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A macroelement for dynamic soil-structure interaction analysis of pile-group foundations

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ABSTRACT: The scope of the paper is to present a macroelement for dynami csoil-structure interaction analysis of pile-group foundations. The new macroelement is based on the single pile macroelement proposed by Li *et al.* (2016) and considers pile group effects. The principal features of the macroelement are first presented. Then, a discussion on an appropriate way to treat pile group effects is undertaken. It is proposed to introduce these effects by means of a decoupled rheological model (composed of an assembly of springs and dashpots) and dynamic interaction factors. The non-linear behavior is concentrated at the level of each pile using the aforementioned single pile macroelement. The performance of the new macroelement for dynamic soil-structure interaction pile-group problems is validated using advanced finite element analyses. The advantages and limitations of the approach are finally discussed.

1 INTRODUCTION

The dynamic response of a structure supported by deep foundations is a complex Soil-Structure Interaction (SSI) problem that requires the use of adapted computational methods. Traditionally, the design of deep foundations under seismic loadings is carried out by means of conservative methods that aim to assure zero damage of the foundation that therefore remains linear elastic. This approach was justified due to the lack of information about the dynamic non-linear behavior of foundations and the lack of adapted numerical tools. Such limitations become however more and more obsolete as an important number of experimental and numerical results are now available as well as new design methods (Pecker *et al.* 2012). In addition, modern design codes as the Eurocode 8 (EC8, EN 1998) recognize the effect of SSI and of the nonlinear energy dissipation that can be important in the case of strong earthquakes. A bibliographic review of the main methods available for the design of piles under seismic loading is presented in Pérez *et al.* (2017). One of them is the macroelement concept, a simplified approach for the simulation of multidirectional non-linear soil-foundation response.

2 THE MACROELEMENT APPROACH

The macroelement can be seen as a multidirectional nonlinear spring that makes possible to concentrate in a single point the overall multidirectional response of the soil and the foundation. It has a 2D or 3D law, described in terms of generalized forces and displacements, decreasing thus dramatically the necessary computational time. Taking into account the nonlinearities and the coupling between the degrees of freedom constitutes the main contribution of this approach. Being a macro-scale numerical tool, one of the inherent particularities and limitations of a macroelement is that it is constructed and calibrated for a specific soil foundation case. However, once calibrated and the limits of the application field dully defined, it can be used intensively with a reduced computational cost which makes this approach an excellent tool for seismic performance-based design.

2.1 *Macroelements for deep foundations*

The macroelement concept was introduced in foundation engineering by Nova and Montrasio (1991). The first macroelements were developed for shallow foundations (Nova and Montrasio 1991, Cremer *et al.* 2001, Chatzigogos 2007, Grange 2008, Chatzigogos *et al.* 2009, Grange *et al.* 2009, Salciarini and Tamagnini 2009 among various authors). The extension to deep foundations is more recent (Correia 2011, Li 2014, Li *et al.* 2016) and is limited to the case of piles in a homogeneous soil profile.

Correia (2011) developed a macroelement for a single pile in a cohesive soil subjected to lateral seismic loading applied at the pile head. The approach is based on a nonlinear elastic constitutive model, representing the elastic behavior under small deformations with the elastic linear impedances proposed by Gazetas (1991) and adopted in EC8 (2005), coupled with a boundary plasticity model. Radiative damping is not explicitly considered but it is possible to add viscous dampers at the pile head like in a conventional substructuring approach.

A new macroelement for deep foundations under monotonic, cyclic and seismic loadings has been introduced by Li 2014 and Li *et al.* 2016. Based on a hypoplastic constitutive law, it is inspired by the macroelement for swallow foundations developed by Salciarini and Tamagnini (2009). The failure surface is defined using a dimensionless formulation with input parameters the bearing capacity of a single pile under horizontal, rotational and vertical loading. It adopts the “intergranular displacement” mutuated from Niemunis and Herle (1997) to reproduce the behavior under cyclic loading. The case of a 1x2 pile group has been also addressed by means of a constant group factor that explicitly modifies the yielding and the failure surfaces.

