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Nonlinear numerical analysis of influence of pile inclination on the seismic response of soil-pile-structure system

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Abstract. Inclined piles are commonly used in civil engineering constructions where significant lateral resistance is required. Many researchers proved their positive performance on the seismic behavior of the supported structure and the piles themselves. However, most of these numerical studies were done within the framework of linear elastic or elastoplastic soil behavior, neglecting therefore the soil non-linearity at low and moderate soil strains which is questionable and could be misleading in dynamic analysis. The main objective of this study is to examine the influence of the pile inclination on the seismic performance of the soil-pile-structure system when both the linear elastic and the nonlinear soil models are employed. Based on the comparative responses, the adequacy of the soil's linear elastic behavior will be therefore evaluated. The analysis is conducted by generating a three-dimensional finite difference model, where a full interaction between the soil, structure, and inclined piles is considered. The numerical survey proved that the pile inclination can have a significant impact on the internal forces generated by seismic activity, specifically on the bending moment and shear forces. The main disadvantages of using inclined piles in this system are the bending forces at the head and pile-to-head connection. It is crucial to account for soil nonlinearity to accurately assess the seismic response of the soil-pile-structure system.

Keywords: inclined piles; numerical analyses; seismic; soil nonlinearity; soil structure interaction

1. Introduction

In the past decades, the complex dynamic behavior of pile foundations grasped the interest of many researchers giving rise to numerous experimental, analytical, and numerical studies. Yet, when lateral forces are applied, civil engineers commonly use the inclined piles due to their substantial lateral resistance. Soil-structure interaction has received great attention in the past 20 years (Homaei and Yazdani 2020). Both numerical and experimental research were conducted to analyze the behaviour of groups of vertical piles under earthquake loading. More recently, the validation of the proposed model for becomes possible with the large shaking table tests carried out on soft soils and saturated liquefiable sands, which provide valuable information about the soil-pile-structure interaction for groups of vertical piles (Li *et al.* 2017, 2018, Liu *et al.* 2020, Yang *et al.* 2019). Such tests are not available for inclined piles. Among the first researchers interested in the analysis of inclined piles' performance under static load were (Meyerhof and Yalcin 1993, 1994) operated experimental studies to examine the bearing capacity of inclined piles in soil. They formulated an empirical equation to predict the ultimate strength of inclined piles under arbitrary load combinations (vertical and horizontal).

Centrifuge static tests implemented on such inclined piles revealed that the latter increases the horizontal resistance of the foundations. The major disadvantages of inclined piles, based on several research arguments, can be summarized as follow: reduction of the bending capacity due to axial forces, excessive rotation on the pile cap, Stress concentration in the pile cap, and residual bending stresses owing to the soil settlement preceding the earthquake.

Nonetheless, some recent studies combined with post-earthquake observations suggest that inclined piles can have a positive impact on the performance of both piles and supported structure (Gazetas and Mylonakis 1998, Gerolymos *et al.* 2008, Poulos 2006).

While several researchers were interested in analysing the performance of inclined piles under static loading, only a few have studied their behavior under seismic loading. (Harn 2004) related the poor performance of inclined piles, under seismic loading, to the lack of knowledge and the absence of analytical tools.

The main experimental research on the dynamic soil-structure interaction problems were conducted using centrifuge facilities (Ngo *et al.* 2019). (Okawa *et al.* 2002) conducted a comparative study between the dynamic performance of a 4x2 fixed head, an end-bearing inclined pile group, and a vertical pile group, all embedded in loose sand. They found that the inclined groups lean to decrease the acceleration amplitude on both the footing and the supported superstructure. They also stated that inclined piles decrease the maximum bending moment at the pile

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cap connection and thus changing the deformation pattern of the group. On the other hand, the results of experimental centrifuge tests conducted by (Escoffier 2012) on the seismic behavior of pile groups showed an important effect of the input frequency content and residual bending stresses (considered non-negligible) were noticed in the case of inclined piles. This latter finding related to residual bending stresses was confirmed by (Li *et al.* 2016), who examined the differences in behavior between inclined and vertical piles under sinusoidal centrifuge tests. They also found that in specific cases, inclined piles improved the resistance of inclined pile foundation system, under seismic loading. This behavior does not only depend on the earthquake's frequency content and amplitude characteristics, but also on the type of superstructure supported. At the soil's resonance frequency, the beneficial effect was found to be more significant for short superstructure. Recently, (Azizkandi *et al.* 2021) carried out an investigation on the performance of inclined piles under explosion loading. They concluded that using an inclined pile group in contrast to a vertical pile group is more desirable, especially when horizontal displacement plays an important role. Centrifuge tests were also used to model the pile-soil interaction in liquefiable slopes(Haigh and Madabhushi 2011) and to validate a simple predictive model for the evaluation of the liquefaction potential of marine sand with piles (Ghorbani *et al.* 2020).

Even though they are cost-efficient and provide valuable information for studying geotechnical constructions, they still have some drawbacks over real scale test, i.e., scale reduction, and measurement errors. That is why they should be complemented by advanced numerical modeling, which is considered to be reliable for the investigation of inclined piles.

A sub-structuring approach in the frequency domain assuming a linear elastic response was adopted by (Medina *et al.* 2015). The authors developed a coupling BEM–FEM model for the assessment of the kinematic interaction factors and the impedances functions. They found that the rake angle of the pile can be beneficial or detrimental, depending on the structural slenderness ratio. The same numerical model was used by (Carbonari *et al*. 2017) to study the effect of different pile groups' geometries and inclinations on the seismic response of bridge piers. The bridge and the piles were simulated using beam elements while taking into consideration a viscoelastic soil behavior.

