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NUMERICAL MODELLING OF PILES GROUP UNDER SEISMIC LOADING IN COHESIVE SOILS: INCLINATION EFFECT

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Abstract. *The system piles-foundation is widely used to ensure the stability of structures when subjected to seismic excitation. The analysis of the seismic response of soil-pile-structure systems constitutes a complex problem in earthquake engineering. Previous studies showed that the damage of piles in seismic area is mainly attributed to the kinematic interaction between piles and soils or (and) to the inertial interaction between the superstructure and the pile foundation which may cause foundation damages. In this paper we present a global numerical modeling of the pile-foundation-pile-cap-structure interaction using FLAC3D Software. The study is conducted by using measures recorded during real earthquakes. The influence of plasticity is investigated for cohesive soils where the soil behaviour is described using Mohr–Coulomb criterion. Moreover, the efficiency of inclined piles in seismic zones is commented, and a parametric study according to piles inclination is also performed. The analysis of the results could give the best piles group configuration in order to minimize the seismic effect on the structures.*

1 INTRODUCTION

Lebanon, which is of special topography of high and steep slopes, is exposed to a high seismic risk because it is crossed by one major and few secondary faults where someone have been discovered recently [1]. Due to demographical and social factors, new constructions in Lebanon are being settled in precarious sites which are often vulnerable to natural disasters. In order to minimize the effect of earthquakes on structures, there is a must of enhancing the foundations of old or new constructions in vulnerable areas.

In the past, several destructive earthquakes have been occurred in Lebanon (years 551, 1202, 1759, 1837 and 1956). Moreover, many earthquakes, of low magnitudes between three and five, have been registered in Lebanon during 2008. These events have increased the anxiety of Lebanese people because of the poor quality of the constructions and their behavior under moderate or severe earthquake events.

The system piles-foundation constitutes an appropriate way and it is commonly used to ensure the stability of constructions when subjected to seismic excitation. However, the analysis of the seismic response of soil-pile-structure systems is a complex problem in earthquake engineering. The phenomenon of soil-pile-interaction structure is complex as it involves many interactions such soil-pile, pile-pile, pile-cap and the whole soil-pile-cap-structure system. Due to the importance of this problem, several studies were conducted including experimental, analytical and numerical attempts to highlight the behavior of such interactions under seismic loading.

In addition to post-earthquake investigations, analytical and numerical analyses show that the damage of piles in seismic area is mainly attributed to the kinematic interaction between piles and soils and/or to the inertial interaction between the superstructure and the pile foundation which may lead to foundation damages, particularly at the pile-cap connection.

Full 3D nonlinear analyses including the soil, piles and the superstructure are still limited. Such studies ([2], [3], [4], [5] and [6]) were conducted in the linear domain to analyze the influence of micropiles inclination and boundaries conditions on the seismic behaviour of the soil-micropile structure system. In the other way, a full 3D finite element analysis was performed to investigate the seismic performance of inclined piles assuming a linear behaviour of the soil and the structure [7].

This paper includes a full 3D coupled modeling of the soil-pile-superstructure interaction under seismic loading considering the elastoplastic behaviour of the soil material. Analysis is performed using the FLAC3D (Itasca, 2005) program under real earthquake records (Kocaeli, 1999). The influence of plasticity is investigated for coherent soil where the soil behaviour is described using the simple and popular non-associated Mohr–Coulomb criterion largely used in engineering practice. The last part discusses the efficiency of inclined piles in seismic zones. Using inclined piles in seismic zones is generally not recommended by international codes, especially when piles are anchored in hard substrata. However, the analysis of the Loma Prieta earthquake ([8], [9] and [10]) showed that structures based on inclined piles were less affected or damaged than other structures.

2 NUMERICAL STUDY OF SOIL-PILE-STRUCTURE SYSTEM

A three-dimensional numerical modeling by finite differences using the software FLAC3D is used in this study to model the soil-pile-structure interaction problem. This part presents and discusses the details of the numerical modeling. We provide a better understanding of the interaction pile-soil-pile-cap-structure by adopting two types of seismic loading. The first type is harmonic and the second uses real recordings of the earthquake occurred in Turkey (Kocaeli, 1999).

For a given configuration of piles, the study was done in the case of coherent soil. The effect of soil behaviour on the system response was investigated by adopting respectively a linear and nonlinear behavior using the type elasto-plastic Mohr-Coulomb. Boundary condition used to simulate the infinite medium that surrounds the soil-pile models is discussed next.