Group effects are strongly frequency dependent even for small groups of piles (Kaynia & Kausel, 1982). Lesgidis *et al.* (2018) have recently developed a frequency dependent macroelement able to reproduce the dynamic properties of the system across various levels of increasing seismic intensity. Their approach can be divided in two elementary components coupled in series: a frequency-independent macroelement that deals with the nonlinear pseudo-static response of the system and an intensity-dependent lumped parameter model that captures the dynamic response. Despite the interest of this approach, the proposed calibration procedure is numerically expensive and time consuming.

In this article, the macroelement developed by Li (2014) is extended to consider pile-group effects. The proposed approach is intended to reduce numerical calibration costs at its minimum while offering a configuration that allows fast changes in the geometrical distribution of piles within the pile group.

3 SINGLE PILE MACROELEMENT

In this paragraph a short presentation is given of the single pile macroelement that is used as the base of the proposed pile group macroelement. For simplicity and in the interest of the presentation, only the basic form of the formulation is presented. This form is suitable for monotonic (not cyclic) loadings but has all the necessary ingredients that are modified afterwards in order to take into account group effects. A detailed formulation of the macroelement can be found in Li (2014) and Li *et al.* 2016.

The response of the pile is described by means of generalized load and displacement vectors (named ***t*** and ***u*** respectively):

$$\boldsymbol{t} = \{V, H, M\}^T \tag{1}$$

$$\boldsymbol{u} = \{w, u, \theta\}^T \tag{2}$$

In order to reproduce nonlinearity, irreversibility and loading dependence, the constitutive equation is formulated in incremental form:

$$\dot{\boldsymbol{t}} = \mathcal{K}(\boldsymbol{t}, \boldsymbol{q}, \boldsymbol{\eta})\underline{\boldsymbol{u}} \tag{3}$$

$$\mathcal{K} = \mathcal{L}(t, q) + N(t, q)\boldsymbol{\eta}^T \tag{4}$$

$$\boldsymbol{\eta} = \dot{\boldsymbol{u}}/||\dot{\boldsymbol{u}}|| \tag{5}$$

where $\mathcal{K}$ is the tangent stiffness matrix and $\boldsymbol{q}$ is a pseudo-vector of internal variables accounting for the effects of the previous loading history. In the above equations, the matrix $\mathcal{L}$ is related to the elastic stiffness matrix $\mathcal{K}^e$ of the system upon full displacement reversal (pseudo-elastic stiffness) by the relation:

$$\mathcal{L} = \frac{\boldsymbol{1}}{\boldsymbol{m_R}}\mathcal{K}^e \tag{6}$$

with m_R a model constant. The elastic stiffness matrix is written:

$$\mathcal{K}^e = \begin{bmatrix} k_v & 0 & 0 \\ 0 & k_{hh} & k_{hm} \\ 0 & k_{hm} & k_{mm} \end{bmatrix} \tag{7}$$

where k_v, k_{hh}, k_{mm} and k_{hm} are respectively the vertical, horizontal, rotational and coupled horizontal-rotational elastic stiffness at the pile head.

The constitutive vector $\boldsymbol{N}$ accounts for the nonlinearity developed in the macroelement. It can be expressed as:

$$\boldsymbol{N}(\boldsymbol{t}) = -\boldsymbol{Y}(\boldsymbol{t})\mathcal{L}\ \boldsymbol{m}(\boldsymbol{t}) \tag{8}$$

In this equation, the scalar function $\boldsymbol{Y}(\boldsymbol{t})$ measures the distance from the current stress state to the final yield surface and $\boldsymbol{m}(\boldsymbol{t})$ defines the direction of the plastic flow, that is given by the unit vector:

$$\boldsymbol{m}(\boldsymbol{t}) = \frac{\partial f/\partial \boldsymbol{t}}{||\partial f/\partial \boldsymbol{t}||} \tag{9}$$

with f the function of the predefined yield surface, defined analytically from the bearing capacity of a single pile: H_0, M_0 and V_0.