The kinematic interaction analysis revealed that for the case of inclined pile group, the rotational component of foundation input motion plays an essential role in the seismic performance of the structure and thus should not be neglected for a consistent prediction of the structural displacements and stress resultants. In addition, (González *et al.* 2020) studied the influence of pile inclination on the seismic response of bridges with different span lengths and piers heights using the substructure approach. The non-linear response of the superstructure was introduced through a hinge developed at the pier's base. They proved that the kinematic seismic response of inclined piles contributed to a reduction in the ductility demand and the input dynamic energy to the system. The popularity of the sub-structuring approach is due to its simplicity and reduced computation time. However, this approach suffers from several limitations and is shown to be too simplified to reproduce the main mechanisms involved in soil structure interaction problems. Several authors pinpointed the delays generated by the sub-structuring approach, which overestimates the response of the soil-structure system subjected to dynamic loading (Abghari and Chai 1995, Mercado *et al*. 2020, Rahmani *et al.* 2016).

Full three-dimensional time history approaches are considered the most rigorous methods that reproduce correctly the soil structure interaction mechanisms and can deal with complex structural geometries and soil conditions. Using a 3D finite element modeling, (Sadek and Shahrour 2004) showed that the inclination of micropiles improves their functioning under seismic loading. It makes it possible to work better the axial component of the micropiles, which has the effect of significantly reducing the sharp force and bending moment induced by the seismic load. In 2006, the same authors (Sadek and Shahrour 2006) evaluated the influence of micropile tip end head connection on the seismic behavior of soil-micropile-structure system. The study showed that the pin connection effect is more pronounced in the group of inclined micropiles and that the embedment of the tips in a rigid layer intensely increases the internal forces, particularly at the interface between the layers. (Giannakou *et al.* 2010) simulated a three-dimensional finite element model to explore the influence of inclined piles on the seismic performance of the linear elastic soil pile structure system. The analysis revealed that for the case of kinematic dynamic loading, the inclined piles lean to confirm their negative reputation, whereas for the case of both kinematic and inertial loading, the inclined piles may be beneficial for the structural performance, depending on the relative ratio of the overturning moment against the shear force transmitted from the superstructure. The previous numerical modeling on the soil-pile-structure interaction has yielded interesting results on the effect of pile inclination under seismic loading. Nevertheless, most of these analyses were carried out within the framework of linear elastic behavior. Among the few studies in nonlinear domain, (Alsaleh and Shahrour 2009) and (Ghorbani *et al.* 2014) conducted 3D numerical investigations on the seismic behavior of inclined micropiles considering elastoplastic behavior for the soil. They used the popular sdeMohr Coulomb model, which relies on linear elasticity. The reason for using such simulations is due to the fact that the constitutive models which aim to replicate the soil nonlinearity are often complex and rarely used in modeling. However, it is well known that the soils exhibit nonlinear behavior even at low strain levels (Jardine 1991, Sadek *et al.* 2010) and this important issue should be integrated in the soil structure interaction problems (Jaber *et al*. 2018, Maheshwari and Sarkar 2011).

This paper aims to study the influence of pile inclination on the seismic performance of the soil-pile-structure system, taking into account the soil non-linearity at a low level through the degradation of the shear modulus with the level of deformation. A three-dimensional global approach by a finite difference code FLAC 3D is used. The calculations are performed under the influence of Kocaeli earthquake. The results provide a better understanding of the effect of soil nonlinearity on the seismic response of the inclined pile-structure system.

2. Numerical model

2.1 Numerical simulation procedure

The analysis is performed through a global three-dimensional approach using the finite difference code FLAC 3D and integrating in the same model, the different components of the soil-pile-structural system.

The soil structure interaction problem under seismic loading is analyzed using a global dynamic approach. The equation of motion of multiple degrees of Freedom structure can be expressed in matrix form as follows

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \tag{1}$$

Where [M], [C], and [K] are the mass matrix, damping matrix and stiffness matrix, respectively, and {F} is the applied force vector.

For the numerical resolution, FLAC3D uses an explicit Lagrangian finite-difference scheme, which is more efficient for non-linear problems than the implicit method in terms of computational efficiency.

Viscous damping is modeled by mean of Rayleigh method, where the mass matrix is taken as a combination of the stiffness and the mass matrix as follow

$$C = \alpha.M + \beta.K \tag{2}$$

One of the important issues in dynamic soil-structure analysis is to absorb the reflective outward waves at the boundaries of the soil domain. In FLAC3D, the lateral boundaries are coupled to a free field grid via Viscous dashpots to simulate adsorbing quiet boundaries. The method consists of performing a free field calculation in parallel with the main grid model. However, to guarantee the efficiency of these boundaries, they should be positioned at a minimum distance from the region of interest. In the present study, the presence of a great mass at the head of the superstructure will originate lateral waves in the soil mass related to the inertial interaction; that's why a preliminary parametric study was conducted in order to define the required position of the lateral absorbing boundaries. Fig. 1 shows the influence of the position of the absorbing boundary on the dynamic amplification at the soil surface in the center of the model. It is well known that harmonic loads are more aggressive than seismic loads (applied in the present); that's why a harmonic wave was applied (loading frequency =1.5 Hz ; amplitude V=0.25 m/s) in order to define the position of the absorbing boundaries. It can be noticed from a value L=60 m, the error becomes negligible. That is why L=80 m was chosen for the numerical model in the present study.

On the other hand, the mesh should ensure correct wave propagation with numerical distortion. A regular mesh was adopted in the zone of interest close to the piles. The minimum size of the mesh depends on the load frequency f and the velocity of wave propagation v mainly in the vertical direction. The wavelength could be expressed as follow

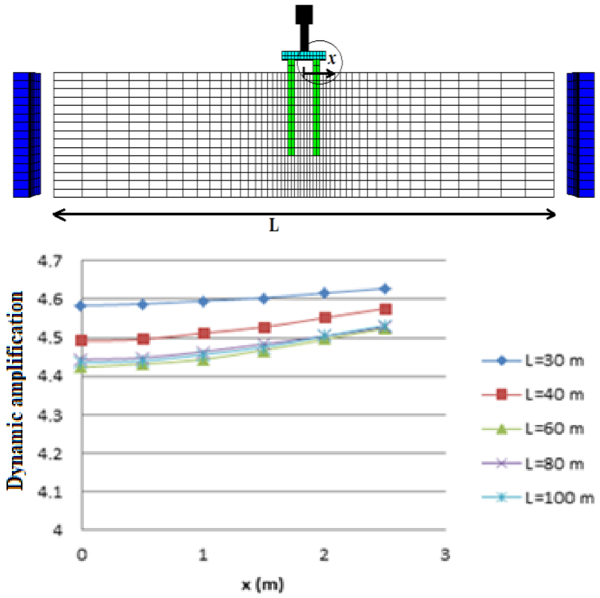


Fig. 1 Influence of the position of absorbing lateral boundaries on the dynamic amplification at the soil surface; harmonic loading (fload=1.5 Hz; amplitude=0.25 m/s)

$$\lambda = \frac{v}{f} \tag{3}$$

With v: wave propagation velocity, and f: frequency of wave propagation.

