2nd Applied Computing in Science & Engineering

(ACSE2) 26-28 July 2017
Canary Islands, SPAIN

Extending

ABSTRACTS

BOOK

ISBN : 978-84-697-4340-9

Edited by: ScienceKNOWconferences

July 2017

ORGANIZING COMMITTEE

Chairman

Prof. Luis M. Sousa Da Silva Ph.D.

ISEP-School of Engineering

Polytechnic Institute of Porto, Portugal

Co-Chairman

Santiago Salamanca Miño PhD.

Electric, Electronic and Automatic Engineering Department

Robotics, Automatics and Production Systems Group

University of Extremadura, Spain

Co-Chaiman

Israel Gonzalez Carrasco PhD.

Computer Science Departament

University Carlos III of Madrid

Local Organizing Committee

José Pablo Suárez Rivero

Department of Cartography and Graphic Expression in Engineering

University of de Las Palmas de Gran Canaria

Gustavo Montero García

Director

Division of Advanced Numerical Algebra of the University Institute of

Intelligent Systems and Numerical Applications in Engineering (SIAN)

David Juan Greiner Sánchez

Division of Advanced Numerical Algebra of the University Institute of Intelligent Systems and Numerical Applications in Engineering (SIAN)

SCIENTIFIC COMMITTEE

PhD. Lozano-Rogado, J. (Extremadura University, Spain)

PhD. Al-Kassir, A. (Extremadura University, Spain)

PhD. Brito, P. (C3i/IPP, Portugal)

PhD Calderón Godoy Antonio José (University of Extremadura, Spain)

PhD. Canito Lobo, J. L. (University of Extremadura, Spain)

PhD. Lafta, W. M. (ASME, IEEE, UoIE, IIE, NSECP, AASCIT Member, Australia)

PhD. António Vieira de Castro, Leading researcher of GILT Group, (ISEP, IPP, Portugal)

PhD. Casquilho, M. (Lisbon University, Portugal)

PhD. González Carrasco, I. (University Carlos III, Spainl)

PhD. Costa, C. (Salamanca University, Spain)

PhD. Cuadros, P. (Extremadura University, Spain)

PhD. Domínguez, J. R. (Extremadura University, Spain)

PhD. Suárez Rivero, J.P. (University of de Las Palmas de Gran Canaria, Spain)

PhD. Fernández, J. (University of Oviedo, Spain)

PhD. Jacob, S. (Oswaldo Cruz Foundation, Brazil)

PhD. Jesus, M. (Lisbon University, Portugal)

PhD. López, F. (Extremadura University, Spain)

PhD. Macías, A. (Extremadura University, Spain)

PhD. Montero García, G. (SIAN, University of las Palmas de Gran Canaria, Spain)

PhD. Marcos, F. (Madrid Polytechnic University, Spain)

PhD. Márquez, M. C. (Salamanca University, Spain)

PhD. Merchán García, M. P. (Extremadura University, Spain)

PhD. Montejo, C. (Salamanca University, Spain)

PhD. Moreira, J. (Oswaldo Cruz Foundation, Brazil)

PhD. Rodrigues, L. (C3i/IPP, Portugal)

PhD. David Juan Greiner Sánchez (SIAN, University of las Palmas de Gran Canaria, Spain)

PhD. Sá, C. (ISEP/IPP, Portugal)

PhD. Sabio Rey, E. (Extremadura University, Spain)

PhD. Salamanca, S. (Extremadura University, Spain)

PhD. Silva, L. (ISEP/IPP, Portugal)

PhD. Takabi, B. (Texas A&M University, USA)

PhD. Vieira Ferreira, L. F. (Lisbon University, Portugal)

INDEX

Integral model for the analysis of pile foundations in stratified soils

G.M. Álamo [(1),*], J.J. Aznárez [(1)], L.A. Padrón [(1)], A.E. Martínez-Castro [(2)],

R. Gallego [(2)], O. Maeso [(1)]

[(1)] Instituto Universitario de Sistemas Inteligentes y Aplicaciones Numéricas en Ingeniería (SIANI), Universidad de Las Palmas de Gran Canaria, Edificio Central del Parque Científico y Tecnológico, Campus Universitario de Tafira 35017 Las Palmas de Gran Canaria, Spain
[*] Tel.:+34-928-457404; e-mail: guillermo.alamo@ulpgc.es

[(2)] Departamento de Mecánica de Estructuras e Ingeniería Hidráulica, ETS de Ingenieros de Caminos, Canales y Puertos, Universidad de Granada, Avenida Fuentenueva s/n, 18002 Granada, Spain

1. Introduction – An efficient three-dimensional numerical model is presented for the dynamic analysis of pile foundations in horizontally layered soils in the frequency domain. The soil is assumed to be composed of a finite number of homogeneous, linear, isotropic, viscoelastic horizontal layers, and its behaviour is modelled through the integral reciprocity theorem in elastodynamics and the use of advanced fundamental solutions for the layered half space [1]. On the other hand, piles are considered as linear, viscoelastic, unidimensional Timoshenko's beams through finite elements. Piles are treated as load lines in the soil formulation in order to incorporate the pile-soil interaction tractions. Finally, the equations of piles and soil are coupled together by imposing compatibility and equilibrium conditions.

