Non Linear Global Numerical Modeling of Pile Group under Seismic Loading

Fadi Hage Chehade
Lebanese University, University Institute of Technology,
Saida & Doctoral School of Science and Technology, Modelling Center, PRASE,
Beirut, Lebanon

Marwan Sadek
LgcGe, University Science and Technology of Lille 1, Villeneuve of Ascq, France

Douaa Bachir
Lebanese University, Doctoral School of Science and Technology, Modelling Center,
PRASE, Beirut, Lebanon

SUMMARY
This paper presents a three dimensional numerical modeling of the soil-pile-structure interaction under seismic loading. It includes an investigation of the influence of plasticity on the seismic response of piles groups. The influence of plasticity is investigated for frictional soil under real earthquake records. The last part concerns the influence of pile inclination on their seismic response.

Keywords: Piles group, non linear interaction, numerical modeling, inclined piles

1. INTRODUCTION

Analysis of the seismic response of soil-pile-structure systems constitutes a complex problem in earthquake engineering. 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 or (and) to the inertial interaction between the superstructure and the pile foundation which may cause foundation damages, in particular at the pile-cap connection.

Non linear full 3D analyses considering the soil, piles and the superstructure are still limited. Such studies were conducted in the linear domain (Sadek and Shahrour, 2004, 2006, Boulanger et al. 1999, Chung 2000, Nikos et al. 2008) to analyse the influence of micropiles inclination and boundaries conditions on the seismic behaviour of the soil-micropile structure system. Gerolymos et al. (2009) used a full 3D finite element analysis to study the seismic performance of inclined piles assuming a linear behaviour of the soil and the structure.

This paper includes a full 3D coupled modelling 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 frictional soils 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 (Bardet et al. 1996) and Kobe (Tokimatsu et al., 1996, Gazetas & Mylonakis 1998) showed that structures based on inclined piles were less affected or damaged than other structures.

2. NUMERICAL STUDY OF SOIL-PILE-STRUCTURE SYSTEM (ELASTIC SOIL)

2.1. Numerical Modeling

2.1.1. Numerical Model Elements

The model consists of a group of four piles of 1m diameter and 10m length, located in a homogeneous soil layer of 15m of thickness. The piles are fixed in a cap of 1m thick with no contact with the ground, and supporting a superstructure. The spacing between piles is $S=3.75D_p$ (D_p: is the diameter of the pile). The behaviour of the soil-pile-structure system is firstly assumed to be elastic with Rayleigh damping. The superstructure is modelled by a single degree of freedom system, consisting of a column of height H_{st} = 1m and a concentrated mass m_{st} = 100 tons placed on the top of column. 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:

$$\left.\begin{aligned} K_{st} &= \frac{3(E_{st}I_{st})}{H_{st}^3} \\ f_{st} &= \frac{1}{2\pi}\sqrt{\frac{K_{st}}{m_{st}}} \end{aligned}\right\} \qquad (1)$$

Then, K_{st} = 86400 kN/m and f_{st} = 1.48 Hz.

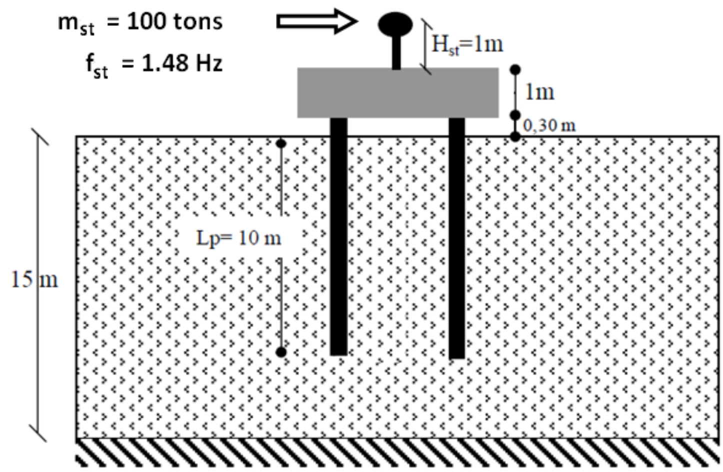


Figure 1. Presentation of the model

2.1.2. Mesh of soil-pile-structure system and boundary conditions

The mesh used is shown in Fig. 2. It is refined around the piles and the area near the superstructure where the inertial forces induce high stresses. The basis of soil is assumed rigid; boundaries are placed far enough from the structure with the use of finite elements and absorbing boundaries ("free field") to reduce the reflection of waves at the edges of the model.