4 PILE GROUP MACROELEMENT

4.1 *Introduction*

A modular approach to the problem is proposed. The main hypothesis is that only the elastic domain is affected by the pile group effects. The non-linearities are concentrated and modeled using single pile macroelements. The pile-soil-pile interaction (group effect) is considered by means of dynamic interaction factors incorporated to the elastic stiffness matrix of the single pile macroelement. Each pile is simulated with a macroelement and all piles are connected to the control node of the pile group considering rigid links.

The dynamic interaction factors for each direction of interest are calculated at each time step following the strategy given in Fig. 1. The elastic dynamic response of the pile group is taken into account by means of a rheological model (uncoupled from the macroelement) which allows the calculation of the corresponding elastic displacement increment that results

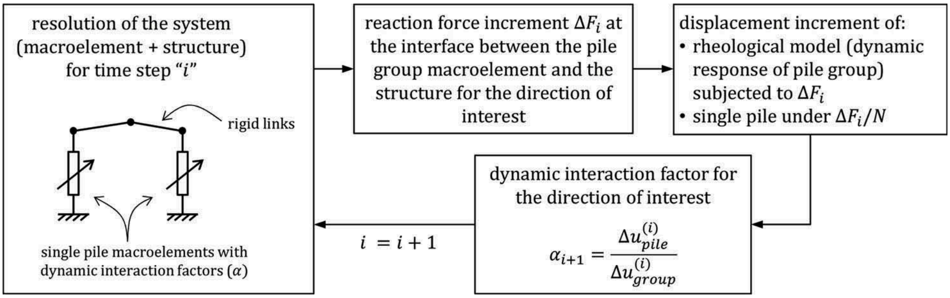

Figure 1. Proposed strategy to take into account pile-group effects using single pile macroelements and dynamic interaction factors in transient calculations.

from the application of the reaction force at the structure-macroelement interface. The response of a single pile is reproduced using the elastic stiffness at zero frequency (the dynamic impedance of single piles is usually frequency independent).

Several are the advantages of this approach as it allows: 1) modeling virtually any pile group distribution, 2) decoupling the phenomena related to the behavior of a single pile and to a pile group and 3) using the existing macroelements for single piles available in the literature.

One of the drawbacks of the actual formulation is that an infinitely rigid base slab is assumed connecting the piles.

4.2 *The dynamic interaction factor*

The dynamic interaction factor α can be interpreted as a reduction factor and is directly applied to the translation component k_{hh} of the macroelement elastic stiffness matrix. The formulae giving the stiffness at the head of a pile embedded in a semi-infinite homogeneous elastic medium can be used as a first approximation in order to find its contribution to the other degrees of freedom:

$$k_{hh} = E_s l_0 \tag{10}$$

$$k_{hm} = -\frac{1}{2} E_s l_0^2 \tag{11}$$

$$k_{mm} = \frac{1}{2} E_s l_0^3 \tag{12}$$

$$l_0 = \sqrt[4]{\frac{4EI}{E_s}} \tag{13}$$

Where l_0 is the transfer length, EI is the pile flexural rigidity and E_s the soil reaction module. The translation stiffness term becomes:

$$k_{hh}^* = \alpha k_{hh} \tag{14}$$

Using the equation (10) the new soil reaction module can be calculated:

$$E_s^* = \alpha^{4/3} E_s \tag{15}$$

The substitution of this new soil reaction module in equations (11) and (12) gives:

$$k_{hm}^* = \alpha^{2/3} k_{hm} \tag{16}$$

$$k_{mm}^* = \alpha^{1/3} k_{mm} \tag{17}$$

Finally, the elastic stiffness matrix controlling the elastic response of the macroelement (7) becomes:

$$\mathcal{K}^e = \begin{bmatrix} k_v & 0 & 0 \\ 0 & \alpha k_{hh} & \alpha^{2/3} k_{hm} \\ 0 & \alpha^{2/3} k_{hm} & \alpha^{1/3} k_{mm} \end{bmatrix} \tag{18}$$

