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Preface

Madrid, 20 de Junio de 2018,

La dinámica estructural es un campo de interés común y de importancia creciente en diversas especialidades de la ingeniería y de la ciencia. Mientras que en algunos campos como las máquinas o los vehículos de transporte ha sido siempre un elemento básico, en otros como la ingeniería civil y la arquitectura, más preocupados tradicionalmente con la estática, se ha convertido en un aspecto muy relevante.

Esta primera conferencia a nivel nacional pretende ser un foro en el que tengan cabida los trabajos de investigación, desarrollo y aplicaciones, permitiendo la discusión, difusión, contacto con otros grupos y establecimiento de colaboraciones. Se organiza con proyección internacional y europea, contando con el apoyo de la European Association for Structural Dynamics (EASD) organizadora de los congresos EURODYN, así como con el apoyo de la Sociedad Española de Métodos Numéricos (SEMNI).

La participación incluye tanto trabajos basados en métodos teóricos y computacionales como experimentales. Por otra parte abarca todos los campos de la dinámica estructural, como son la ingeniería mecánica, el transporte, ingeniería civil y arquitectura, ingeniería sísmica e ingeniería de materiales. Aunque ubicados en especialidades de ingeniería distintas todos estos campos comparten conceptos y métodos comunes de dinámica.

Esta primera conferencia pretende iniciar una serie que se desarrolle de forma periódica. Asimismo se propone constituir una Asociación Española de Dinámica Estructural que articule las actividades de colaboración y difusión, y que sirva de interlocutora con otros órganos nacionales e internacionales como la EASD.

Desde el comité organizador queremos dar la bienvenida a todos los participantes y ponernos a disposición para el desarrollo de la conferencia.

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SECTION 6: Seismic engineering, soil-structure dynamic interaction

DIRECT MODEL FOR THE DYNAMIC ANALYSIS OF PILED STRUCTURES ON NON-HOMOGENEOUS MEDIA

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Abstract. A time-harmonic numerical model for the direct dynamic analysis of piled structures including soil-structure interaction effects is presented in this work. Superstructures are defined as a combination of beam and shell finite elements with the possibility of including concentrated masses and inertias. The soil-foundation interaction is limited to the one produced along the pile shaft and is modelled by a formulation based on the integral expression of the reciprocity theorem in elastodynamics and the use of specific Green's function for the layered half space. In this formulation, piles are modelled as Timoshenko's beam finite elements and treated as load lines acting within the soil. The coupling between piles and superstructures is made by imposing equilibrium and compatibility conditions at the shared pile head nodes. Because of the employed soil formulation, the resulting model only involves variables related to the structural or pile nodes, omitting any discretization of the surrounding soil. The present model was originally developed for the seismic analysis, including soil-structure interaction effects, of offshore wind turbines structures with pile foundations. However, its general formulation allows the computation of the dynamic response of any typology of piled structures (or group of structures) taking dynamic soil-structure interaction and wave propagation through the layered soil into account.

Key words: Soil-Structure Interaction, Integral Model, Finite Elements, Direct Approach, Layered Soil

1 INTRODUCTION

Pile foundations are commonly used in bridge piers, tall buildings and marine constructions. They are specially useful in soils where the superficial layers present low bearing capacity and to transmit large horizontal loads to the terrain.

Generally, when analysing the response of piled structures, substructuring approaches are used. They include the stiffness and filtering effects of the foundation through impedance functions and kinematic interaction factors, respectively. However, piled structures can also be analysed through direct models that compute, in one single step, the coupled response of the structure and foundation. In this work, a direct model for the dynamic analysis of piled foundations in layered soils is presented.

2 MODEL OVERVIEW

The proposed three-dimensional model is formulated in the frequency domain, within the scope of linear elasticity. The structures and piles are modelled through finite elements, while the interaction between the piles and soil is represented through distributed forces acting along load lines inside the soil domain. The coupling between the foundation and the structural elements is made by imposing compatibility (in terms of nodal displacements and rotations) and equilibrium (through pile-structures coupling reactions) conditions. The system can be excited by body waves that propagate through the layered soil from a far-away source. The material damping for all components is assumed to be hysteretic, through the definition of complex elastic constants.