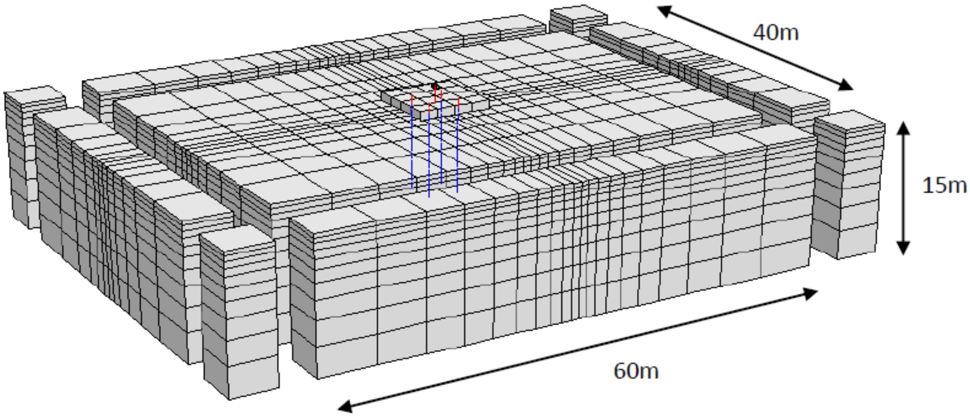


Figure 2. Mesh used in the numerical modeling

2.1.3. Mechanical properties

The Soil, piles and superstructure mechanical properties are summarized in the Table 1.

Table 1. Mechanical properties of soil-pile-superstructure system

Material	Density (Kg/m^3)	Young Modulus (MPa)	Poisson's ratio	Damping ratio	Axial rigidity (MN)	Flexural rigidity ($MN.m^2$)
Soil	$\rho = 1700$	E = 8	$\upsilon = 0.3$	$\xi = 5\%$		
Pile	$\rho = 2500$	E = 24000	$\upsilon = 0.3$	$\xi = 2\%$	$E_pA_p = 18850$	$E_pI_p = 1178$
Structure	$\rho = 2500$	E = 24000	$\upsilon = 0.3$	$\xi = 2\%$		

2.2. Seismic Loading

The soil-structure system is subjected to two types of loading. The first one corresponds to a harmonic loading with a frequency equal to the soil natural frequency. This loading is very severe and may lead to large internal forces that are not representative to a real earthquake that's why the second loading is a real one. It corresponds to the 1999 Kocaeli earthquake in Turkey with a frequency contents close to the natural frequencies of the soil-structure system.

2.2.1. Harmonic loading

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

2.2.2. Real loading

This loading is applied as a velocity at the base of the soil mass. The record for the base acceleration, velocity, and displacement waves are shown in Figure 3. It marks a maximum speed of 40 cm/s and a maximum acceleration of 0.247g. Fourier analysis of the record of the earthquake's velocity results in a power spectrum that reveals a dominant frequency at f = 0.9 Hz (lower peaks are observed at 0.6 and 1.3 Hz) to be compared with the natural frequencies of the soil (0.67 Hz) and the superstructure (1.4 Hz).

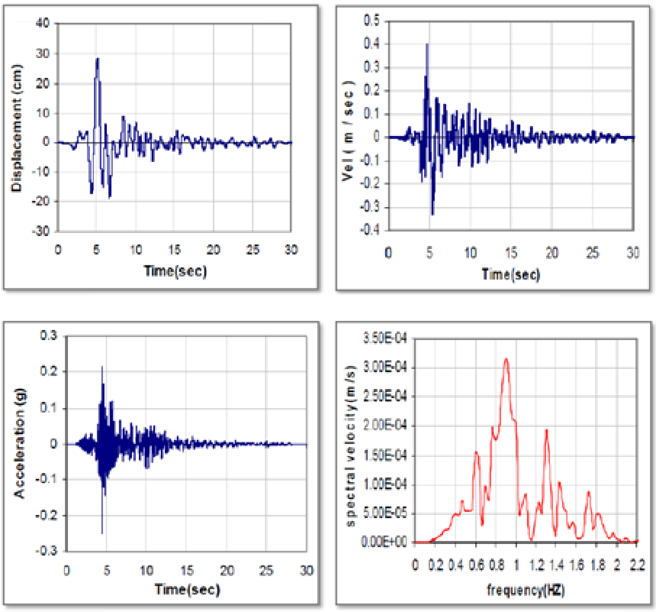


Figure 3. The real seismic loading - Turkey, Kocaeli

The Kocaeli earthquake in Turkey (1999) is chosen since it has frequency contents close to the natural frequencies of the soil-structure system which enhance the development of soil plasticity.