(Lysmer and Kuhlemeyer 1969) proves that the mesh size should be less than 1/8 to 1/10 of the wave length λ, in other terms, the minimum mesh size is determined as follow

$$\Delta l = \frac{v_s}{10.f} \tag{4}$$

With v_s: shear wave propagation.

2.2 3D Mesh and Model Description

The soil unbounded medium is idealized as a finite domain coupled with adsorbing boundaries. The free field boundaries are applied along the lateral boundaries in order to absorb the outward waves, while a quiet boundary is applied at the base of the model to simulate the elastic bedrock. An 8-node solid element (brick element) mesh is used for the soil as well as for the structural elements, including the piles. Indeed, the use of beam elements is not relevant for high diameters piles and could lead to erroneous results.

The superstructure is modeled as an SDOF (Single Degree of Freedom linear oscillator) system composed of a concentrated mass (200 Tons) and a column of 3 m height with a square cross-section area of 1 m2. The piles are represented by solid elements, characterized by a Young Modulus (Ep=30 000 MPa), an equivalent diameter of 1 m,

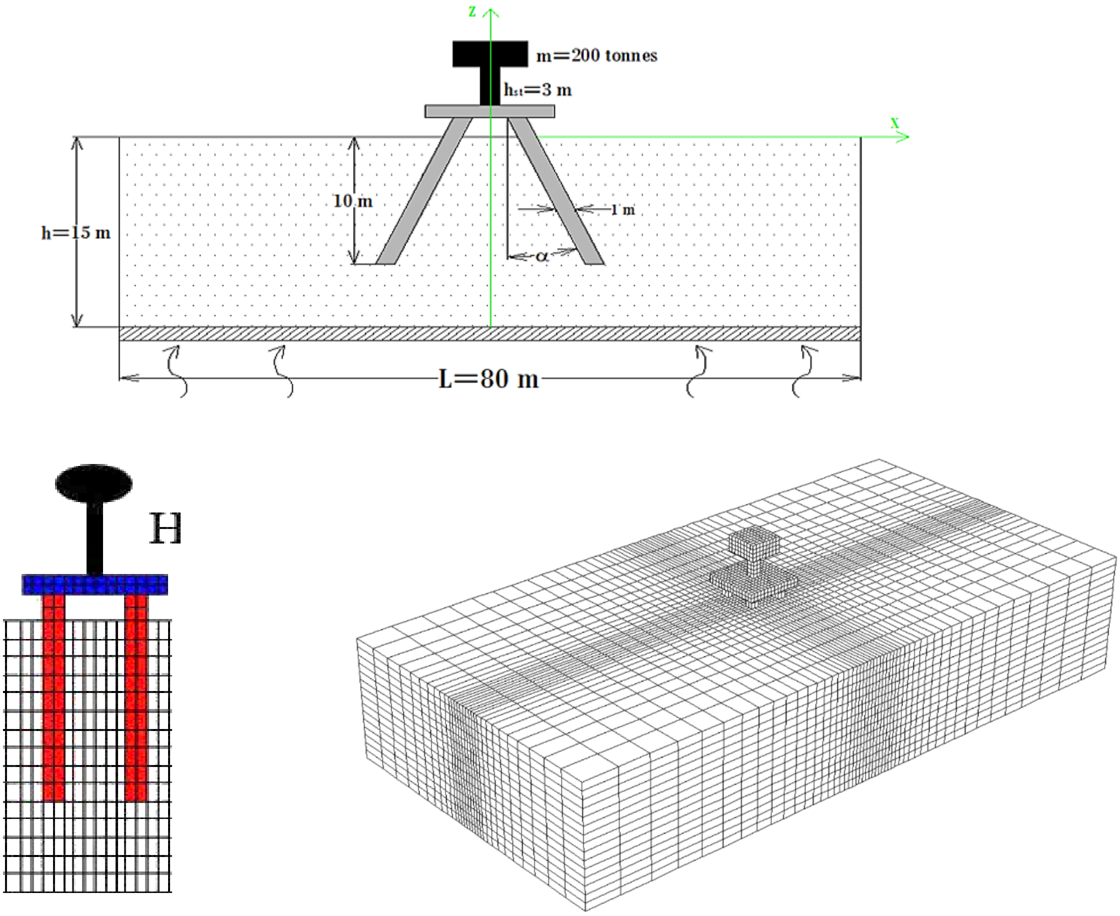


Fig. 2 Model Geometry and 3D corresponding mesh

and a length of 10 m. At the vicinity of the piles and superstructures a regular horizontal mesh refinement of 0.5 m is adopted. For the linear model, the damping ratio is assumed to be 5% for the soil and 2% for the structure and the piles. The piles are rigidly connected to a 7 m×7 m square cap 1 m thick, assumed to be free of contact with the soil, as depicted in Fig. 1. The center-to-center distance S, between the piles at the ground surface level, is 4 m. Each pile group is defined by an inclination angle α where three different configurations are analyzed for α=0°, 10°, and 20° (See Fig. 3). Note that in practice, the angle of rake is commonly in the 10°-15° range, but higher values (20°, 25° or even 30°) of inclinations were investigated in the literature in both numerical studies and centrifuges tests (Escoffier 2012, Gerolymos *et al*. 2008, Ghorbani *et al.* 2014, Medina *et al.* 2015).