2.1 Modeling description

Figure 1 shows a schematic representation of the numerical model, which contains a group of four piles of 1m of diameter and 10m of length, located in a 15m of a homogeneous soil. Piles are fixed in a cap of 1m thick with no contact with the ground, and supported a superstructure of column height H_{st} = 1m and a concentrated mass m_{st} = 100 tons placed on the top of the column and modeled by a single degree of freedom system. The spacing between piles is $S=3.75D_p$, where D_p is the diameter of the pile. The behaviour of the soil-pile-structure system is assumed to be elastic with Rayleigh damping. The fundamental frequency of the soil layer is equal to f_1 = 0.67 Hz. The rigidity (K_{st}) and the frequency of the superstructure (f_{st}), assumed fixed at its base, are calculated using the following expression:

$$K_{st} = \frac{3(E_{st} I_{st})}{H_{st}^3} \quad (1)$$

$$f_{st} = \frac{1}{2\pi}\sqrt{\frac{K_{st}}{m_{st}}} \quad (2)$$

Using equations (1) and (2), K_{st} = 86400 KN/m and f_{st} = 1.48 Hz.

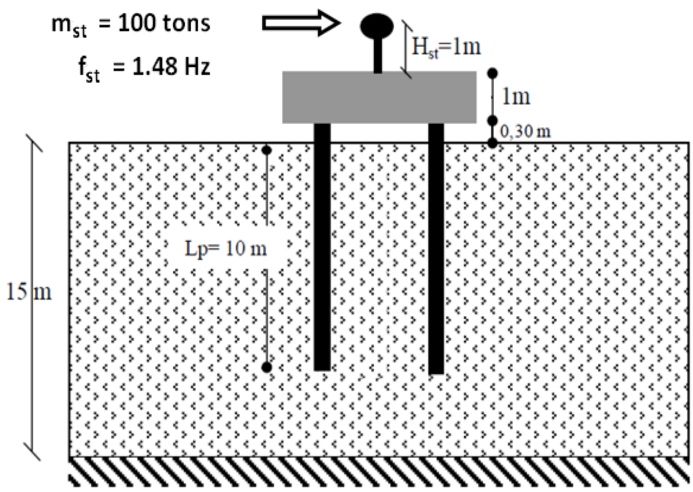


Figure 1: Modeling presentation.

2.2 Modeling mesh and boundary conditions

Figure 2 represent the mesh of the numerical model. Meshing was refined around piles and the area near the superstructure where the inertial forces induce high stresses. The basis of soil is assumed rigid. Transmitting boundary conditions are used to reduce wave reflections at model boundaries which are placed far enough from the structure with the use of finite elements and absorbing boundaries called "free field". The soil columns in the boundaries can be made to respond to the input motion, or for computational efficiency, free field displacements with time, computed separately, can be given as boundary conditions for the soil column nodes.

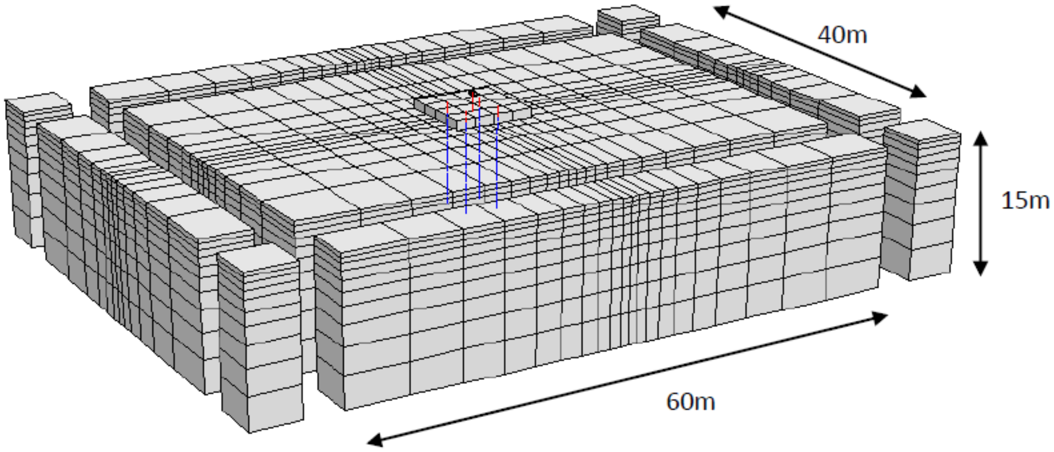


Figure 2: Modeling mesh and boundaries.

2.3 Mechanical properties of soil-pile-structure system

The soil and pile were modeled with elastic material with the properties given in Table 1. Rayleigh's damping was also incorporated in this study with 5% critical damping. The base was fixed while lateral boundaries were set as described in section 2.2.

Material	Density ρ (Kg/m^3)	Young's modulus E (MPa)	Poisson's ratio υ	Damping ratio ξ	Axial rigidity (MN)	Flexural rigidity (MN.m^2)
Soil	1700	8	0.45	5%		
Pile	2500	24000	0.30	2%	E_p*A_p = 18850	E_p*I_p = 1178
Structure	2500	24000	0.30	2%		

Table 1: Mechanical properties of soil-pile-structure system.