2.3. Comparison of Maximum Dynamic Forces in Piles

The forces induced in the piles due to the real seismic loading of Kocaeli, of frequency f = 0.9 Hz, are represented in Table 2 and Figure 4, compared with forces induced in piles due to the harmonic loading 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. Harmonic loading is very detrimental and causes excessive forces compared to real earthquake loading. That's why, only real record is used in the following analysis.

Table 2. Response of piles for different types of loading

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, Kocaeli	7.36	5.4	145	453.8

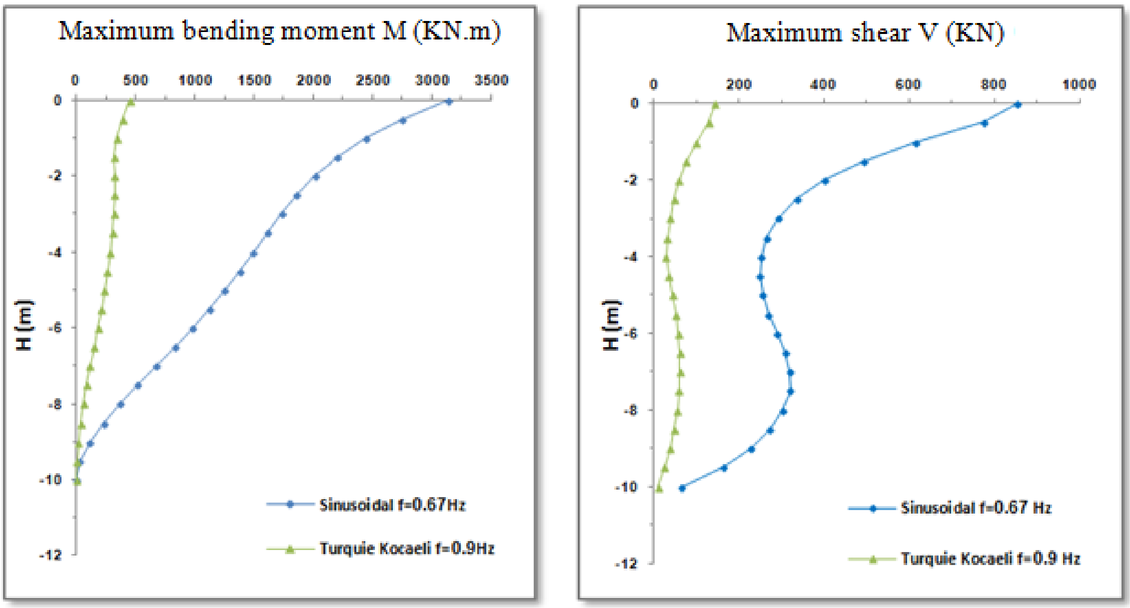


Figure 4. The maximum dynamic forces in the piles

3. EFFECT OF SOIL PLASTICITY

3.1. Introduction

This section deals with the effect of nonlinearities on the behaviour of the soil-pile-structure system, in particular, the influence of soil plasticity on the system response. Numerical simulations are performed using real seismic loading (Turkey, Kocaeli 1999). The soil behavior is described by an elastic-perfectly plastic Mohr-Coulomb. Only the case relative to frictional soil is presented in this paper.