Assuming a linear elastic behavior, the fundamental frequency of the soil layer is equal to fs = 1.50 Hz. The fixed base fundamental frequency of the superstructure is f_{FB} =3.22 Hz, while its flexible base frequency is f_{FL} =2.33 Hz (27% smaller than f_{FB}). The procedure to assess the structure's flexible base frequency consists of subjecting the whole system to a forced vibration followed by a free vibration phase. Analyzing the frequency content of the free vibration oscillation leads to the identification of the system's natural frequencies.

2.2 Seismic input

Fig. 4 shows the time history of the input motion and the corresponding Fourier spectrum. The load is applied at the base of the soil massif in terms of an imposed velocity, where the seismic records of Kocaeli earthquake with magnitude 7.4 and velocity 0.40 m/s is used (Parish *et al.* 2009). The dominant frequency of the input motion is about 0.9 Hz, as illustrated in the Fourier spectrum (See Fig. 4(b)). The analysis will focus on the first 6 s of the input motion, where the motion amplitude is most significant at 1 to 2 seconds (See Fig. 4(a)).

2.3 Modeling of the soil behavior

Every constitutive model available in the literature has its advantages but also its limitations. The strain thresholds for which non linearities may appear are usually of small values (10-6 - 10-4). Therefore, it's interesting to investigate the validity domain of the linear model and explore the impact of this simplification on the soil-pile-structure response. It's well known that most earthquakes exhibit or induce only one or 2 high amplitude cycles. As an alternative to a fully non-linear method, which could require excessive computational cost, sigmoidal curves (G-epsilon method), as schematically shown in Fig. 5, are well-

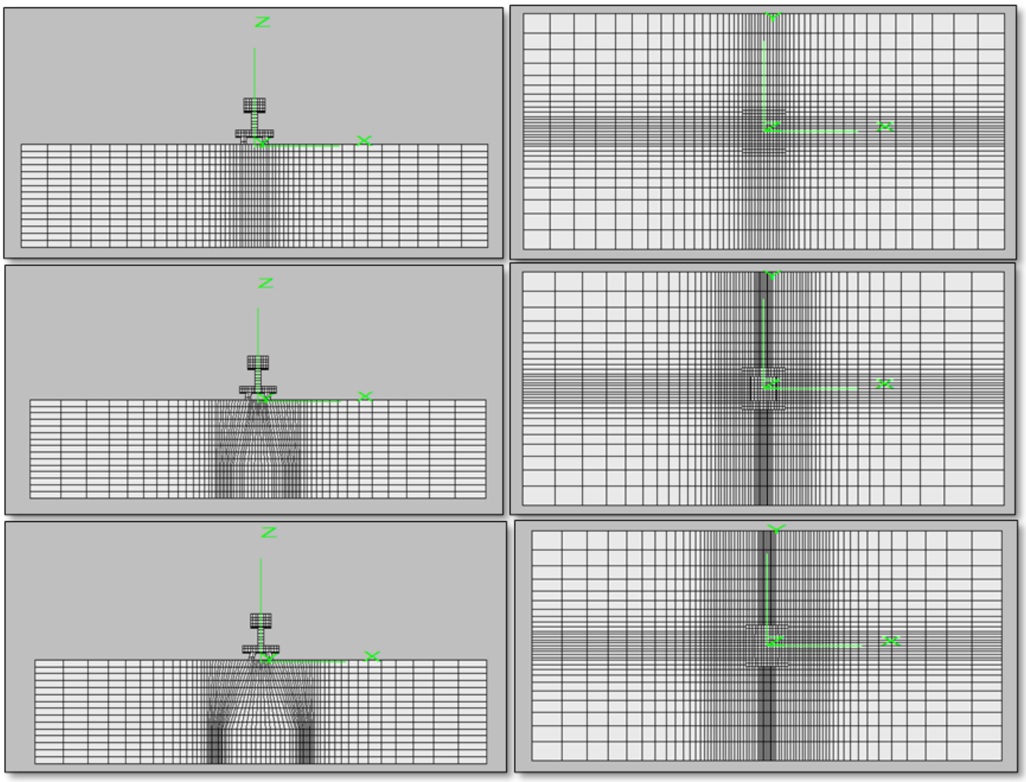
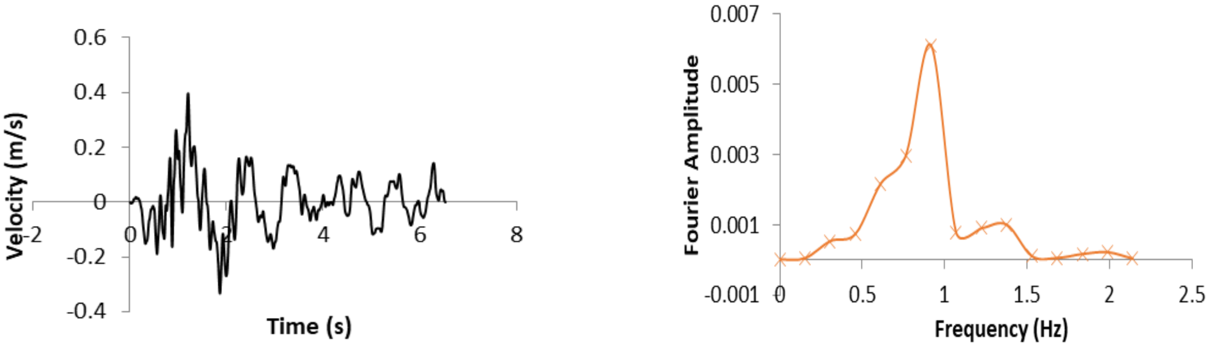


Fig. 3 Meshes adopted for different inclinations (α=0°, 10°, and 20°)



(a) Kocaeli input motion

(b) Fourier Spectrum

Fig. 4 Seismic input motions

suited for the purpose of representing modulus degradation curves. It consists of updating the value of soil modulus and damping factor at each step of the calculation. Note that for explicit schemes, the time step is significantly reduced in order to ensure a good convergence of the method. The non-linear behavior of the soil is represented by a modulus degradation curve characterized by a reduction factor Ms represented in Eq. (5).

$$M_s = \frac{a}{1+\exp(-(\log(\gamma)-x_0)/b)} \quad (5)$$

For our study, we use the following parameters for Sands, a = 1.014, b = -0.4792, x0 = -1.249 (Seed and Idriss 1969). Fig. 5 illustrates the variation of the normalized shear modulus and the hysteretic damping with the shear strain. Note that the initial characteristics of the soil are E0=39 MPa, G0=15 MPa, and ν = 0.3. These values are adopted in the case of linear behaviour.

