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A comprehensive approach to small and large-scale effects of earthquake motion variability

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ABSTRACT

This work deals with the evaluation of the effects of the spatial variability of earthquake input motion on the dynamic response of structures. The variability of the free-field motion both over the area of a single foundation as well as over the distance between independent foundations of large structures is considered.

Two significant applications of the proposed numerical procedure are presented. In the first one a base isolated nuclear reactor building is considered where the issue of the rocking excitation on the peak value of axial forces in the isolation devices and acceleration in the building structure is investigated. Extended structures having tall members are considered as second application. A cable-supported bridge model, formerly studied within a simpler representation of the seismic ground motion, serves as case study in which spatial variability acts at different scales.

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1. Introduction

The variability of the earthquake motion is a subject that has been vastly studied in the literature (e.g. the review in [23]). The term spatial variation denotes the differences in amplitude and arrival time (phase) of seismic motions over extended areas. The variability stems from the relative surface-fault motion for sites located on either side of the causative fault, soil liquefaction, landslides and from the general transmission of the waves from the source through the different earth strata to the ground surface.

The effects of the spatial variation of the seismic ground motion is deemed to be important for the response of structures of large dimensions, e.g. nuclear power plants, pipelines, tunnels, dams and medium-long-span bridges. The interest here is therefore the variability of the earthquake motion both over the area of the single foundation of a building as well as over the distance between independent foundations of large structures.

At any rate, in the case of large or heavy structures the ground motion at surface cannot be directly used as the seismic input of the structural analysis since the so termed Soil-Structure Interaction (SSI) has to be accounted for. Indeed, effects of SSI come to be of outmost importance in the evaluation of the response of structural systems and generally cannot be neglected.

The essence of SSI is that the motion that will occur to the foundation differs from the free field one. The differences are due both to the effect of the stiffness of the structure-foundation system on the soil motion over the area of the foundation and to the modification of the soil motion induced by the inertia forces developing in the vibrating structure. The first effect has been termed as the kinematic interaction, the second as the inertial interaction.

A typical kinematic interaction effect arises in the case of soil-structure analyses of rigid foundations, where the foundation-soil compatibility constraint results in a sort of averaging effect applied to the free-field motion: this effect delivers, in turn, reduced translational components but is also responsible for the occurrence of torsional and rocking motions [26,22,20].

Under these premises, the seismic input motion at the base of the structural system can be completely defined by the six components defining the motion of the rigid mat, which can be derived by the small-scale spatial model of the free-field motion at the ground foundation interface.

The above considerations hold true also for systems under multi-support excitation, e.g. medium-long-span bridges supported by multiple piers and bents. In this case, however, the large-scale spatial variability of the ground motion will lead to different averaged seismic excitation applied to the base-mat of each pier that will also differ due to the time delay in the arrival of the seismic waveforms and to the modification of the motion due to scattering, non-linear soil response and other effects [23]. For

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modeling this effects, the hypothesis that seismic excitation propagates with a constant velocity on the ground surface is often assumed along with an exponential decay of the coherency function.

The paper extends what presented in Domaneschi et al. [10] and Domaneschi et al. [11], upon which is based. It includes the following additional research: the definition of an *efficient* and *comprehensive* method to take into account the spatial variation of the seismic input components both over the base of a single foundation, schematized as a rigid body (kinematic interaction effect), as well as between independent rigid foundations (wave passage and coherency decay effects).

By considering that seismic motions are realizations of space-time random fields, i.e., multi-dimensional and multivariate random functions of position in space [23], the proposed model is formulated starting from the stochastic field describing the free-field motion. Before averaging the seismic input components, the random motion at the contact points between the soil and the foundation is described by means of direct spectral densities and cross spectral densities. For the latter functions an innovative formulation is proposed in order to account for a possible correlation between different components of the dynamic excitation at the same point on the soil-foundation interface, while literature coherency functions are adopted to relate the same ground motion components at different points.

The equations relating free-field earthquake ground motion and the excitation at the base of either a single rigid base mat or multi-support foundations are illustrated in detail. Applications of the proposed formulation are devoted to the definition of the dynamic input for two limit cases: for a large single rigid mat foundation (that of a proposal for a base isolated NPP [18]) and for several small well separated foundations (namely, at the supports of a cable-stayed bridge benchmark [9], The Bill Emerson Memorial Bridge). Regarding the latter application, it is worth noting that a more refined seismic excitation is defined with respect to the guidelines of the original benchmark [3]: these were focused only on the bi-directional horizontal nature of seismic excitation, while in the present paper the vertical component of the earthquake is included, as are the rotational components.