It should be noted that only the interaction factor related with the lateral response of the macroelement has been addressed in the above development. In the full formulation, another interaction factor (independent of the aforementioned α factor) needs to be applied to the vertical direction stiffness terms.

5 A MACROELEMENT FOR PILE-GROUPS - NUMERICAL APPLICATIONS

5.1 *Presentation*

In order to validate the performance of the proposed pile group macroelement, a numerical application is shown hereafter. More specifically, the response of a 5 pile group in dense Fontainebleau sand under cyclic loading is studied (Fig. 2). Following the macroelement approach for pile groups presented in the previous paragraph, the pile group is modeled using five single macroelements (Li (2014) and Li *et al*. 2016) at the exact location of the piles. The elastic stiffness terms of the macroelements have been modified to incorporate the dynamic interaction factor presented in section 4. Calibrated parameters for the macroelement of a single vertical pile in a dense Fontainebleau sand profile are given in Table 1. Pile heads are connected by rigid links and the loading is applied at the center of the pile group.

The results of the macroelement based model are compared to those of a full-nonlinear finite element model in ABAQUS that uses a hypoplastic constitutive law to reproduce the soil behavior (Wolffersdorff 1996). The constitutive model parameters have been calibrated using triaxial Fontainebleau sand (NE34) experiments, see Li (2014).

A Newmark direct integration scheme is used to solve the dynamic equilibrium equation of the system. Force-time loading histories are applied at the control node of the pile group. A 2-way cyclic signal with tapered parts is used to apply the loadings to the single pile and pile group models. This allows a direct comparison between finite element and macroelement based models and ensures that the same loading is applied at the control node at every time step. Figure 3 shows the normalized time representation of the applied signal.

5.2 *Numerical results*

The response of a single pile under a cyclic lateral loading at a frequency of 1Hz and two different loading levels is first studied hereafter, prior to the numerical application of the pile group model. The response of the single pile macroelement model is compared to the finite element model of a single pile. The results are given in figure 4. It is observed that the single pile macroelement captures correctly the response of the single pile at both low and high amplitude loadings. The lateral displacement and the rotation of the pile head are correctly predicted.

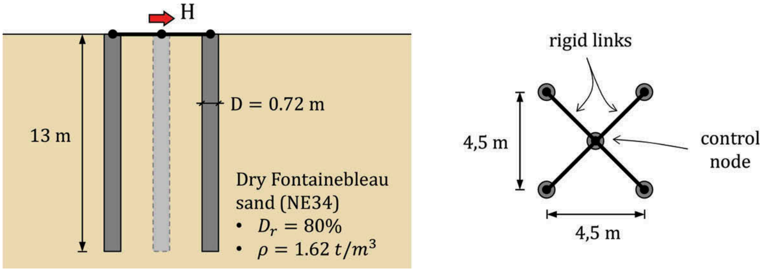

Figure 2. Case study

Table 1. Parameters of the hypoplastic macroelement for a single vertical pile in Fontainebleau sand calibrated using a FEM model

Description and related behavior	Parameter	Value
Low deformation response with elastic stiffness	k_{hh}	2.17E05 kN/m
	k_{mm}	5.42E05 kNm/rads
	k_{hm}	2.39E05 kN/rad
	k_v	1.77E06 kN/m
Failure criterion with the bearing capacity of a single pile	H_0	0.5E04 kN
	M_0	0.45E05 kNm
	V_0	2.5E04 kN
Evolution of the failure surface	κ	2.5
Cyclic behavior	m_R	2
	m_T	2
	R	6E-03
	β_r	0.5
	χ	0.4