2. Methodology – Piles are discretized through 2-noded elements with 5 degrees of freedom each representing the three displacements and the two bending rotations of the pile (the torsional rotation is omitted because no torsional resistance is contemplated between the piles and soil). The lateral displacements and rotations of each pile element are modelled by using cubic and quadratic shape functions that satisfy the static governing equation of the Timoshenko's beam [2], while the axial displacements of the pile are modelled with linear shape functions. By the assembly of the elemental stiffness and mass matrices, the global finite element system of equations that must be solved in order to obtain the nodal values of the pile displacements and rotations ($\boldsymbol{u}^p$) is:

$$(\mathbf{K} - \omega^2 \boldsymbol{M})\boldsymbol{u}^p = \boldsymbol{F} \tag{1}$$

where $\mathbf{K}, \mathbf{M}$ are the global stiffness and mass matrices, ω is the angular frequency, and $\boldsymbol{F}$ is the vector of nodal forces acting over the pile. The pile damping is assumed to be hysteretic and is included into the stiffness matrix through the definition of a complex material Young's modulus $E_p^* = \mathrm{Re}[E_p](1 + 2\mathrm{i}\beta_p)$, being β_p the damping coefficient. Inclined piles can also be considered through a proper rotation of the elemental matrices.

The forces acting over the pile can be separated into two different types: the ones produced by the boundary conditions imposed at the pile head or tip ($\boldsymbol{F}^{\mathrm{ext}}$), and the ones produced by the interaction between the pile and the soil. The last ones are represented as tractions ($\boldsymbol{q}^p$) acting along the pile shaft in each orthogonal direction of the space. The soil-pile interaction tractions are modelled inside each element by using linear shape functions, and their equivalent nodal loads are obtained by using matrix $\boldsymbol{Q}$, whose elemental matrices are defined by integrating the corresponding shape functions for the tractions, displacements and rotations in the sense of the principle of virtual displacements. Including the aforementioned external forces into Eq. (1), the pile system of equations results in:

$$(\mathbf{K} - \omega^2 \boldsymbol{M})\boldsymbol{u}^p - \boldsymbol{Q}\boldsymbol{q}^p = \boldsymbol{F}^{\mathrm{ext}} \tag{2}$$

On the other hand, the equations that governs the soil behaviour are obtained by using the reciprocity theorem in elastodynamics assuming harmonic variables [3]. Considering two different elastodynamic states $S(\Omega, \omega; \boldsymbol{u}, \boldsymbol{\sigma}, \boldsymbol{b})$ and $S^*(\Omega, \omega; \boldsymbol{u}^*, \boldsymbol{\sigma}^*, \boldsymbol{b}^*)$ defined over a domain Ω with boundaries Γ, they can be related by applying the reciprocity theorem as:

$$\int_\Gamma \boldsymbol{p}^* \boldsymbol{u} \, d\Gamma + \int_\Omega \boldsymbol{b}^* \boldsymbol{u} \, d\Omega = \int_\Gamma \boldsymbol{p}\boldsymbol{u}^* \, d\Gamma + \int_\Omega \boldsymbol{b}\boldsymbol{u}^* \, d\Omega \tag{3}$$

where $\boldsymbol{u}$ is the vector of displacements, $\boldsymbol{p}$ the tractions at the boundaries compatible with the stress tensor $\boldsymbol{\sigma}$, and $\boldsymbol{b}$ the body forces acting inside the domain. In order to determine the state S, it is necessary to define the state S^*, which is usually referred to as fundamental solution. In this work, the specific Green's functions proposed by Pak and Guzina [1] for the horizontally layered half space are used as fundamental solution. These Green's functions are defined as the response of any point of the layered half space to a punctual load acting in each of the three orthogonal directions of the space. As the fundamental solution satisfies the free-surface boundary condition ($\boldsymbol{p}^* = 0$ at Γ), and its body forces can be represented as a Dirac's delta acting on the collocation point κ ($\boldsymbol{b}^* = \delta(\boldsymbol{x}^\kappa)$), the left-hand side of Eq. (3) is reduced to the displacements at the collocation point $\boldsymbol{u}^\kappa$. On the other hand, the unknown state S also satisfies the free-surface boundary condition ($\boldsymbol{p} = 0$ at Γ) so the third integral of Eq. (3) also vanishes. Regarding the body forces of state S, they correspond to the pile-soil tractions that are acting on the soil along the load lines Γ_p that represent the piles ($\boldsymbol{b} = \boldsymbol{q}^s$ at Γ_p and 0 elsewhere). Including all these considerations into Eq. (3), the integral equation of the reciprocity theorem results in:

$$\boldsymbol{u}^\kappa = \int_{\Gamma_p} \boldsymbol{q}^s \boldsymbol{u}^* \, d\Gamma_p \tag{4}$$

Each component of this vectorial equation corresponds to the application of the punctual load at one of the three orthogonal directions of the space. By applying Eq. (4) to every pile node, and using linear shape functions to represent the soil-pile interaction tractions inside the pile elements, the following system of equations is obtained:

$$\boldsymbol{u}^s = \boldsymbol{G}\boldsymbol{q}^s \tag{5}$$

where the elements of the influence matrix $\boldsymbol{G}$ are obtained through a numeric Gaussian quadrature integration process of the displacement Green's functions times the proper shape functions along the pile elements. As the calculation of the fundamental solution demands a great computational effort, a special procedure has been implemented in order to take advantage of the fact that many of the terms of the influence matrix coincide due to the regular disposition of the piles in the groups. This way, each different submatrix is computed once, and assembled into all the corresponding positions. Also, a special non-nodal collocation strategy must be employed in order to evaluate this integral when the collocation point belongs to the integration element (see [4,5]).

Finally, the pile and soil systems of equations are coupled together by imposing compatibility conditions in terms of the pile and soil displacements ($\boldsymbol{u}^s = \boldsymbol{u}^p$), and equilibrium conditions for the soil-pile interaction tractions ($\boldsymbol{q}^s = -\boldsymbol{q}^p$). This way, the following system of equations is obtained, which can be solved once the pile head and tip boundary conditions are stablished:

$$\begin{bmatrix} (\boldsymbol{K} - \omega^2 \boldsymbol{M}) & -\boldsymbol{Q} \\ \boldsymbol{I} & \boldsymbol{G} \end{bmatrix} \begin{bmatrix} \boldsymbol{u}^p \\ \boldsymbol{q}^p \end{bmatrix} = \begin{bmatrix} \boldsymbol{F}^{\mathrm{ext}} \\ 0 \end{bmatrix} \tag{6}$$

3. Results and Discussion - In order to illustrate the capabilities and accuracy of the model, pile impedance functions for single piles and pile groups in homogeneous and layered soils are presented and compared to previous results found in the literature. The impedance function K_{ij} of a pile foundation is defined as the ratio between the force (or moment) in direction i and the produced displacement (or rotation) in direction j. They are frequency-dependent and complex-valued, whose real and imaginary components represent the stiffness (k_{ij}) and damping (c_{ij}) of the pile foundation.

As verification results, Image 1 presents the horizontal, vertical and rocking impedance functions for a 4x4 pile group embedded in different soils (G1, G2: properties that increase linearly with depth; G3: homogeneous soil). Their values are normalized by the static stiffness of the single pile and plotted as functions of the dimensionless frequency $a_o = \omega d / c_s$, where d is the pile diameter and c_s is the shear wave velocity of the soil. For the soils whose properties depend on the depth, the value of the shear wave velocity corresponding to the position of the pile tip is used. The results of the proposed model are compared to the ones presented by Miura et al. [6], obtaining a good agreement between the two methodologies.