2.4 Seismic loading

In a seismic analysis, seismic load can be applied either as a displacement, acceleration, or velocity time history at the base of the model. In this paper, we provide a better understanding of the interaction pile-soil-pile-cap-structure by adopting two types of seismic loading. The first type is harmonic and the second uses real recordings of the earthquake occurred in Turkey (Kocaeli, 1999).

Initially, numerical simulations were performed with a harmonic load of 10 cycles, with a frequency equal to the fundamental frequency of the soil (floading = $f_{1,sol}$ = 0.67 Hz), and an acceleration amplitude of 0.2g (V_g = 0.46 m/s).

The real seismic loading chosen is registered in Kocaeli in Turkey 1999 (Station Ambarli; KOERI source). This loading is applied as a speed at the base of the soil mass. It marks a maximum speed of 40 cm/s and a maximum acceleration of 0.247g see Figure 3. It is found that the frequencies involved are lower than 3 Hz with a maximum peak corresponding to f=0.9 Hz, which is between the fundamental frequency of soil (f_1 = 0.67 Hz) and that of the structure (f_{st} = 1.48 Hz).

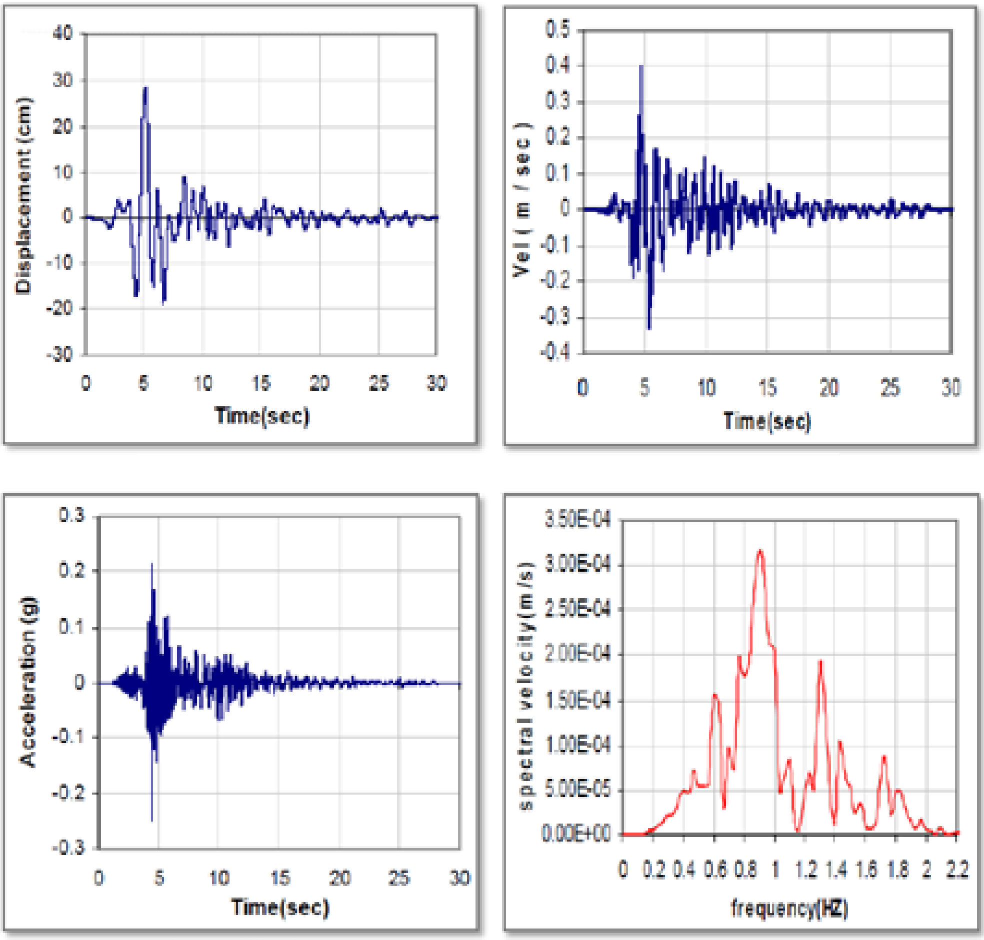
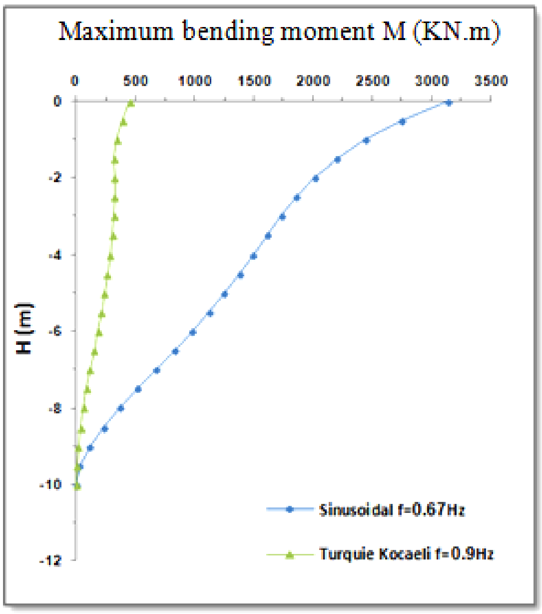


Figure 3: Real seismic loading -Turkey, Kocaeli.