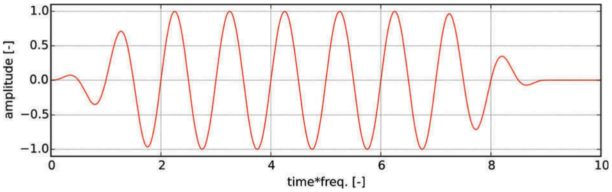

Figure 3. Normalized time representation of the 2-way cyclic signal with tapered parts used to apply loads to the single pile and the pile group models.

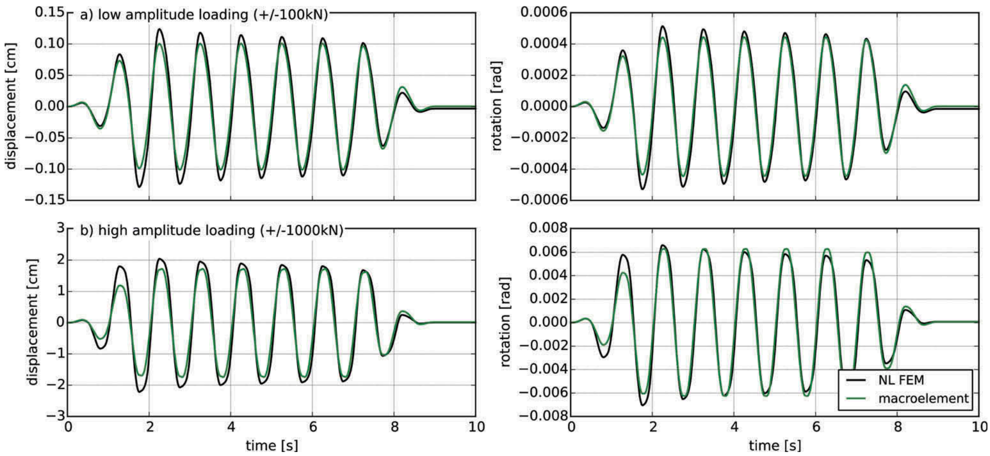

Figure 4. Response of a single pile under lateral cyclic loading at 1Hz, finite element model vs macroelement: a) low amplitude and b) high amplitude loading.

Once the parameters controlling the response of a single pile macroelement dully verified and adjusted, the response of the pile group model under different loadings can be studied. In this numerical application a constant dynamic interaction factor α is used. This is possible given that the frequency of the applied signals stays the same over time (in other words, the associated resolution scheme presented in Figure 1 is not used and its performance is therefore not studied in the present article).

The pile group models are tested using several lateral cyclic loadings applied at the level of the control node. Two different frequencies (1 Hz and 2 Hz) and two different loading levels