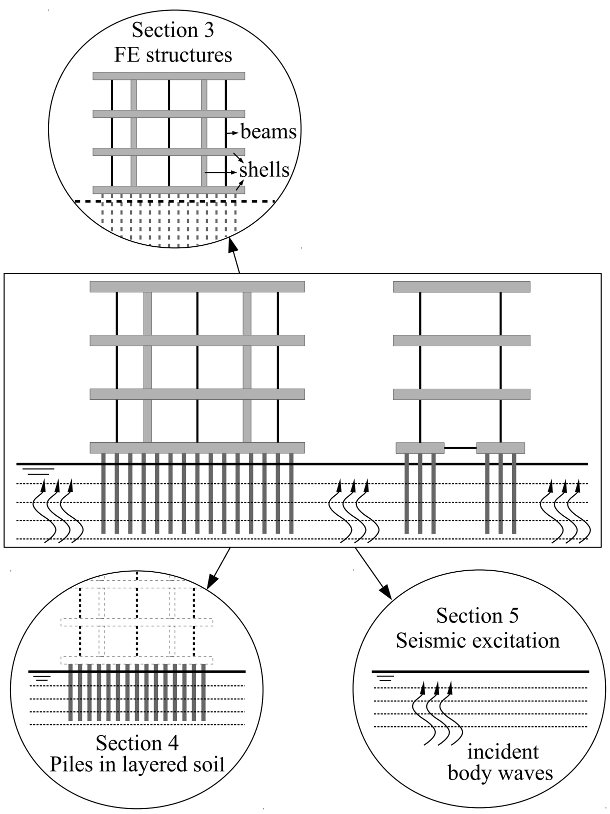

Figure 1: Sketch of the model.

The model and its different components are sketched in Fig. 1. In the following sections, the formulation of each part of the system (i.e., structures, foundation and seismic excitation) is briefly detailed. Once the equations of each of them are considered, and the proper boundary conditions are imposed, a linear system of equations (LSE) is obtained that can be solved to compute the structural and foundation response. This system has the form:

$$\mathcal{A}\ \left\{\bar{\mathbf{u}}^{\mathrm{p}}, \bar{\mathbf{q}}^{\mathrm{p}}, \bar{\mathbf{F}}^{\mathrm{pb}}, \bar{\mathbf{u}}^{\mathrm{b}}\right\}^{\mathrm{T}} = \mathcal{B}(\mathrm{b.c.}, \bar{\mathbf{F}}^{\mathrm{b}}_{\mathrm{ext}}, \bar{\mathbf{u}}_{\mathbf{I}}) \tag{1}$$

where $\mathcal{A}$ is the matrix of coefficients of the LSE; the unknowns of the system correspond to the pile nodal displacements and rotations $\bar{\mathbf{u}}^{\mathrm{p}}$, the nodal values of the soil-pile interaction tractions $\bar{\mathbf{q}}^{\mathrm{p}}$, the pile-structure reactions $\bar{\mathbf{F}}^{\mathrm{pb}}$ and the structural nodal displacements and rotations $\bar{\mathbf{u}}^{\mathrm{b}}$; and $\mathcal{B}$ is the vector of known coefficients obtained from the boundary conditions (b.c.), the external forces acting over the structures $\bar{\mathbf{F}}^{\mathrm{b}}_{\mathrm{ext}}$ and the nodal displacements of the incident field $\bar{\mathbf{u}}_{\mathbf{I}}$. Note that the proposed model, despite including soil-foundation interaction effects, presents no variables related to any soil discretization.

3 STRUCTURES MODEL

The analysis of the superstructures is conducted by a finite element (FE) representation of them. Unidimensional (beam) and bidimensional (shell) elements can be freely combined, with the only restriction that the different elements have to be connected through their nodes.

