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The effect of soil–foundation–structure interaction on the wind-induced response of tall buildings

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ABSTRACT

The aim of this work is to provide a contribution towards the qualitative and quantitative assessment of soil–foundation–structure interaction effects on the dynamic response of tall buildings founded on relatively rigid rafts, and subjected to wind loading. The mechanical response of the soil–foundation system is modeled using two different approaches: in the first, the (visco)elastic system response is defined in terms of impedance coefficients; in the second, an inelastic, 6 DOF macroelement recently proposed for shallow foundations on coarse-grained soils is adopted. The macroelement approach allows to account for the non-linear and irreversible behavior of the soil–foundation system, and to consider the experimentally observed coupling between the different degrees of freedom in the inelastic regime. The results of a series of numerical simulations highlight the importance of considering SFSI effects in the analysis, and allow to identify the effects of the different constitutive assumptions made for the soil–foundation system. In particular, it is found that the permanent displacements and rotations accumulated at the foundation level in the inelastic simulations can give rise to significant permanent displacements at the building top. Moreover, significant differences are observed on the predicted forces and moments distribution at the building base for the two SFSI approaches considered.

1. Introduction

The current trend of constructing taller and increasingly slender buildings implies that such structures often experience excessive wind-induced vibrations, which may cause discomfort to occupants and serviceability design problems.

In conventional engineering practice, tall buildings are often designed considering the base of the structure fixed to the ground, thus neglecting soil–foundation–structure interaction (SFSI) effects. Although this can be considered reasonable for low rise buildings on relatively stiff soils, the effect of SFSI becomes prominent for heavy structures resting on relatively soft soils (see, *e.g.*, [1]). In fact, soil deformability modifies the modal characteristics of the system in terms of natural periods and modal shapes. Moreover, the nonlinear and hysteretic behavior of the foundation soil and the radiation damping increase the overall energy dissipation of the system. Both effects may lead to an increased overall deformation of the system, with the accumulation of significant irreversible displacements, and to a different distribution of the internal forces, with a net reduction in the structural demand.

The most commonly used method to account for SFSI effects is modeling the soil–foundation system with a series of (visco)elastic elements – one for each degree of freedom of the system – whose stiffness and damping coefficients are defined through equivalent springs and dashpots (see, *e.g.*, [1–3]). In some cases, this approach could be rather inaccurate, as it does not consider the possible coupling between the different degrees of freedom and the inelastic response induced by plastic deformations which might develop in the foundation soil even at relatively low load levels.

Recently, a number of alternative, more accurate modeling strategies have been proposed in the literature to account for SFSI effects see, *e.g.*, [4, for a review]. A quite versatile and powerful approach is based on the use of the finite element method to set-up a detailed model of the soil–foundation system in the "near field" – corresponding to a limited soil region, delimited by artificial boundaries – while using linear elasticity to model the "far field" response. In the near field, the soil can be described with either nonlinear elastic or fully inelastic models, capable to account for the main features of the soil response under cyclic/dynamic loading conditions see, *e.g.*, [5–7]. This approach has many advantages but also some drawbacks, depending on the problem at hand [8]. In particular, the main disadvantage is found in the high computational cost associated to the very large number of degrees of

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freedom required to discretize the soil volume in the near field, particularly in the inelastic regime.

To overcome this difficulty, a number of alternative simplified approaches have been extensively developed during recent years. Among these, the *macroelement* approach is particularly worth mentioning. It consists in lumping the response of the foundation–soil system into a single computational node, using a single inelastic constitutive equation written in terms of generalized loads and displacements to describe it. This allows to obtain a dramatic reduction of the degrees of freedom, while preserving the ability of effectively reproducing the nonlinear, irreversible and hysteretic response of shallow foundations subject to nonproportional, cyclic/dynamic loading conditions. The macroelement approach dates back to the pioneering work of Nova & Montrasio [9], and has been exploited for cyclic/dynamic loading applications in many more recent works, see, *e.g.*, [10–18].

As in Nova & Montrasio, the inelastic constitutive equations for the macroelement can be cast within the framework of the classical theory of – isotropic or anisotropic – hardening plasticity [10–14,19]. A different approach was pursued by Salciarini & Tamagnini [16], who adopted the theory of hypoplasticity with internal variables ([20,21]) to construct a macroelement formulation suitable for monotonic and cyclic loading conditions. Further applications of hypoplastic macroelements for shallow foundations are reported in [17,22,23]. A comparison between the two modeling approaches in the analysis of the seismic response of a r.c. bridge is presented in [17].

Although many applications of the SFSI models for buildings subjected to earthquake excitation can be found in the literature, only a few studies were carried out for wind-excited structures. Some of these applications were addressed to slender line structures (*e.g.*, wind turbine towers and antennas [3]) and to high-rise buildings equipped with passive control systems, where the SFSI can produce the mistuning of the devices [24,25]. Although the importance of accounting for SFSI in wind-excited structures is well known [26], only the classical approach based on the use of impedance coefficients to derive the stiffness and damping coefficients of the equivalent springs and dashpots representing the soil–foundation system appears to have been used so far to assess SFSI effects from a quantitative standpoint.