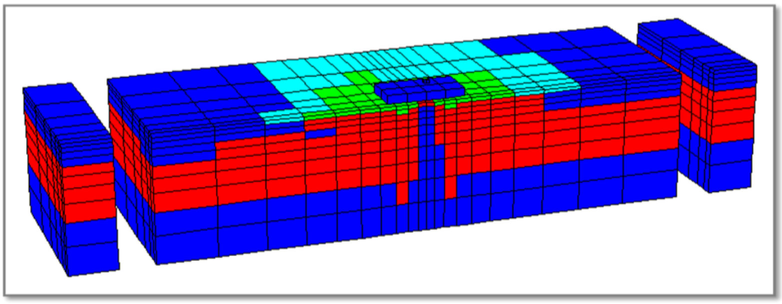
3.2. Plastic Calculation

A parametric study was conducted to know the effect of plasticity for frictional soil on the seismic behaviour of the soil-pile-structure system. The mechanical properties of the soil are given in Table 3. The friction angle is considered of 30° and a low cohesion of 2 kPa. To know the influence of dilatancy, two values were chosen respectively $\psi = 0°$ and $\psi = 20°$. A slight damping of Rayleigh is used for the soil. The behaviour of the cap-structure system is assumed to be elastic. The mesh is identical to that presented above.

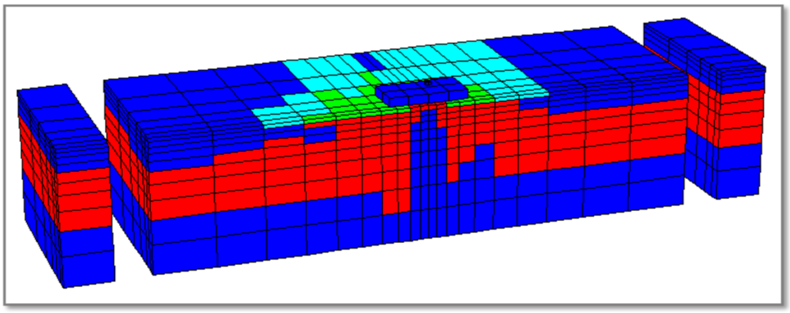
Table 3. Mechanical properties of frictional soil

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	30	0 or 20

The extension of plasticity under seismic loading is shown in Fig. 5. Note that the plasticity is localized near the surface due to the low soil confinement at this zone. The seismic loading induces plasticity at the top of soil and the energy is injected into the structure. Plasticisation of the soil around the pile head makes it weaker; it leads to the formation of a gap around the pile head which confirms the post seismic observations.



a) ψ = 0º



a) ψ = 20º

Figure 5. Extension of plasticity - frictional soil (C =2 KPa, ψ = 0º and ψ = 20º)

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

Fig. 6 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.