Six degrees of freedom per node are considered corresponding to the three displacements and the three rotations in the space. For the beam elements, 2-noded elements are used. Cubic and quadratic shape functions that satisfy the static governing equation of the Timoshenko's beam [1] are considered for the lateral behaviour, while linear shape functions are used for the axial and torsional modes. On the other hand, 4-noded and 9-noded Mixed Interpolation of Tensorial Components (MITC) shell elements [2, 3] are used for the bidimensional elements. In addition to the afore-mentioned elements, additional concentrated masses or moments of inertia can be included at the structural nodes.

By assembling the elemental stiffness and mass matrices of all structural elements, the FE equations can be written as:

$$\left(\mathbf{K}^{\mathrm{b}} - \omega^2 \mathbf{M}^{\mathrm{b}}\right) \bar{\mathbf{u}}^{\mathrm{b}} = \bar{\mathbf{F}}^{\mathrm{b}}_{\mathrm{ext}} + \bar{\mathbf{F}}^{\mathrm{pb}} \tag{2}$$

where $\mathbf{K}^{\mathrm{b}}$ and $\mathbf{M}^{\mathrm{b}}$ are the global stiffness and mass matrices of the structure, and ω is the excitation circular frequency.

4 SOIL-PILE MODEL

The soil-pile model corresponds to the integral model previously presented by the authors for the analysis of pile foundations [4]. In this model, the soil behaviour is obtained from the application of the integral expression of the reciprocity theorem in elastodynamics and the use of specific Green's functions for the layered half space [5]. In the soil equations, piles are reduced to unidimensional load lines, and the interaction phenomena are taken into account through distributed forces along these lines, avoiding any meshing of the pile-soil interfaces. On the other hand, the use of the layered half space Green's functions that already satisfy the free-surface and layer interfaces conditions, avoids any meshing of the soil contours. The additional stiffness and mass introduced by the piles are taken into account through their FE equations, which are coupled to the soil equations by imposing compatibility and equilibrium conditions. In the following, each part of the foundation system is detailed.

4.1 Pile finite element equations

For the pile discretization, the same beam elements than the ones used for the structures are considered. In addition to the 6 displacements and rotations, 3 extra unknowns per node are included corresponding to the nodal values of the soil-pile interaction tractions acting over the piles. Linear shape functions are used to model these interaction tractions inside each element. The corresponding FE equations are:

$$\left(\mathbf{K}^{\mathrm{p}} - \omega^2 \mathbf{M}^{\mathrm{p}}\right) \bar{\mathbf{u}}^{\mathrm{p}} = \mathbf{Q}^{\mathrm{p}} \bar{\mathbf{q}}^{\mathrm{p}} - \bar{\mathbf{F}}^{\mathrm{pb}} \tag{3}$$

where $\mathbf{K}^{\mathrm{p}}$ and $\mathbf{M}^{\mathrm{p}}$ are the global stiffness and mass matrices of the piles, and $\mathbf{Q}^{\mathrm{p}}$ is the global matrix that transforms the distributed loads into equivalent nodal loads.

4.2 Soil equations

The integral expression of the reciprocity theorem in elastodynamics once the boundary conditions of the Green's functions and the studied problem are considered results in:

$$\mathbf{u}^{\kappa} = \int_{\Gamma_p} \mathbf{u}^{*} \mathbf{q}^{s} \; \mathrm{d}\Gamma_p \tag{4}$$

where $\mathbf{u}^{\kappa}$ is the vector containing the three displacements of the collocation point κ, Γ_p denotes the load lines representing the piles, $\mathbf{u}^{*}$ is the tensor containing the fundamental solution in terms of displacements and $\mathbf{q}^{s}$ is the vector of soil-pile interaction distributed loads acting over the soil.

Applying Eq. (4) to all pile nodes, and considering linear shape functions to discretize $\mathbf{q}^{s}$ inside each pile element, the following LSE is obtained:

$$\bar{\mathbf{u}}^{\mathrm{s}} = \mathbf{G}^{\mathrm{s}} \bar{\mathbf{q}}^{\mathrm{s}} \tag{5}$$

where $\bar{\mathbf{u}}^{\mathrm{s}}$ is the vector of soil displacements at the pile nodes, $\mathbf{G}^{\mathrm{s}}$ is the influence matrix obtained by Gaussian integration of the fundamental solution times the linear shape functions, and $\bar{\mathbf{q}}^{s}$ is the vector with the nodal soil-pile interaction tractions acting over the soil.