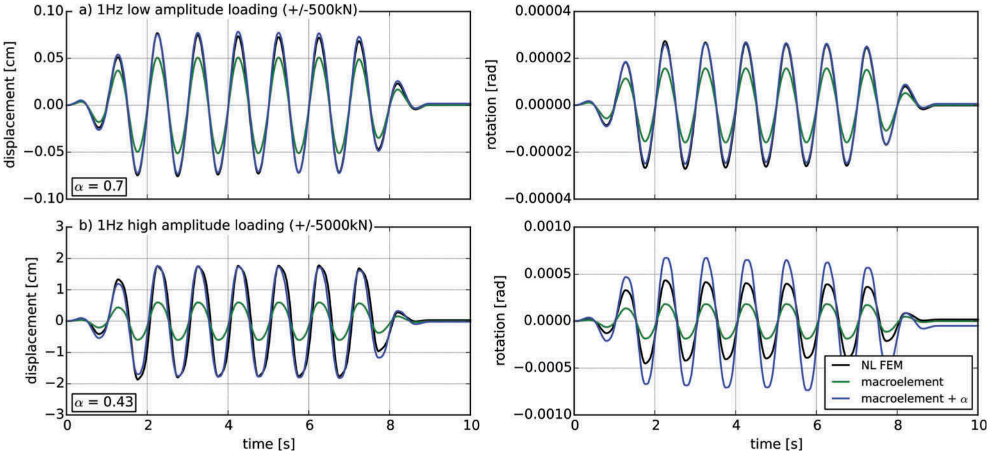

Figure 5. Response at the pile group head under a lateral cyclic loading at 1 Hz and two different amplitude loadings using the finite element model, the pile group macroelement and the pile group macroelement with α factor.

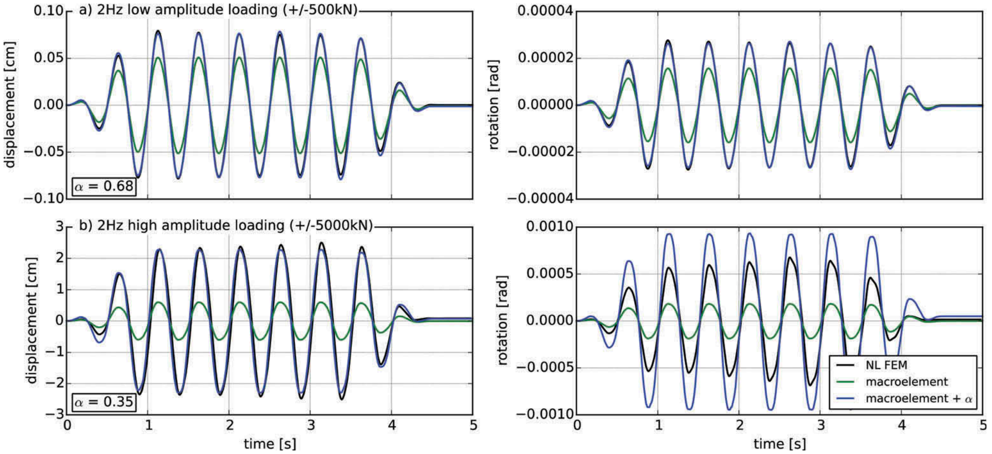

Figure 6. Response at the pile group head under a lateral cyclic loading at 2 Hz and two different amplitude loadings using the finite element model, the pile group macroelement and the pile group macroelement with α factor.

(500 kN and 5000 kN) are used. The results of these simulations are given in Figures 5 and 6. The response of three different models is compared: a non-linear finite element model with a hypoplastic soil constitutive law, a pile group macroelement without the interaction factor α and a pile group macroelement with the interaction factor α numerically calibrated to reproduce the lateral displacement response of the pile group from the finite element model.

The response of the pile group macroelement with the calibrated interaction factor α is very satisfactory in the case of low amplitude loadings (Figs. 5a and 6a). Both the lateral displacement and the rotation are well captured. When no interaction factor is used however, the response of the pile group macroelement is stiffer compared to the finite element model. A group effect is observed in the response of the system and its value slightly depends on the frequency of the loading. The α factor values used in the simulations are 0.7 and 0.68 in the case of cyclic loadings of 1Hz and 2Hz respectively.

In the case of high amplitude loadings (Figs. 5b and 6b), the pile macroelement model with the calibrated α factor is able to capture the lateral displacement response of the pile group at both frequencies. The rotational response of the pile group is however less accurate. The adopted interaction factors are 0.43 and 0.35 for the 1Hz and 2Hz cyclic loadings respectively. The response of the pile group macroelement with no interaction factor is found stiffer than that of the finite element model. Differences are greater than for the low amplitude loadings.

Using the adopted α factor to capture the group effect, it can be seen that the group effect depends at the same time on the frequency and the intensity of the loading. The variation of group effect with frequency is more important in the case of high amplitude loadings.