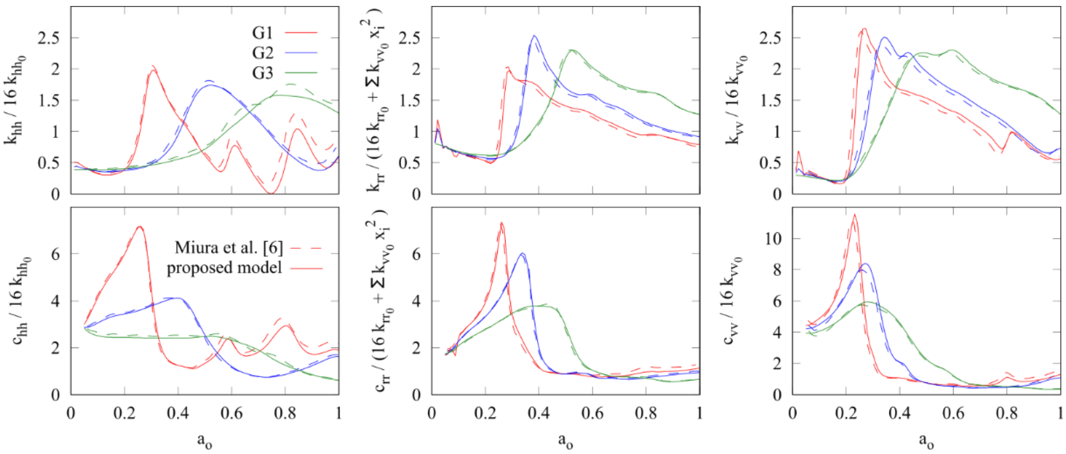

Image 1. Horizontal, rocking and vertical impedance functions for 4x4 pile groups embedded in different soils. Comparison with Miura et al.