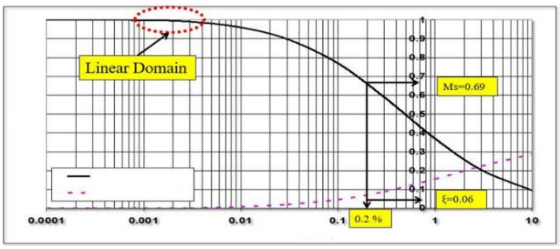
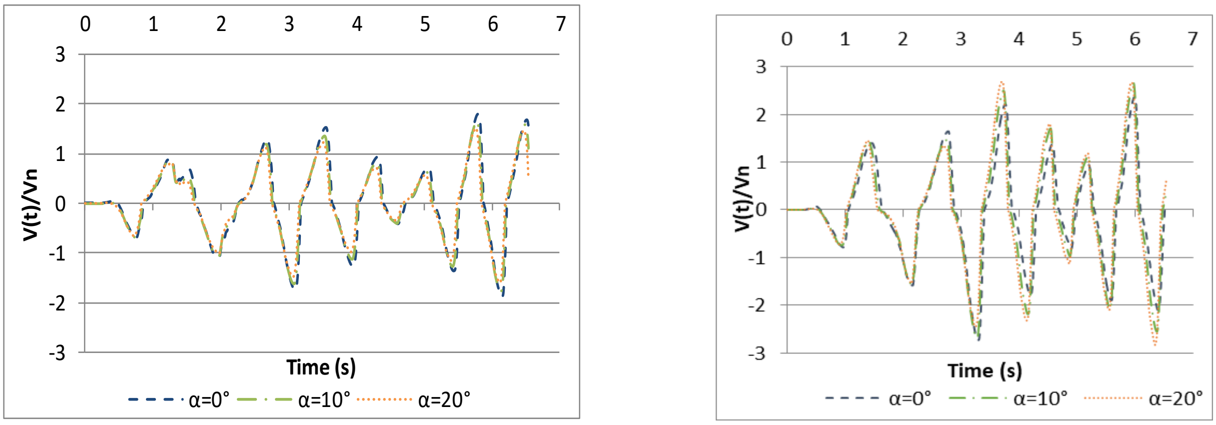


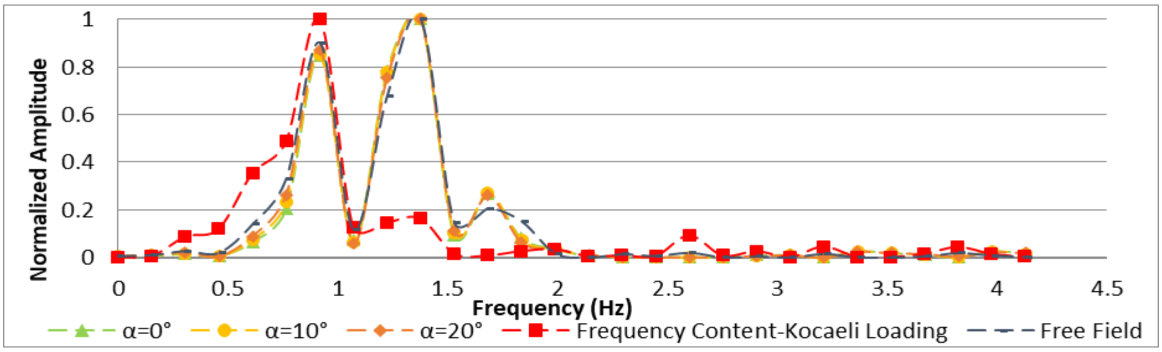
Fig. 5 Modulus reduction factor and Hysteretic Damping curves



Linear Non-Linear

Fig. 6 Dynamic Amplification of the velocity at the Mass level - Linear vs Nonlinear

Linear



Nonlinear

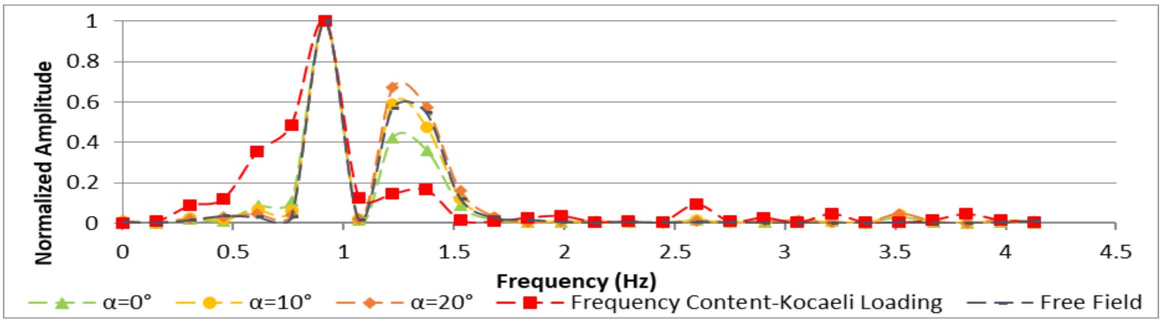


Fig. 7 Normalized Fourier spectrum of the velocity at the Mass level

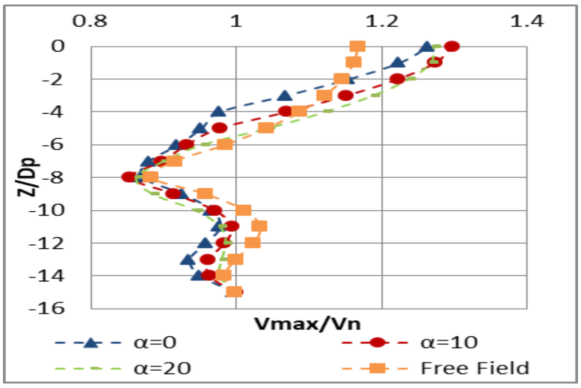
3. Results and discussions

This section is divided into two parts. The first part concerns the influence of pile inclination and soil nonlinearity on the evolution of the lateral oscillation of the soil-pile system. The second part is devoted to studying the effect of pile inclination on the seismic-induced internal forces in the piles for both soil constitutive models (linear and nonlinear).