3 DYNAMIC FORCES IN PILES

Figure 4 and table 2 shows the forces induced in the piles due to the real seismic loading of Kocaeli, of frequency f = 0.9 Hz. These forces are compared with forces induced in piles due to the harmonic load of frequency f = 0.67 Hz. Figure 4 shows a significant influence of the dominant frequency loading that can lead to significant efforts values exceeding the bearing capacity of piles and especially when this frequency equals to the natural frequency of the soil.



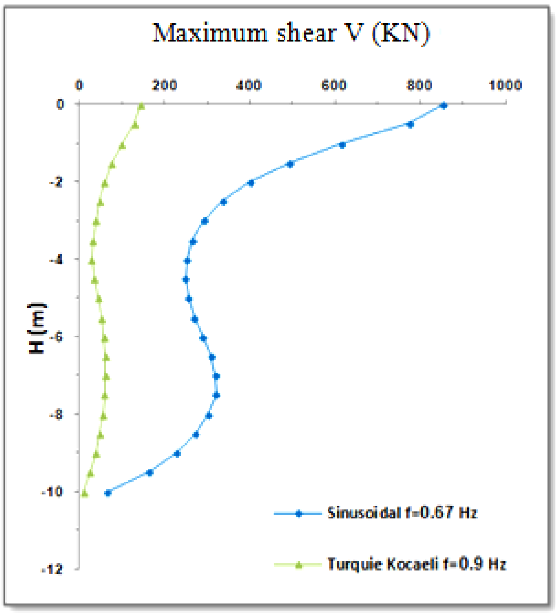


Figure 4: Maximum dynamic forces in piles.

Loading	Acc mass (m/s^2)	Acc cap (m/s^2)	Max shear force V (KN)	Max bending moment M (KN.m)
Sinusoidal	34.71	33.1	854.8	3137
Turkey, Koacaeli	7.36	5.4	145	453.8

Table 2: Response of piles for different types of loading.

4 SOIL PLASTICITY

Since the aim of this study is to understand the effect of nonlinearity on the behaviour of the soil-pile-structure system, in particular, the influence of soil plasticity on the system response, nonlinear soil models were used in the 3D finite element analyses. Numerical simulations are performed using real seismic loading (Turkey, Kocaeli 1999). The influence of plasticity is investigated for coherent soil where the soil behaviour is described using an elastic-perfectly plastic Mohr–Coulomb criterion.

4.1 Plastic calculation

The effect of plasticity for coherent soil on the seismic behaviour of the soil-pile-structure system is verified by a parametric study. To study the effect of plasticity cohesive soils on the seismic response of piles, calculations were performed with several values of cohesion (C = 20, C = 50, C = 100 kPa). The characteristics of the soil layer are given in Table 3. A slight Rayleigh damping is used for the soil to avoid the pseudo-resonance in small shear deformation. System behavior cap-structure is assumed to be elastic. The mesh is identical to that shown before.

ρ_s (Kg/m^3)	E_{0s} (MPa)	υ_s	K_0	ξ_s (%)	C (KPa)	ϕ (°)	ψ(°)
1700	8	0.3	0.5	5	2-50-100	0	0

Table 3: Mechanical properties of coherent soil.