6 CONCLUSIONS

Comparisons with non-linear finite element simulations demonstrate the good performance of the pile group macroelement with a dynamic interaction factor, especially in the case of low amplitude loadings with limited non-linearity. Differences have been found regarding the rotational response of the system at high amplitude loadings and therefore future studies should focus in this aspect. In order to validate the approach, it is necessary to study more complex loadings and several intensity levels. The variation of the interaction coefficient α at every time step and the way it affects the system should be also addressed.

The proposed pile group macroelement with a dynamic interaction factor remains simple and computational fast. It is therefore suitable for numerical parametric studies and engineering design practice.

REFERENCES

Chatzigogos, C. 2007. Comportement sismique des fondations superficielles: Vers la prise en compte d'un critère de performance dans la conception. Ph.D. thesis, Ecole Polytechnique, France.

Chatzigogos C, Pecker A, Salençon J. 2009. Macroelement modeling of shallow foundations. *Soil Dynamics and Earthquake Engineering*, 29(5):765–781.

Correia, A. 2011. A pile-head macro-element approach to seismic design of monoshaft-supported bridges. Ph.D. thesis, ROSE School, IUSS Pavia, Italy.

Cremer, C., Pecker, A. & Davenne, L. 2001. Cyclic macro-element for soil-structure interaction: material and geometrical non-linearities. *International Journal for Numerical and Analytical Methods in Geomechanics*, 25, 1257-1284.

EN 1998-5. 2005. Eurocode 8: Calcul des structures pour leur résistance aux séismes. Partie 5: Fondations, ouvrages de soutènement et aspects pratiques. AFNOR.

Grange, S. 2008. Modélisation simplifiée 3D de l'interaction sol-structure: application au génie parasismique. Ph.D. thesis, Institut Polytechnique de Grenoble, France.

Grange S, Kotronis P, Mazars J. 2009. A macro-element to simulate 3D soil-structure interaction considering plasticity and uplift. *International Journal of Solids and Structures*, 46(20):3651–3663.

Kaynia, A.M. & Kausel, E. 1982. Dynamic behavior of pile groups. 2nd International Conference on Numerical Methods in Offshore Piling, Austin, TX, pp. 509-532.

Lesgidis, N., Sextos, A. & Kwon, O.-S. 2018. A frequency-dependent and intensity-dependent macroelement for reduced order seismic analysis of soil-structure interacting systems. *Earthquake Engineering & Structural Dynamics*, 47, 2172-2194.

Li, Z. 2014. Experimental and numerical study of deep foundations under seismic loading: vertical piles and inclined piles. Ph.D. thesis, Ecole Centrale de Nantes, France.

Li, Z., Kotronis, P., Escoffier, S. & Tamagnini, C. 2016. A hypoplastic macroelement for single vertical piles in sand subject to three-dimensional loading conditions. *Acta Geotechnica*, 11, 373-390.

Nova R, Montrasio L. 1991 Settlements of shallow foundations on sand. *Geotéchnique* 41(2):243–256.

Pecker, A., Paolucci, R., Chatzigogos, C., Correia, A.A. & Figini, R. 2012. The role of non-linear dynamic soil-foundation interaction on the seismic response of structures. II International Conference on Performance Based Design in Earthquake Geotechnical Engineering, Taormina.

Pérez, J., Cuira, F., Kotronis, P. & Escoffier, S. 2017. *Etat de l'art sur les méthodes de calcul d'un pieu et d'un groupe de pieux sous chargement sismique*. 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul.

Salciarini D, Tamagnini C. 2009. A hypoplastic macroelement model for shallow foundations under monotonic and cyclic loads. *Acta Geotechica* 4(3):163–176.

von Wolffersdorff, P.-A. 1996. A hypoplastic relation for granular materials with a predefined limit state surface Mechanics of Cohesive-frictional Materials, John Wiley & Sons, Ltd., 1, 251-271.