4.3 Soil-pile coupling

The pile and soil systems of equations are coupled together by imposing compatibility ($\bar{\mathbf{u}}^{\mathrm{s}} = \bar{\mathbf{u}}^{\mathrm{p}}$) and equilibrium ($\bar{\mathbf{q}}^{\mathrm{s}} = -\bar{\mathbf{q}}^{\mathrm{p}}$) conditions. This way, all soil variables are expressed in terms of the pile ones.

5 SEISMIC EXCITATION

The seismic excitation is modelled through planar wave-fronts that propagates through the soil. The total displacement field is assumed to be the superposition of the incident field produced by these waves plus the scattered field produced by the diffraction and refraction phenomena induced by the presence of the piles. Noting that Eq. (5) is written in terms of the scattered field, it can be easily rewritten in terms of the total displacements field as:

$$\bar{\mathbf{u}}^{\mathrm{s}} = \mathbf{G}^{\mathrm{s}}\bar{\mathbf{q}}^{\mathrm{s}} + \bar{\mathbf{u}}_{\mathbf{I}} \tag{6}$$

6 APPLICATION EXAMPLE

To illustrate the abilities of the presented model, the 4-storey building defined in Fig. 2 is considered. The transfer functions of the lateral displacements of the first and last floors with respect to the free-field motion are presented in Fig. 3. Two scenarios are compared in order to manifest the influence of soil-structure interaction: the infinitely-rigid base (no SSI), and the flexible soil (SSI).

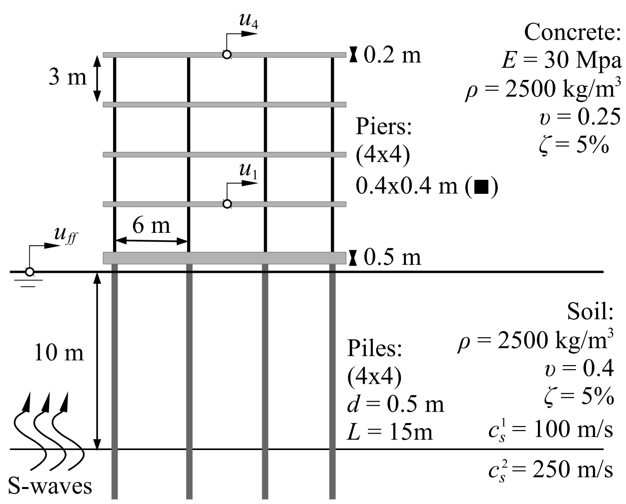

Figure 2: Definition of the application example.

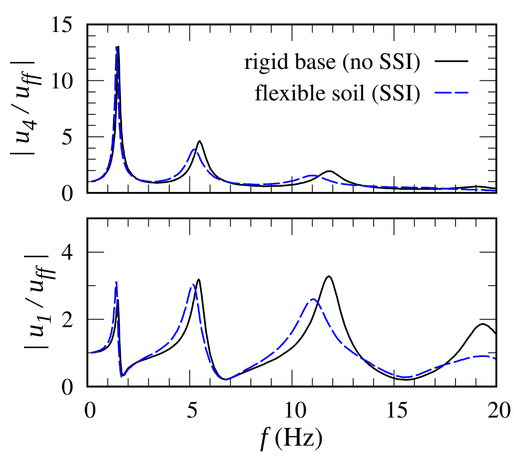

Figure 3: 1$^{\text{st}}$ and 4$^{\text{th}}$ floor displacements.

7 CONCLUSIONS

This work presents a direct model for the analysis of piled structures in layered soils including soil-structure interaction effects. The use of specific Green's functions for the layered half space in the soil equations and the treatment of the piles as load lines avoid any meshing of the soil domain, significantly reducing the number of degrees of freedom of the model. The capabilities of the proposed formulation are shown through an example.

8 ACKNOWLEDGMENTS

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