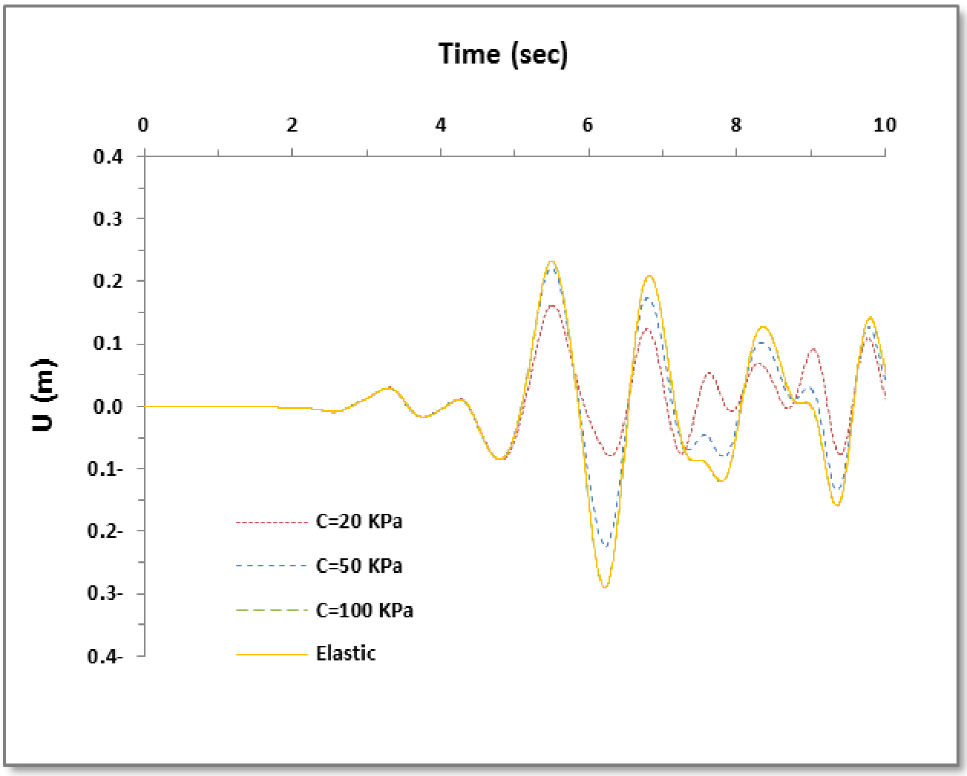


Figure 5: Amplification of the lateral displacement at the top of Superstructure in function of soil cohesion (Kocaeli, Turkey, Vg = 40 cm /s, f_{ch} = 0.9 Hz, A_g = 0.247g)

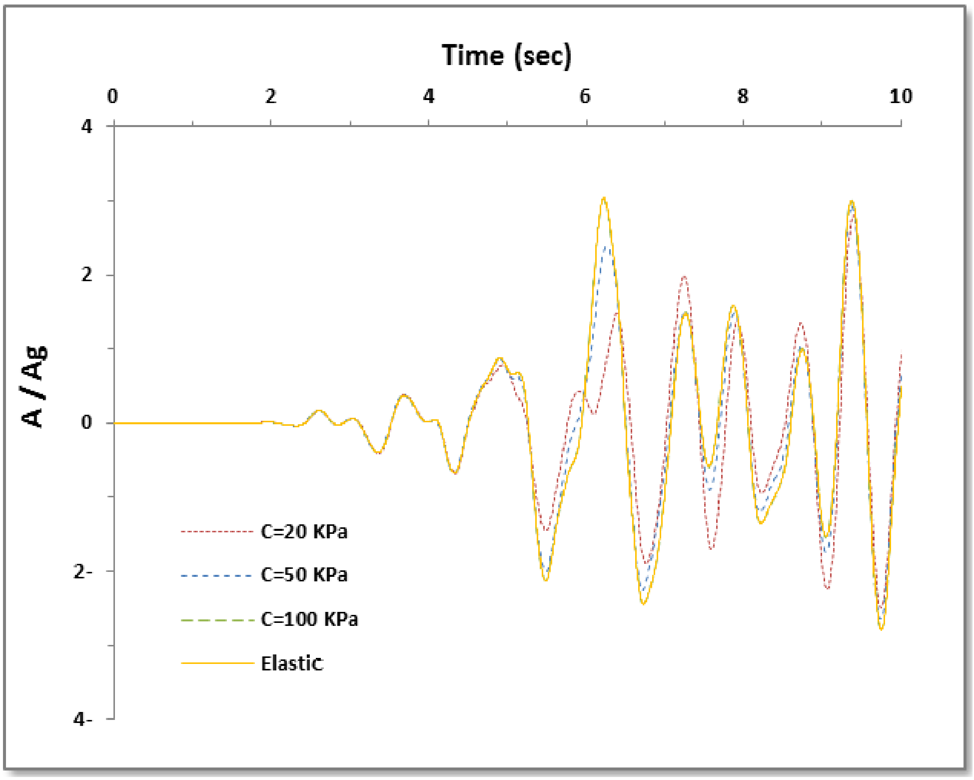
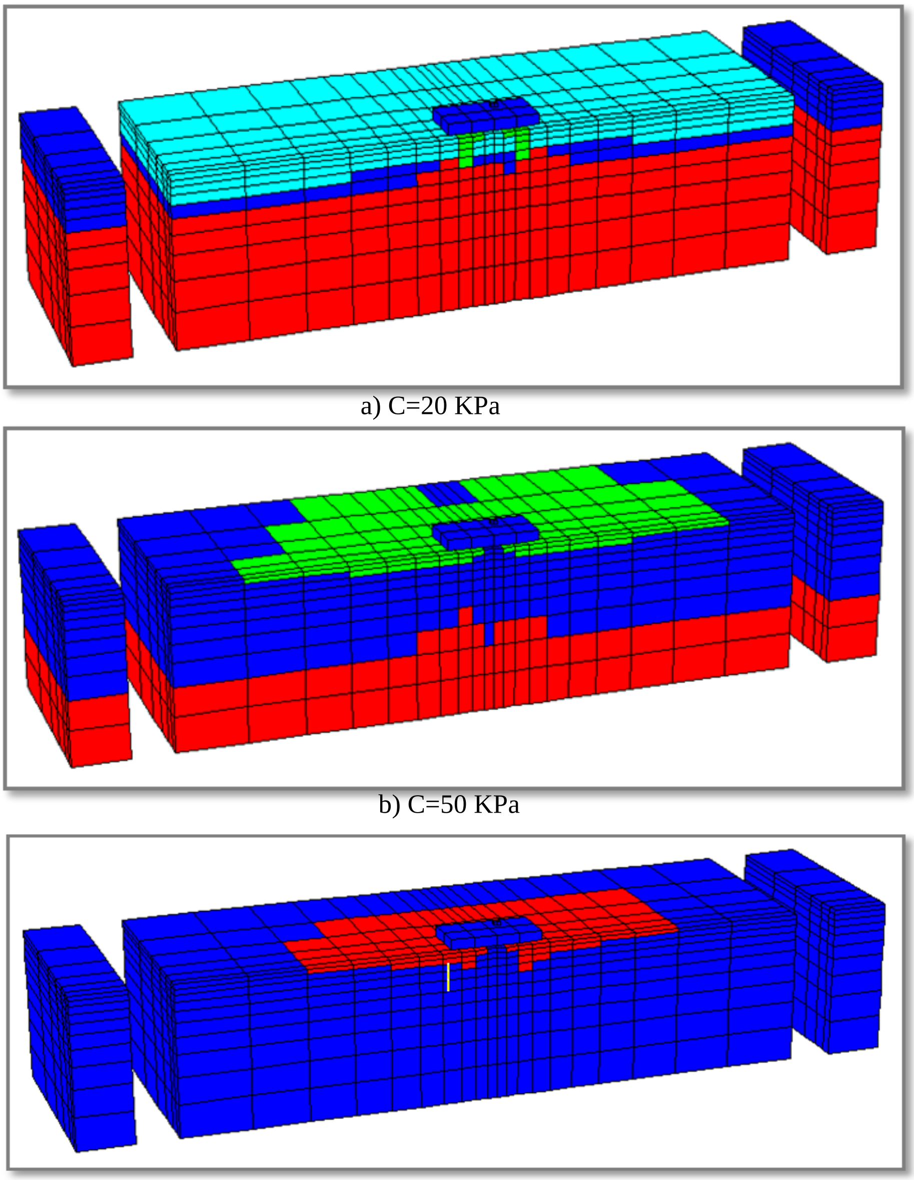