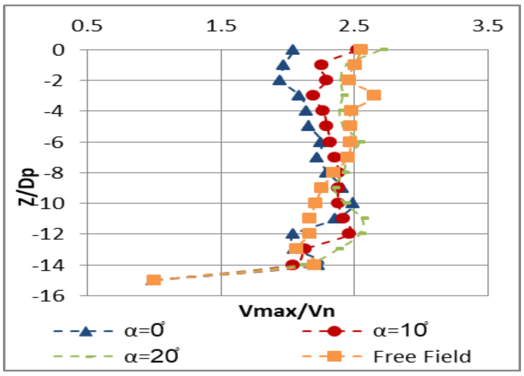
3.1 Lateral oscillation

Fig. 6 shows the history of the velocity dynamic amplification at the mass levels for both linear and non-linear models. For the linear model, the maximum dynamic amplification was observed when the piles are vertical (1.89), it decreased by 6.35% when α = 10º (1.77) and by 15.34% when α=20º (1.60). The decrease in the amplification is directly related to an increase in the lateral stiffness of the substructure and the whole system.. In contrast, when we compare these results with those obtained in the non-linear domain, we see that the change in the maximum dynamic amplification with inclination α in the non-linear domain is not significant (only 1.46% when α = 10º and 4.03% when α = 20º). This could be attributed to the soil-non linearity at the soil-pile interface, where higher non linearities might be developed for inclined piles.

Peak values of the dynamic amplifications of the soil are also given in Table 1. It can be noticed that the variation of the maximum dynamic amplification with the inclination α is less significant in the nonlinear domain when compared to the linear one. However, when comparing linear to non-

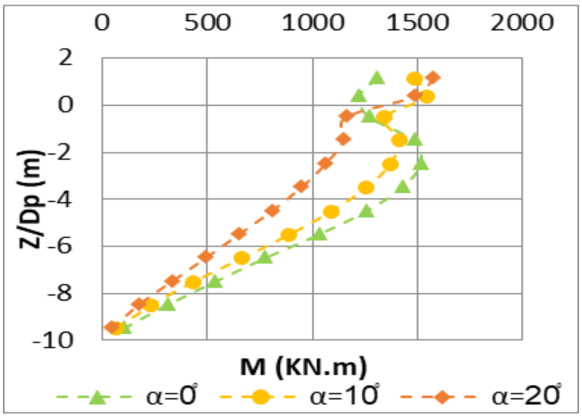


Linear

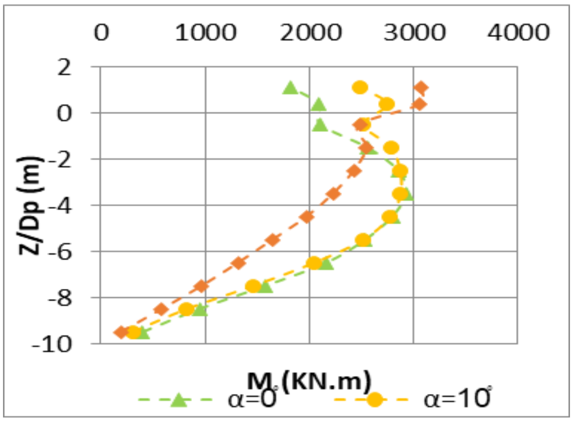


Non-Linear

Fig. 8 Dynamic Amplifications of the soil at the Center of System - Linear and Nonlinear



Linear



Non-Linear

Fig. 9 Maximum Bending Moment-Linear and Nonlinear

Table 1 Maximum Dynamic Amplification of the soil, Linear and Non-linear

	Linear				Non-Linear			
Inclination	Free Field	α=0°	α=10°	α=20°	Free Field	α=0°	α=10°	α=20°
Dynamic Amplitude	1.17	1.26	1.30	1.27	2.65	2.50	2.53	2.7
Difference (%)	-	7.69	11.11	8.55	-	-5.66	-4.53	1.89

linear behavior, the latter shows larger values than those obtained when linear behavior is assumed. This result breaks the popular concept stating that nonlinear behavior accompanied by higher damping will automatically lead to a reduction in the system response. Indeed, the phenomenon is more complicated and depends on several parameters such as the frequency content of the loading and the different resonance frequencies of the soil structure system.

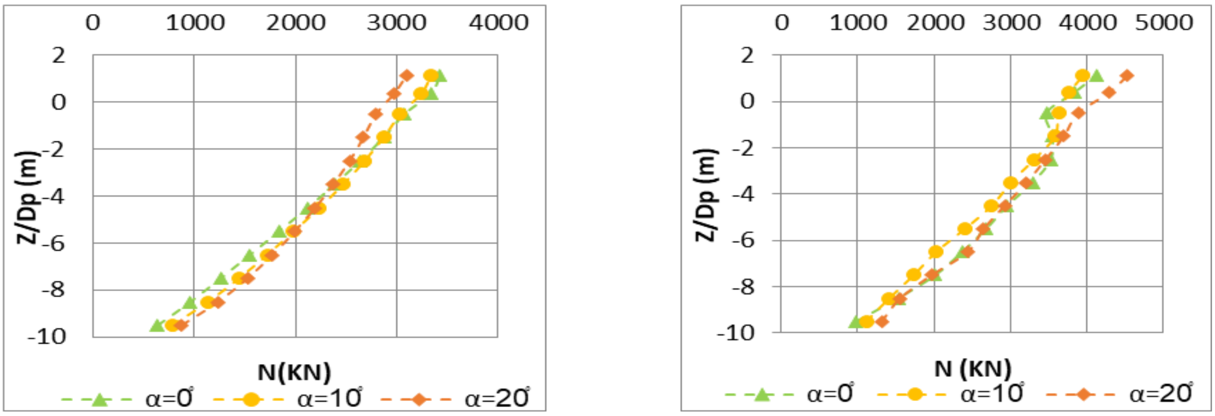
Fig. 7 depicts the normalized Fourier spectra of the velocity that occurred at the mass level together with the loading and the free field. The linear model shows the presence of two dominant peaks which correspond to the peak loading frequencies (loading = 0.9 and 1.37 Hz), whereas the nonlinear model shows the significant peaks, and amplification at the lower frequency of 0.9 Hz. Non-linear behavior leads to higher dynamic amplification at low frequencies, which could be explained by the decrease in rigidity for high shear strain levels of the soil.