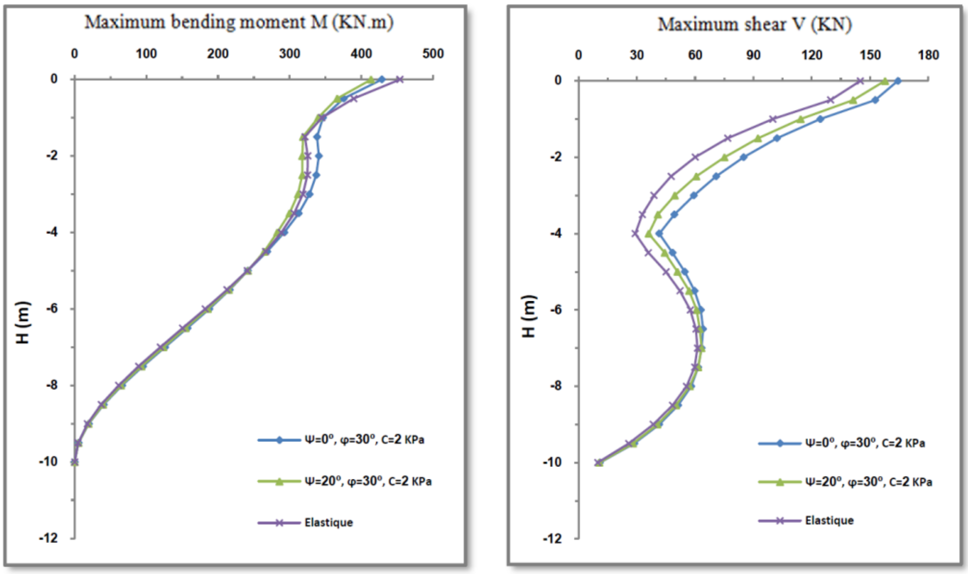


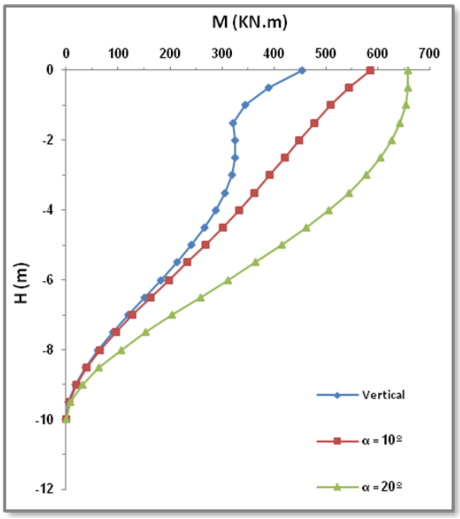
Figure 6. Influence of frictional soil plasticity on the dynamic forces in the piles (Kocaeli earthquake, Turkey 1999)

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

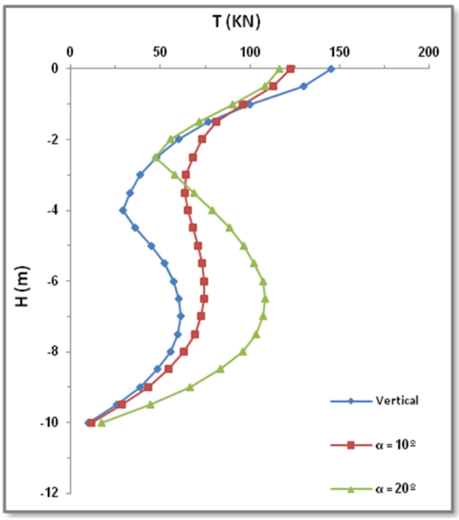
ψ (º)	Acc mass (m/s^2)	Acc cap (m/s^2)	Max shear force V (KN)	Max. bending moment M (KN.m)
Elastic	7.36	5.4	145	453.8
0	7.431	5.775	164.3	428.5
20	7.391	6.147	157.7	413.6

4. EFFECT OF INCLINATION

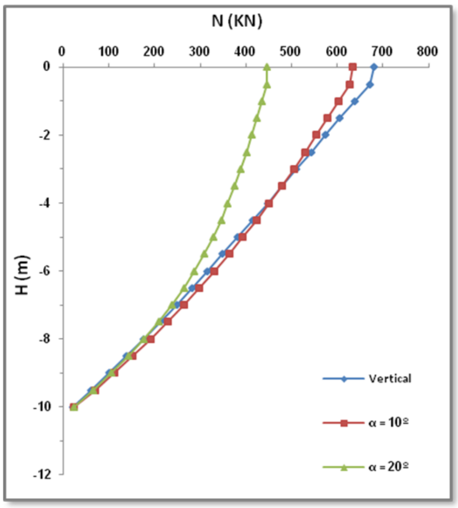
In this section, we analyze the effect on the pile inclination on the seismic answer of the system pile-soil-cap. The case that has been modelled is similar to that earlier, except that the four piles are inclined outwardly. To properly analyze the influence of pile inclination on their seismic response, results of calculations are presented for the two values of inclination angles respectively α=10º and α= 20º.The results are summarized in Figure 7 and Table 5. For the example presented here, the inclination of the pile leads to a reduction of the numerical values of the normal load and lateral displacement of the pile group. However we can remark that along the pile, the values of the moment and the shear have been increased. Table 5 illustrates that on the maximal values of internal forces and the amplification at cap and the structure head have been reduced when the value of the inclination increases except for the value of the bending moment.



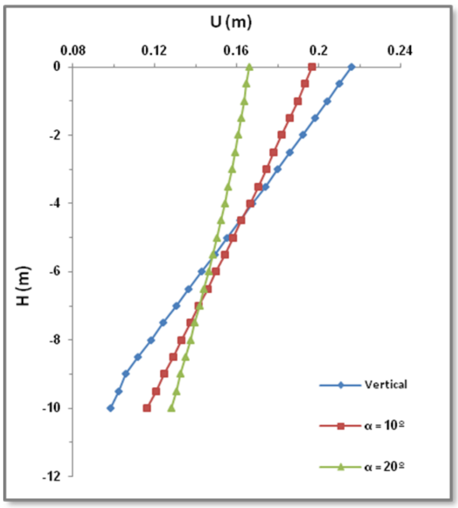
a) Bending moment



b) Shear force



c) Normal force



d) Displacement

Figure 7. Influence of inclination of piles on the seismic response of pile groups (Registration of Turkey, Vg = 40 cm/s, f = 0.9 Hz, Ag = 0.247g)