Figure 6: Amplification of the lateral acceleration at the top of Superstructure in function of soil cohesion (Registration of Turkey, Vg = 40 cm /s, f_{ch} = 0.9 Hz, A_g = 0.247g)

The Figures 5 and 6 illustrate a comparison between the elastic response and elasto-plastic. We observe that the two responses are identical at the beginning of loading until a time equal to 2.5 s. Beyond this time, the soil begins to plasticize and the two responses diverge in particular in the case of cohesion C = 20 kPa. The elasto-plastic response becomes weakened due to the damping induced by the plasticity of soil.

4.2 Extension of plasticity

The extension of plasticity under seismic loading for the three values of cohesion is shown in Figure 7. The soil behavior is usually elastic with cohesion of 100 kPa (Figure 7-c). Decreasing cohesion, the plasticity spreads from the base and extends near the surface, (Figure 7-a). Note that, for a coherent soil, the plasticity criterion is exceeded at the base of the soil, which leads to a high energy dissipation and transmission of waves on the surface.



a) C=20 KPa

b) C=50 KPa

c) C=100 KPa

Figure 7: Extension of plasticity (C=20 KPa, C=50 KPa and C=100 KPa).

4.3 Comparison of Numerical Results in Elastic Zone and Elasto-plastic One

Figure 8 shows the internal stresses induced in piles. The variation of the maximum shear force at the top is related to the change of acceleration. For the bending moment, the results at the top are not significantly affected by the change of the angle of dilatancy. The results are illustrated in Table 4.

C (KPa)	Acc mass (m/s^2)	Acc cap (m/s^2)	Max shear force V (KN)	Max bending moment M (KN.m)
Elastic	7.360	5.777	145	453.8
20	6.783	3.232	144.1	292.3
50	7.113	4.574	156.5	421.2
100	7.322	5.6	168.9	455

Table 4: Influence of coherent soil plasticity on the dynamic forces in the piles.