The profiles of dynamic amplification with depth are shown in Fig. 8, for different inclinations. For linear behavior, the effect of higher modes of vibration and a higher dynamic is observed at low depth in comparison to the free field (z, 2Dp) which could be explained by the inertial effect due to the oscillation of the superstructure. Moreover, the maximum dynamic amplification obtained at the soil center for the inclined piles group (α=10 and 20°) is slightly higher than those obtained for the vertical piles group. On the other hand, the profile of the dynamic amplification observed in the nonlinear model is completely different from the linear one. It's clear that the effect of higher modes is less significant in this case. Once again, at the upper part of the soil mass, the profile of dynamic amplification shows larger values in the case of inclined piles in comparison to the vertical piles group.

3.2 Internal forces

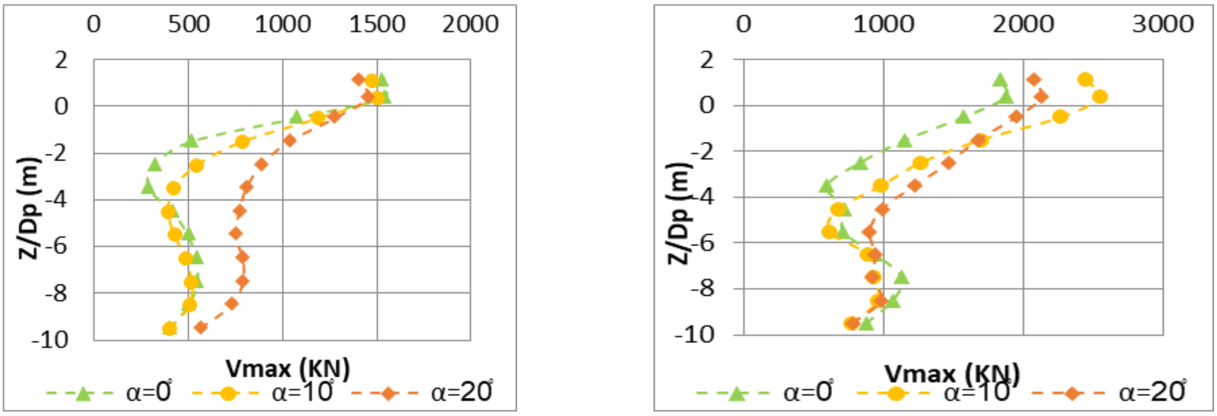
The influence of inclination (α) on the seismic induced internal forces in the piles for both linear and nonlinear models is illustrated in Figs. 9-11.

By examining the influence of the pile inclination on the maximum bending moment (Fig. 8), it is found that for both



Linear Non-Linear

Fig. 10 Maximum Axial Forces-Linear and Nonlinear



Linear Non-Linear

Fig. 11 Maximum Shear Forces-Linear and Nonlinear

domains (linear and nonlinear), the maximum moment is localized in the span for vertical piles (α=0°) and in the pile-head interface for inclined piles (α=10° and 20°). It is noted that with respect to the vertical piles, the maximum bending moment at the span (z ≈ 4Dp) decreased by 6.76% and 1.69% for α=10º, and by 23.47% and 12.98% for α=20º for linear and nonlinear models, respectively. On the other hand, the bending moment at the pile-head interface increased by 14% and 31.39% for α=10º and by 20.84% and 47.04% for α=20º when compared to the results obtained for α = 0º. Regarding the axial forces, the maximum span value slightly increases with the inclination and the ultimate value of the axial force is located at the pile-head interface for both soil models. In contrast, it is witnessed that in the nonlinear domain, the axial force at the head pile interface has its maximum value for α=20°, whereas for the linear model, this value decreases with the inclination (See Fig. 10). This is related to the variation of dynamic amplification of the superstructure with inclination.

Concerning the shear forces of both models, it is observed that the effect of kinematic interaction is more important (See Fig. 11). Indeed, close to the center zone of the piles, the inclined piles are subjected to higher shear forces compared to vertical ones, and a significant discrepancy is observed between α=0° and α=20°. At the piles' head, the inclination led to a slight decrease in the maximum shear force in the case of a linear model, while the opposite is observed for non-linear model.

The effect of the soil constitutive model on the seismic response of the inclined pile-structure system is studied as well. In particular, the influence of soil degradation with the level of deformation on the system response (soil non-linearity). It is observed that soil degradation leads to an increase in the internal forces for the three pile inclinations. Further, the bending moment M, the axial force N, and the shear force V are not only controlled by the mass' acceleration of the superstructure and the response of the soil and piles, but also by the state of the soil surrounding the piles, in particular on the surface. The linear elastic model represents the soil with a single Young's modulus value that doesn't depend on the stresses. Consequently, the soil stiffness is calculated at the beginning, based on the starting stresses, then remains constant for the whole analysis. The overestimated stiffness value in the linear elastic model with respect to the degrading strain-dependent stiffness in the nonlinear behavior, justifies the decrease in results in the linear elastic domain.

