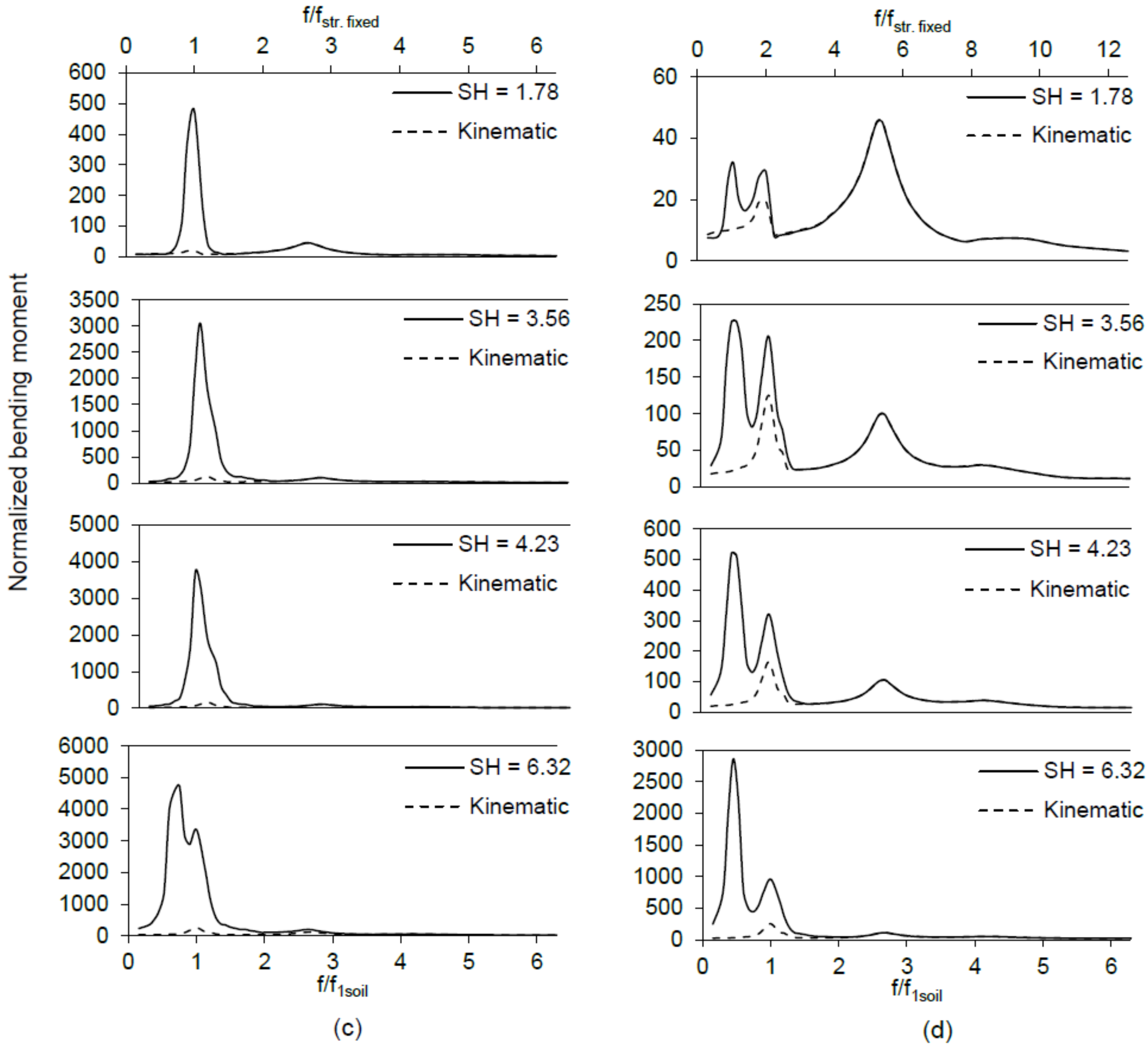

Figure 2. Maximum normalized bending moment amplitude (at the most adverse location along the pile) for homogeneous soil layer (A =0.001m/s2) and: (c) (1/σ) = 0.10 and (d) (1/σ) = 0.04.

1. The largest maximum values of kinematic bending moment in a pile do not always occur at the fundamental frequency of the deposit: for certain relative soil-pile stiffness (S_H=1.78), the largest peak can be shown to occur at the second natural frequency. This could be interpreted according to Kavvadas and Gazetas (1993) who attributed the magnitude of the seismic kinematic bending moment developed in a pile to two counteracting mechanisms: (1) the magnitude of the normalized curvature of the pile displacement shape; (2) the overall amplitude of the pile displacement profile (Kavvadas and Gazetas 1993). The second mechanism usually dominates, and thus the response is largest at the fundamental mode, but in some cases such as the one presented in Fig. 2 (S_H=1.78), the first mechanism is prevalent and the peak response occurs at the second mode.

2. For piles supporting structures characterized by their $f_{SSI} \geq f_{1soil}$ (1/σ = 0.42, 0.25, and 0.10) shown in Figs. 2a-c, the maximum bending moment in a pile is generally higher than the kinematic interaction counterparts in frequency bands approaching f_{1soil} and f_{SSI}. In contrast, bending moments in piles supporting structures, characterized by their $f_{SSI} < f_{1soil}$ (1/σ = 0.04) shown in Fig. 2d, are identical to their kinematic interaction values except in a frequency range closes to f_{SSI}. The maximum seismic forces induced in piles in this case ($f_{SSI} < f_{1soil}$) can be largely due to the kinematic interaction if the excitation frequency is not close to the natural frequency of the soil-pile-structure system. These results imply that one cannot disregard, without justification, the kinematic interaction in the seismic

design of piles supporting structure with $f_{SSI} < f_{1soil}$ especially when the predominant frequency of the design excitation is not close to f_{SSI} of the coupled SPS system.