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

	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

5. CONCLUSION

In this paper we present a three dimensional numerical modeling of the soil-pile-structure interaction under seismic loading. The effect of the plasticity has been investigated in the case of a frictional soil as well as the effect of the dilancy angle. The numerical modeling has been carried by using harmonic excitation and real seismic loading recorded during the kocaeli earthquake (Turkey, 1999). The effect of the pile inclination has been also analyzed.

The harmonic loading leads to high values of the internal forces (Bending moment, shear) especially when the frequency of the load is near to the proper frequency of the soil. For, the example treated here, the plasticity of the soil has a little effect of the results. For frictional soil, the plasticity spreads from the surface due to the low confinement of the soil in this area. Plasticisation of the soil around the piles head makes them more vulnerable, the post seismic observations of damaged piles show the formation of a vacuum around the head of the piles.

The inclination of piles leads to a reduction in the lateral amplification of the superstructure resulting from an increase in the rigidity of the system. The inclination of piles can be beneficial on both, the dynamic behavior and the behavior of the superstructure. It depends on the interaction of the frequency of the seismic load with the frequencies of the soil-pile-structure. The inclination increases the lateral stiffness of the foundation which, unfortunately, can cause a significant increase in the load transmitted to the foundation to the superstructure.. Despite the improved performance of inclined piles, the bending forces at the top of piles are still very significant.

ACKNOWLEDGMENT

We thank the Lebanese National Council of Scientific Research in Lebanon for the funding of this work.

REFERENCES

Bardet J.P., Idriss, I.M., O'Rourke, Adachi, N., Hamada, M., and Ishihara, K. (1996). North America-Japan Workshop on the Geotechnical Aspects of the Kobe, Loma 138 Prieta, and Northridge Earthquake. Report No. 98-36 to National Science Foundation, Air Force Office of Scientific Research, and Japanese Geotechnical Society. Osaka, Japan.

Boulanger R.W., Curras C.J., Wilson D.W., Abghari A.A. (1999). Seismic Soil-Pile-Structure Interaction Experiments and Analyses. *Journal of Geotechnical and Geoenvironmental Engineering* **125:9,**750-759.

Chung Y. (2000). Etude Numérique de l'interaction Sol-Pieu-Structure sous Chargement Sismique, Thèse de Doctorat, Université de Sciences et Technologie de Lille.

Gazetas, G. and Mylonakis, G. (1998). Seismic Soil-Structure Interaction: New Evidence and Emerging Issues. Emerging Issues Paper, Geotechnical Special Publication No 75, *ASCE*, **2**,1119-1174.

Gerolymos N., Escoffier S., Gazetas G. and Garnier J. (2009). Numerical Modeling of Centrifuge Cyclic Lateral Pile Load experiments. *Earthquake Engineering and Engineering Vibration* **8**:**1**,61-76.

Itasca Consulting Group, FLAC: Fast Lagrangian Analysis of Continua, vol. I. User's Manual, vol. II. Verification Problems and Example Applications, Second Edition (FLAC3D Version 3.0), Minneapolis, Minnesota 55401 USA, 2005

Sadek M, Shahrour I (2004). Three-dimensional finite element analysis of the seismic behaviour of inclined micropiles. *Soil Dynamics and Earthquake Engineering* **24**,473–485.

Sadek M, Shahrour I (2006) Influence of the head and tip connection on the seismic performance of micropiles (2006). *Soil Dynamics and Earthquake Engineering*, **26:6**,461-468

Tokimatsu K., Arai H. and Asaka Y. (1997). Deep Shear Structure and Earthquake Ground Motion. Characteristics in Sumiyoshi Area, Kobe City, Based on Microtremor Measurements, *J. Struct. Constr. Eng., AIJ,* **491**,37-45.

Nikos Gerolymos, Amalia Giannakou, Ioannis Anastasopoulos, George Gazetas (2008). Evidence of beneficial role of inclined piles: observations and summary of numerical analyses. Springer Science and Business Media B. V.