In this paper, the wind-induced response of high-rise buildings with relatively rigid raft foundations resting on a relatively homogeneous soil is analyzed considering two different approaches for modeling the complex behavior of the soil–foundation system: (i) the classical approach based on impedance coefficients; and, (ii) the hypoplastic macroelement model developed by [22]. A series of numerical analyses are carried out on a case study consisting of a square tall building, 180 m high. The superstructure is modeled as an equivalent dynamic system with 6 DOFs for each floor, whose parameters are calibrated with an optimization process.

The outline of the paper is as follows. After a brief review of the simplified modeling approaches used to describe the global response of the soil–foundation system (Section 2), a summary of the main features of the hypoplastic macroelement model adopted in the study is given in Section 3. Section 4 describes in detail the particular case study examined, while the main results obtained from the numerical simulations are presented in Section 5. Finally, some concluding remarks are given in Section 6.

2. Global modeling approaches for SFSI effects

In global approaches, the mechanical response of the soil–foundation–superstructure system to assigned loading conditions, is described by means of a single constitutive equation, expressed in terms of generalized forces and conjugated generalized displacements. In this work, the vector of the generalized forces $\boldsymbol{T}$ is defined as:

$$\boldsymbol{T} := \left\{ V, \quad H_x, \quad M_y/B_x, \quad H_y, \quad M_x/B_y, \quad Q/\sqrt{B_x B_y} \right\}^T \tag{1}$$

while the work-conjugated generalized displacement vector $\boldsymbol{U}$ is given by:

$$\boldsymbol{U} := \left\{ U_z, \quad U_x, \quad \Theta_y B_x, \quad U_y, \quad \Theta_x B_y, \quad \Omega\sqrt{B_x B_y}, \right\}^T \tag{2}$$

In Eqs. (1) and (2), V, H_x, H_y, M_x, M_y and Q are the resultant forces and moments acting on the foundation; $U_z, U_x, U_y, \Theta_x, \Theta_y$ and Ω are the corresponding displacements and rotations, while B_x and B_y are the width and length of the foundation, assumed of rectangular shape (see Fig. 1).

In what follows, the two global approaches adopted in this work to evaluate SFSI effects are briefly summarized.

2.1. Linear elastic approach

In this approach, the motion of the foundation, resting on a homogeneous elastic half space, is related to the applied load by the following simple, linear constitutive equation:

$$\boldsymbol{T} := \boldsymbol{\mathcal{K}} \boldsymbol{U} \tag{3}$$

where $\boldsymbol{\mathcal{K}}$ is a positive definite, symmetric matrix defined as:

$$\boldsymbol{\mathcal{K}} = \begin{bmatrix} k_{vv} & 0 & 0 & 0 & 0 & 0 \\ & k_{u_x u_x} & k_{u_x \theta_y} & 0 & 0 & 0 \\ & & k_{\theta_y \theta_y} & 0 & 0 & 0 \\ & & .. & k_{u_y u_y} & k_{u_y \theta_x} & 0 \\ & \mathrm{symm} & .. & .. & k_{\theta_x \theta_x} & 0 \\ & .. & .. & .. & .. & k_{\omega\omega} \end{bmatrix} \tag{4}$$

where the components $k_{\alpha\beta}$, with $\alpha, \beta \in \{v, u_x, \theta_y, u_y, \theta_x, \omega\}$, are constant stiffness coefficients – functions of soil stiffness and foundation geometry – which can be obtained from the theory of elasticity or by means of simplified approaches, such as, for example, those outlined in Refs. [1,27]. In this type of models, radiation

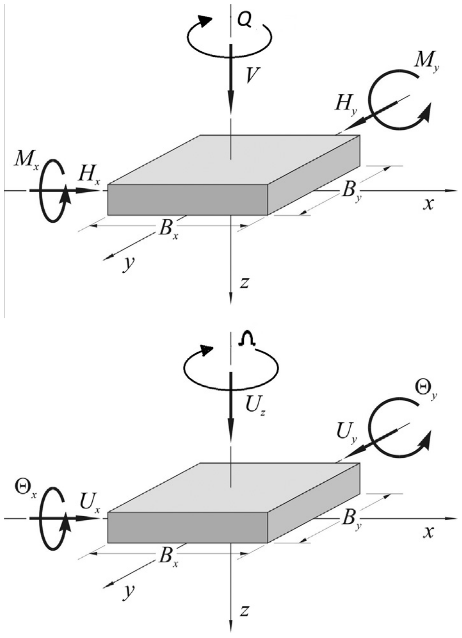

Fig. 1. Notation adopted for (a) generalized forces and (b) displacements components.