4.1 Effect of nonlinearity on seismic forces in piles.

Because the effect of nonlinearity is very much dependent on the intensity of excitation, this effect has been discussed by changing the amplitude of input motions. A higher value of base excitation amplitude (A =1.0 m/s^2) was used to investigate the effect of nonlinearity on the magnitude of seismic forces induced in piles. Figure 3 shows the effect of changing the excitation intensity on the spectrum of maximum-along-the-pile kinematic bending moment amplitude. Each plot in Fig. 3 corresponds to a different value of pile parameter, S_H. As expected, the effect of nonlinearity is to decrease the effective natural frequency of the ground (i.e. natural periods lengthening), shifting to the left the location of the resonant peaks. Figure 3 shows also that the maximum seismic kinematic bending moment amplitude generally increases as S_H increases, namely as the pile becomes more flexible.

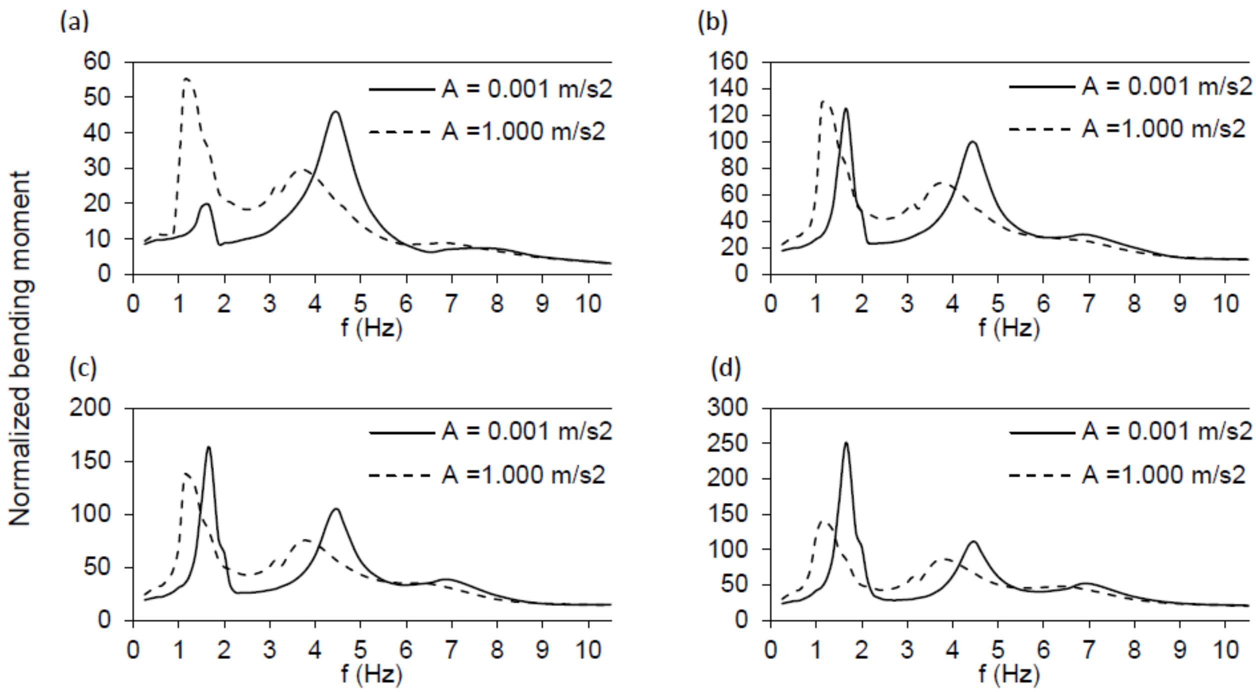

Figure 3. Effect of nonlinearity on maximum normalized seismic kinematic bending moment amplitude (at the most adverse location along the pile) for inhomogeneous soil layer and: (a) SH=1.78, (b) SH=3.56, (c) SH=4.23, and (d) SH=6.32.

5 CONCLUSIONS

A 2D FE analysis based on a multi-shear mechanism constitutive relationship, FLIP is implemented to investigate the interplay between kinematic and inertial interactions in the development of piles forces under seismic loading. Different values of structure's natural frequencies and pile's rigidities were used in this study to define the most salient features of the problem. A number of useful findings have emerged:

1. The maximum kinematic seismic force induced in a pile does not always occur at the fundamental frequency of the deposit. For certain relative soil-pile stiffness as well as excitation amplitudes, the largest peak of the kinematic seismic forces can be revealed to occur at the second natural frequency.
2. Except in a band approaching the natural frequency of the soil-pile-structure system where the inertial interaction dominates the pile forces, the kinematic interaction can be the prime contributor to the seismic forces in the pile especially for relatively short/stiff piles or where the structure's natural frequency is lower than ground fundamental frequency. In these cases, one cannot ignore, without justification, the kinematic interaction in the seismic design of piles supporting structure especially when the predominant frequency of the design excitation is not close to fSSI of the soil-pile-structure system.
3. The effect of nonlinearity on maximum seismic bending moment amplitude of piles supporting structures was significant in relatively flexible piles in reducing the magnitudes of the largest maximum bending moment as well as the associated excitation frequencies.

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