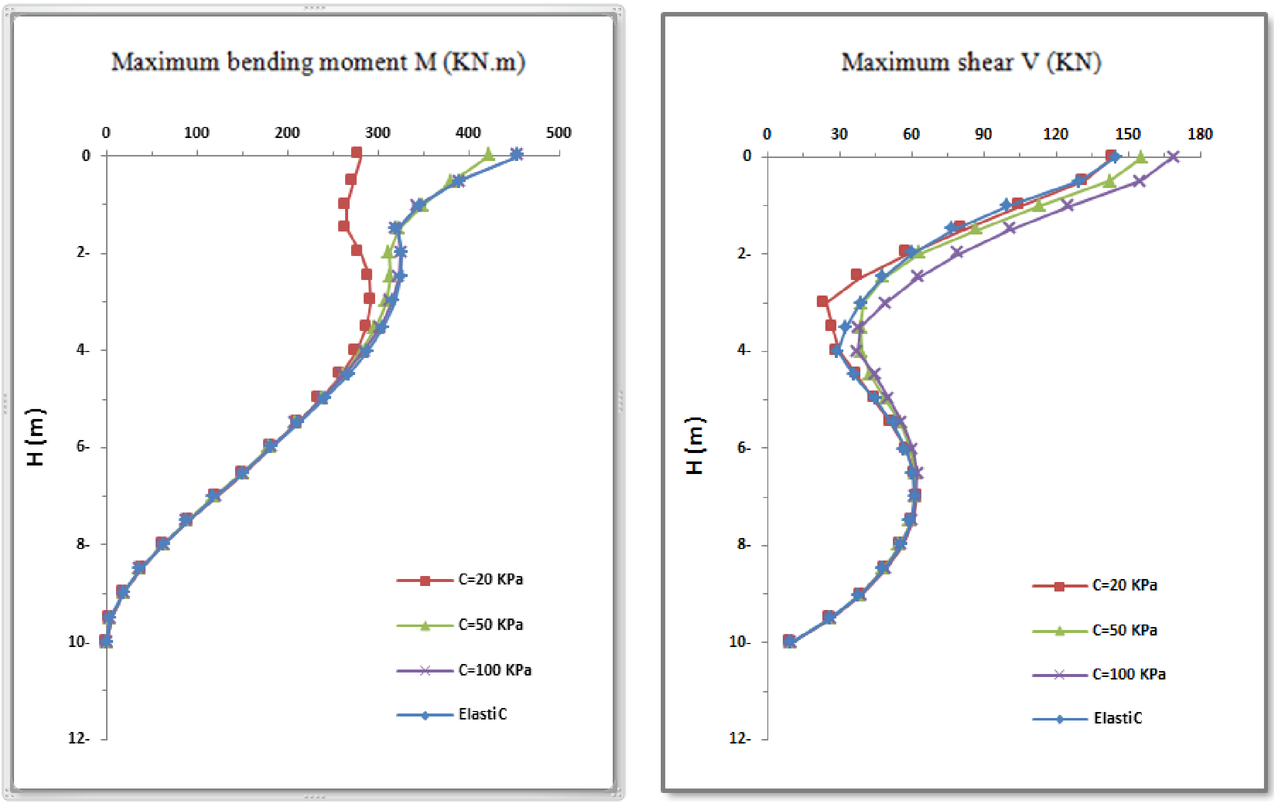
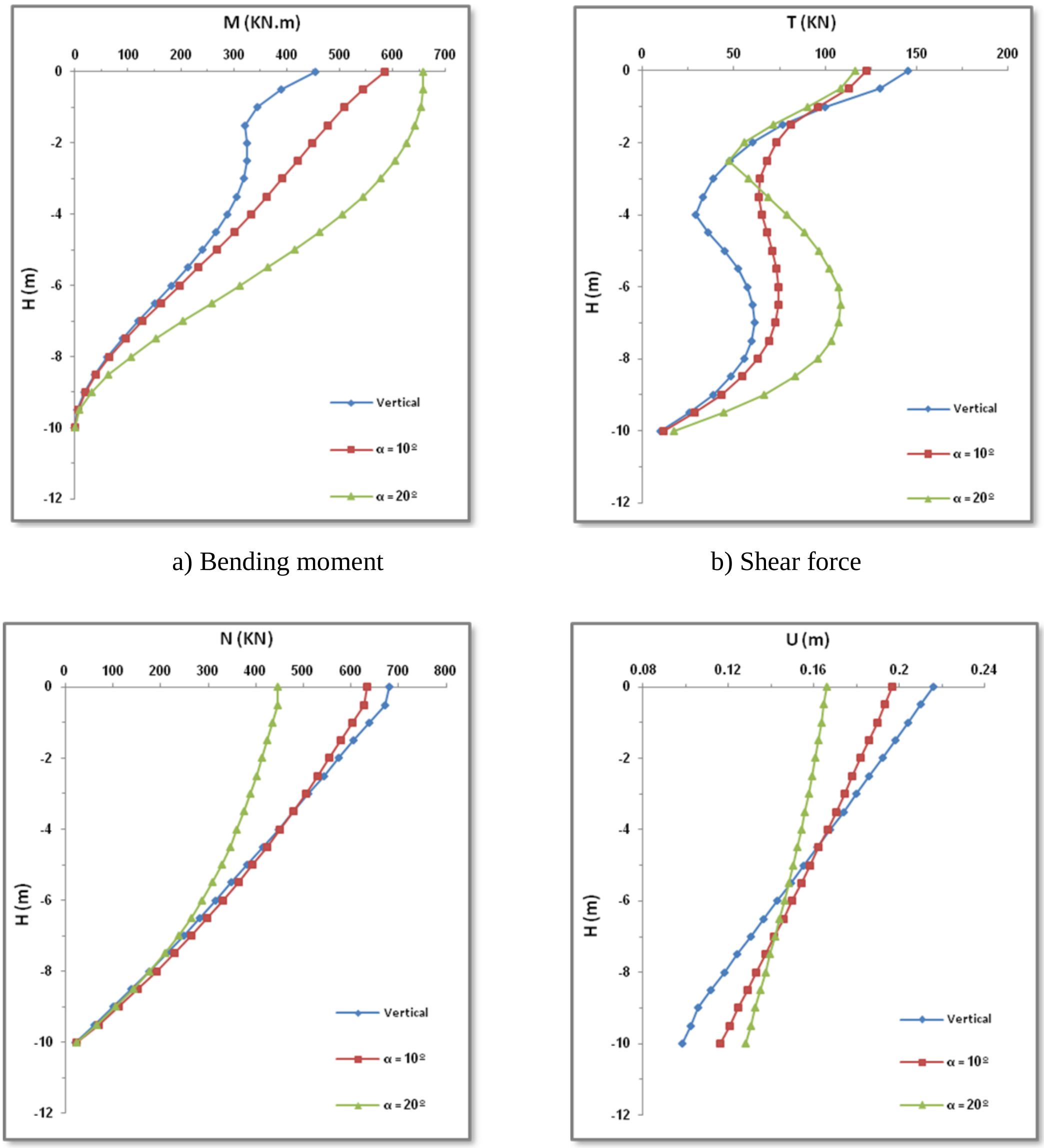