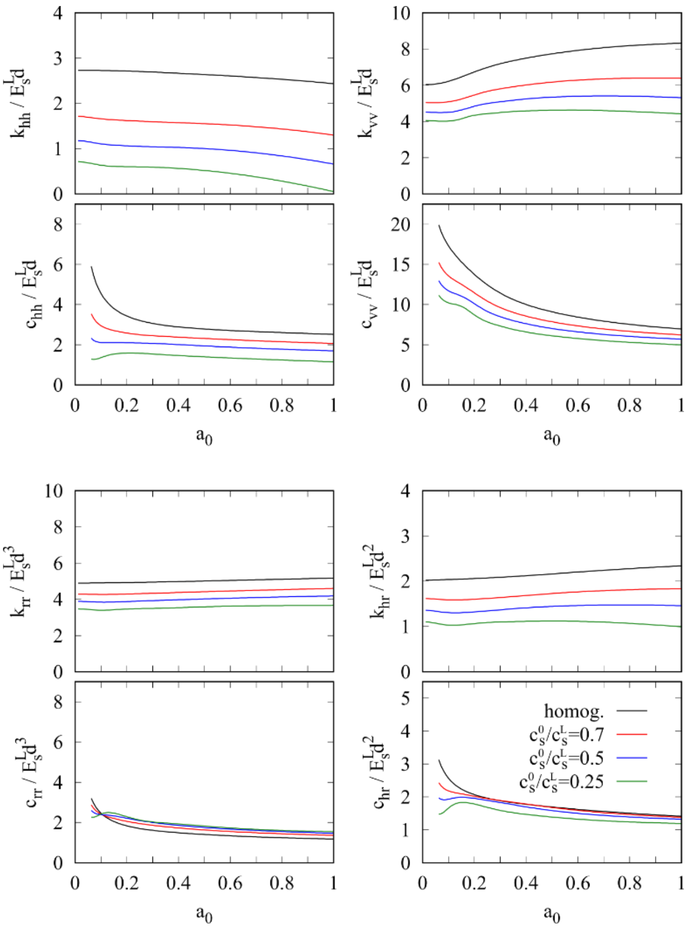

Image 2. Effect of the soil profile on the impedance functions for a single pile

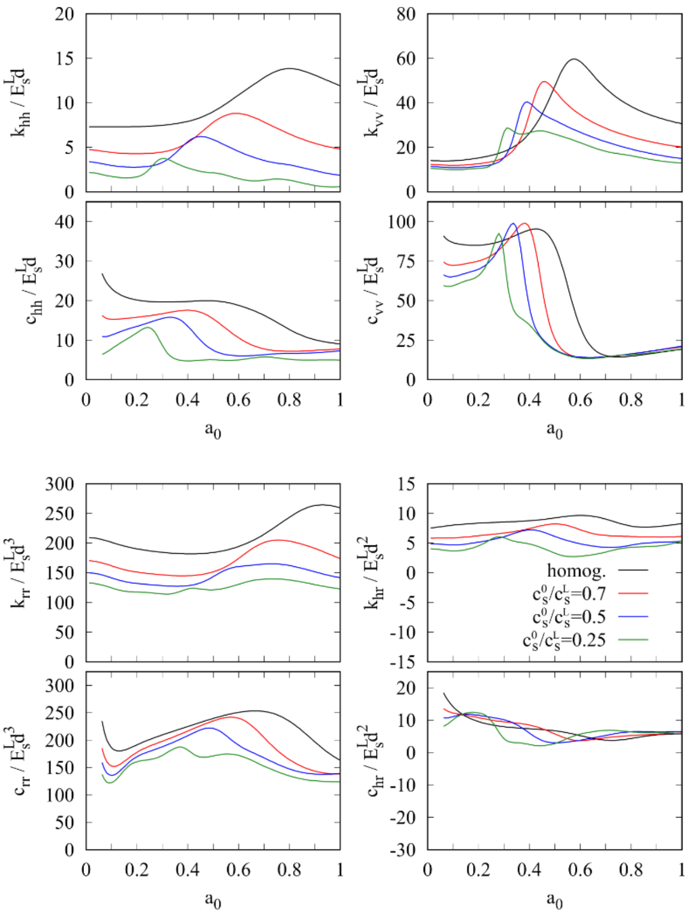

Image 3. Effect of the soil profile on the impedance functions for 2x2 pile group

Images 2 and 3 present the horizontal, vertical, rocking and horizontal-rocking coupling impedance functions for a single pile and a group of 2x2 piles, respectively. Different soil profiles are considered by defining a linearly-increasing soil Young's modulus along the pile length. For depth below the pile tip, a homogeneous half space with the same properties as the ones corresponding to the pile tip is assumed. These properties (E_s^L, c_s^L) are the ones used to normalize the impedance functions and define the dimensionless frequency. On the other hand, the non-homogeneity of the soil profile is determined by the ratio between the shear wave velocity at the free-surface level and the shear wave velocity at the tip depth (c_s^0/c_s^L). A homogeneous profile is also contemplated as reference results.

Regarding the pile properties, they are determined by the following dimensionless parameters: pile-soil Young's modulus ratio $E_p/E_s = 100$, soil-pile density ratio $\rho_s/\rho_p = 0.7$, Poisson's ratio of soil $\nu_s = 0.4$ and pile $\nu_p = 0.25$, hysteretic damping coefficient of soil $\beta_s = 5\%$ and pile $\beta_p = 0\%$, pile aspect ratio $L/d = 15$, and, for the group configuration, a separation between the piles of $s/d = 5$. These values are chosen as typical for concrete pile foundations.

Attending to Image 2, it is found that as the soil becomes more non-homogeneous, both the stiffness and damping terms of the impedance functions of the single pile decrease due to the reduction of the soil stiffness at the superficial layers when the relation c_s^0/c_s^L decreases. This effect specially affects the horizontal stiffness term, but is not found for the damping term of the rocking impedance, whose values increase as the soil becomes more non-homogeneous.

Contrary to the impedance functions of the single pile, which are nearly frequency independent, the results of Image 3 present peak values at some frequencies due to the group effects. Those peaks take place at smaller values of the dimensionless frequency as the soil profile becomes more variable. As commented before, in general terms, the impedance functions for the non-homogeneous soils present lower values than the ones of the homogeneous profile.

A comprehensive study of the effects of the soil profile on the impedance functions of vertical and inclined pile groups through the use of the proposed model can be found in [5].

4. Conclusions - The use of the advanced Green's functions, which already satisfy the free-surface and layer interfaces boundary conditions, simplifies the formulation to the extent that only the pile variables (displacements and tractions) are needed. Thus, the high memory requirements and the uncertainties related to the soil mesh are completely avoided, allowing the use of the proposed model for studying the response of large pile foundations in soils with a high number of layers in a very computationally efficient way.

5. Acknowledgements - This work was supported by Subdirección General de Proyectos de Investigación of the Ministerio de Economía y Competitividad (MINECO) of Spain and FEDER through research project BIA2014-57640-R. G.M. Álamo is a recipient of FPU research fellowship FPU14/06115 from the Ministerio de Educación, Cultura y Deporte of Spain.

6. References

[1] R.Y.S. Pak and B.B. Guzina, *J. Eng. Mech.,* **128**(4), (2002) p. 449.
[2] Z. Friedman and J.B. Kosmatka, *Comput. Struct.*, **47**(3), (1993) p. 473.
[3] L.T. Wheeler and E. Sternberg, *Arch. Ration. Mech. Anal.,* **31**(1), (1968) p. 51.
[4] L.A. Padrón, J.J. Aznárez, O. Maeso and A. Santana, *Earthq. Eng. Struct. Dyn.*, **39**(12), (2010) p. 1343.
[5] G.M. Álamo, A.E. Martínez-Castro, L.A. Padrón, J.J. Aznárez, R. Gallego and O. Maeso, *Eng. Struct.*, **126**, (2016) p. 379.
[6] K. Miura, A.M. Kaynia, K. Masuda, E. Kitamura and Y. Seto, *Earthq. Eng. Struct. Dyn.,* **23**, (1994) p. 183.

ScienceKNOW
Scientific Knowledge Conferences
for education