2. Stochastic modeling of the seismic input motion for rigid foundations

In a discretized approach [22], the free-field motion at foundation-ground "contact" area can be described by a vector listing the displacements of a finite number of points/nodes; the vector can be partitioned into its three translational components as:

$$\mathbf{q}_c^{(f)}(t) = \begin{Bmatrix} \mathbf{q}_{c,1}^{(f)}(t) \\ \mathbf{q}_{c,2}^{(f)}(t) \\ \mathbf{q}_{c,3}^{(f)}(t) \end{Bmatrix} \tag{1}$$

where $\mathbf{q}_{c,3}^{(f)}(t)$ lists the vertical displacements of all observed points, while the vectors $\mathbf{q}_{c,1}^{(f)}(t)$ and $\mathbf{q}_{c,2}^{(f)}(t)$ collect the horizontal components of motion. Therefore, the vector $\mathbf{q}_c^{(f)}(t)$ has a number of components which is three times the number of considered points on the ground surface. A Cartesian coordinate system (x_1, x_2, x_3) located on the surface of the half-space is adopted.

2.1. Single rigid foundation case

Because of soil-structure interaction, the dynamic load at the base of a single foundation does not correspond to the free-field motion and it has to be correctly determined prior to the analysis of the response of the structural system.

According to a standard procedure, the motion of the system can be decomposed into a pseudo-static and a dynamic component, i.e. where the pseudo-static component is defined as the motion occurring when the mass and the damping of the structure are set to zero, i.e. the one due to kinematic interaction, while the dynamic component accounts for inertial interaction.

The pseudo-static component can be in turn decomposed into the sum of two terms as:

$$\mathbf{q}_c^{(p)}(t) = \mathbf{q}_c^{(f)}(t) + \mathbf{q}_c^{(a)}(t) = \boldsymbol{\eta}\mathbf{q}_0^{(p)}(t) \tag{2}$$

In the previous equation lists the free-field displacements and the ones related to the added motion due to the presence of a surface foundation. Having set equal to n_c the number of contact points at the interface between the soil and the base of a generic foundation, the vectors $\mathbf{q}_c^{(f)}(t)$ and $\mathbf{q}_c^{(a)}(t)$ have dimensions $(3n_c, 1)$, while their components with respect to the model axes $\mathbf{q}_{c,j}^{(f)}(t)$ and $\mathbf{q}_{c,j}^{(a)}(t)$, $j = 1,2,3$, have dimensions $(n_c,1)$. In case of *rigid* foundations, the vector collects the 6 components of the pseudo-static motion of the centroid at the soils-structure interface (Fig. 1), while a constant matrix $\boldsymbol{\eta}$ of dimensions $(3n_c,6)$ accounts for the kinematic constraints between each contact point and the centroid. Therefore, the seismic input excitation at soil-structure interface is obtained by "filtering" the ground motion at contact points and the number of degrees of freedom of the problem is reduced with respect to the assumption of a flexible base. Regarding the components of the vector, they account for three translations, the torsional contribution (rotation of the foundation about the vertical axis) and the two rocking components (rotation of the basemat about the two horizontal axes), as depicted in Fig. 1 for a cross-section of the soil-foundation system. Therefore, the rotational components of the seismic input at the base of a rigid mat foundation are described as a function of the translational displacements of the points at the soil-foundation interface. For a rigid foundation, a constant matrix $\boldsymbol{\eta}$ defines the kinematic relations among displacements at contact points and the motion of the centroid of the basemat.

In order to extend the formulation in the frequency domain, it is possible to apply the Fourier transform to quantities defined in Eq. (2), e.g.:

$$\tilde{\mathbf{q}}_c^{(p)}(f) = \int_{-\infty}^{\infty} \mathbf{q}_c^{(p)}(t) e^{-i2\pi f t} dt \tag{3}$$

where the tilde is adopted to denote quantities defined in the frequency .

Considering the ground subsystem, the relation between the displacements at contact points and the corresponding contact forces (Fig. 1) acting at the soil-foundation interface is established, in the frequency domain, in terms of the impedance functions. It can be stated that:

$$\begin{aligned}\tilde{\mathbf{F}}_c^{(p)}(f) &= \mathbf{E}_{cc}^g(f)\tilde{\mathbf{q}}_c^{(p)}(f) = \mathbf{E}_{cc}^g(f)(\tilde{\mathbf{q}}_c^{(f)}(f) + \tilde{\mathbf{q}}_c^{(a)}(f)) \\ &= \mathbf{0} + \mathbf{E}_{cc}^g(f)(\tilde{\mathbf{q}}_c^{(p)}(f) - \tilde{\mathbf{q}}_c^{(f)}(f))\end{aligned} \tag{4}$$

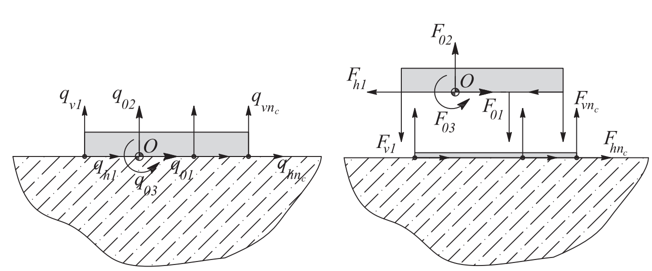

Fig. 1. Displacements at contact points and contact forces at the soil-rigid mat foundation interface.

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