Figure 8: Influence of coherent soil plasticity on the dynamic forces in the piles (Kocaeli earthquake, Turkey 1999).

5 EFFECT OF INCLINATION

The model studied in this part is exactly the same presented above, except that the four piles are inclined outwardly by two angles α = 10º and α = 20º. To properly analyze the influence of pile inclination on their seismic response, results of calculations are presented for the two values of inclination. For convenience, the normal force and the shear force are normalized by the maximum inertial force induced at the top of the superstructure. Meanwhile, the bending moment is normalized by the maximum overturning moment induced by the inertial force at the base of the superstructure. The results are summarized in Fig. 9 and Table 5.



a) Bending moment

b) Shear force

c) Normal force

d) Displacement

Figure 9: Influence of inclination of piles on the seismic response of pile groups (Registration of Turkey, V_g = 40 cm/s, f = 0.9 Hz, A_g = 0.247g)

	α = 0º	α = 10º	α = 20º
Amplification at the head of cap	5.40	5.217	3.445
Amplification at the head of structure	7.36	6.526	3.580
Maximum bending moment M (KN.m)	453.8	584.6	657.6
Maximum shear force T (KN)	145	122.8	116.5
Maximum axial force N (KN)	681.1	633.4	446.8

Table 5: Influence of inclination on the seismic response of pile groups.

6 CONCLUSIONS

- The response of piles used as foundation elements is governed primarily by the inertial interaction which depends on the mass and frequency of the superstructure. The forces induced by this interaction are concentrated at the top of piles.
- The inertial forces of the superstructure induce significant efforts in the pile and contribute significantly to the damage of structures and their foundations under seismic forces. The forces induced by the inertial interaction depend substantially of the fundamental frequency of the superstructure and the soil, in comparison with the frequency of the load.
- For a cohesive soil, plasticity propagates from the base and extends to the surface. This leads to a high plasticity energy dissipation and transmission of waves on the surface. Contact with soil-pile head is assigned to a low value of cohesion. Taking into account that the plasticity reduces internal stresses in the piles.
- The inclination of piles leads to a reduction of the lateral amplification of the superstructure resulting from an increase in the rigidity of the system.
- The inclination of piles may be beneficial for the dynamic behavior of the superstructure. It depends on the interaction of the frequency of the load with the frequency of the soil-pile-structure.

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