In addition, the adoption of a nonlinear elastic model causes an increase in amplification at the structure level,

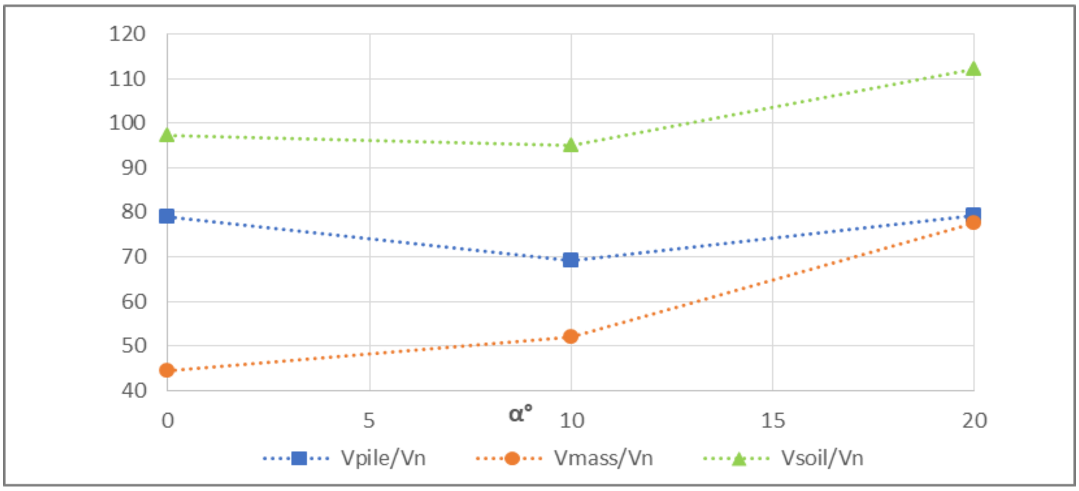


Fig. 12 Trend of Variation in the Dynamic Amplification of Pile, Soil and Mass between Linear and Nonlinear

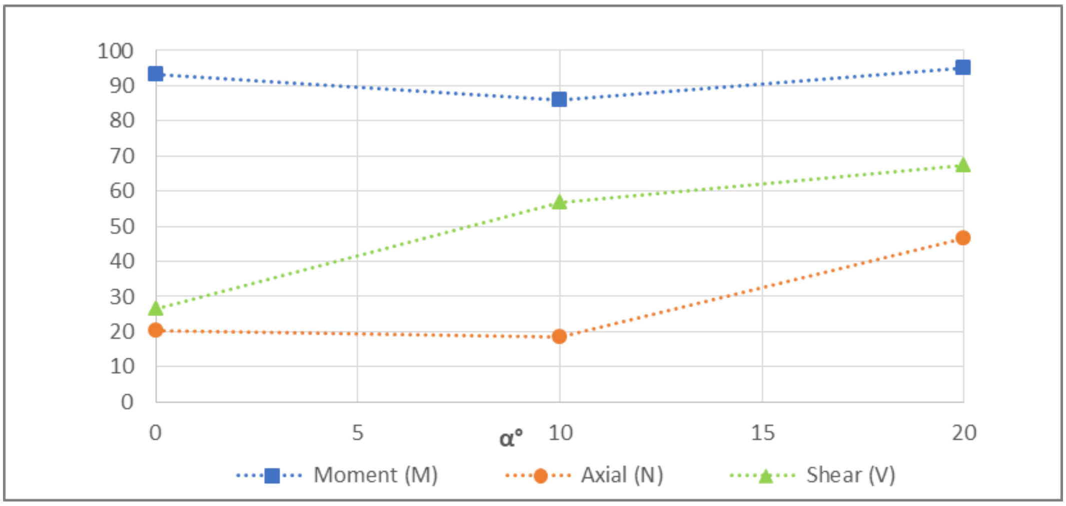


Fig. 13 Trend of Variation of Internal Forces Straining the Pile under Study between Linear and Nonlinear

which can reach 52% and 77.5% for α=10° and α=20° respectively (See Fig. 12). The increase in the amplification of the nonlinear system also leads to such increase in the efforts at the piles, especially for the bending moment and the shear effort. The bending moment and the shear force obtained with a nonlinear system inclined by 20 ° are of the order of 95% and 67%, respectively, larger when compared with those corresponding in the linear system. The trend of variation of the internal forces induced in the pile studied in the nonlinear domain compared to that obtained in the linear domain for the three cases of inclination is shown in Fig. 13 that highlights the importance of integrating the nonlinear behavior in the assessment of the dynamic response of the piles.

4. Conclusions

The present study assessed the influence of pile inclination and soil behavior on the seismic response of the soil-pile-structure system. This was accomplished by taking into consideration three different pile inclinations (0°, 10°, and 20°), as well as considering two different constitutive models (linear and nonlinear). The investigations were performed under the influence of the Kocaeli earthquake. The main conclusions drawn from this survey are:

- The soil nonlinearity results in increasing the amplification at the level of structure and controlling the tensor of internal forces that stresses the piles. Therefore, the linear elastic model revealed its inadequacy in this paper in presenting the real dynamic behavior of the soil-pile-structure system. The use of linear model should be limited for low amplitude shakings.
- The seismic response of the pile-soil-structure system depends on several parameters like the loading amplitude and its frequency content, the resonance frequencies of the soil and structure, and the inclination of the piles. When nonlinear behavior is taken into account, special attention should be given to low frequencies due to the soil softening.
- For non-linear model, the profile of dynamic amplification in the upper part of the soil mass shows higher values in the case of inclined piles in comparison to vertical piles' group. However, the influence of inclination on the dynamic amplification at the mass level is not very significant. On the other hand, the influence of inclination is notable in terms of the seismic induced internal forces in the piles,

mainly the bending moment and the shear force. For the studied case, it was observed that for the center zone of the piles governed by the kinematic interaction, the inclination leads to a reduction of the bending moment while the pile-to-head connection remains the most important disadvantage of the use of inclined piles because of the moment increase. Regarding the shear force in the piles, it increases with the increase of inclination for both the center zone and the pile head.

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