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# The influence of uncertain local subsoil conditions on the response of buildings to ground vibration

Manthos Papadopoulos *, Stijn François, Geert Degrande, Geert Lombaert

*KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, 3001 Leuven, Belgium*

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ABSTRACT

This paper examines the influence of imperfect knowledge of the local subsoil conditions on the prediction of building response to ground-borne vibration. The focus is on problems of environmental ground vibration in the wide frequency range between 1 Hz and 80 Hz. A probabilistic finite element-perfectly matched layers model is developed for the analysis of the dynamic soil-structure interaction problem where the shear modulus of the soil is modeled as a conditional random field. A subdomain formulation is employed to impose loading by an incident wave field in the model. The uncertainty on the subsoil properties is propagated to the response of a building by means of Monte Carlo simulation. A case study is considered to investigate the influence of the spatial correlation length of the random field representing the shear modulus of the subsoil, and the foundation type of the building. The structural response uncertainty varies over frequency bands but as a general trend increases with frequency. The foundation type of the building is a crucial parameter determining the structural response and the associated uncertainty bounds.



## 1. Introduction

In the built environment, environmental ground vibration is produced by sources such as road and railway traffic or construction and industrial activities. The passage of vehicles over uneven roads or tracks and the operation of heavy machinery generate elastodynamic waves that propagate through the soil and impinge on the foundation of nearby structures leading to structural vibrations. These vibrations may lead to malfunctioning of sensitive equipment, discomfort of people, and, at very high levels, structural damage. Furthermore, noise can be re-radiated from floors and walls.

Dynamic soil-structure interaction (SSI) plays a crucial role in the prediction of the response of buildings to ground-borne vibration. Studies on dynamic SSI initiated in the field of earthquake engineering for the design and construction of structures of high importance such as nuclear power plants, arch dams and long-span bridges [1–3]. More recently, the growing traffic volume, the development of high-speed railway lines, and the expansion of underground transportation networks in densely populated urban areas (Fig. 1) have led to an interest in the problem for environmental vibration where computational models have been developed for both the prediction of the induced incident wave field and the structural response [4–6].

In these computational models, the semi-infinite extent of the soil needs to be taken into account by allowing the radiation of elastodynamic waves to infinity. At present, this is achieved by using either coupled finite element (FE)-boundary element (BE) formulations [7] or finite element formulations in conjunction with appropriate absorbing boundary conditions (ABC) [8,9] or perfectly matched layers (PML) [10–12]. In FE-BE formulations, a subdomain approach is followed [2,13] where finite ele-

* Corresponding author.
*E-mail addresses:* manthos.papadopoulos@kuleuven.be (M. Papadopoulos), stijn.francois@kuleuven.be (S. François), geert.degrande@kuleuven.be (G. Degrande), geert.lombaert@kuleuven.be (G. Lombaert).

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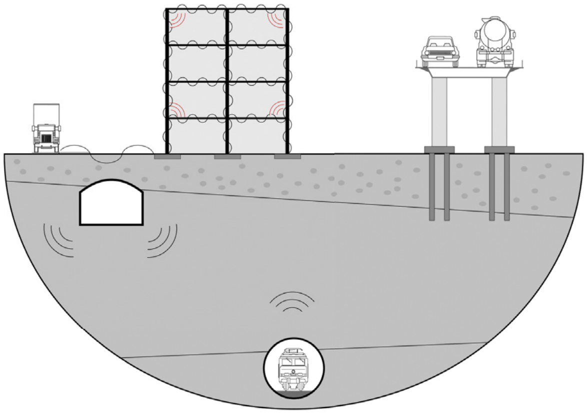

**Fig. 1.** Traffic induced vibrations in the built environment.

ments are used to model the structure (and possibly a limited bounded volume of the soil) and boundary elements are used to model the unbounded soil which is usually idealized as a horizontally stratified halfspace. The radiation conditions are implicitly satisfied if the boundary element formulation is based on the Green's functions of the stratified halfspace [14,15].

Whereas in earthquake engineering the focus is on the low frequency range between 0 and 10 Hz, the frequency range of interest in environmental induced vibrations extends up to 80 Hz for building vibration and up to 250 Hz for re-radiated noise. The much wider frequency range of interest imposes two challenges on the computational models. The first is the greater computational cost and the second is the lack of robustness as the response prediction at high frequencies gets more sensitive to local variations of model parameters and modeling errors. The unknown or imperfectly known excitation, material and geometric properties of the model are sources of parametric uncertainty while the modeling simplifications and assumptions are sources of non-parametric uncertainty.

Although the soil is usually idealized as a horizontally stratified halfspace composed of homogeneous layers, geotechnical investigations suggest that the soil properties exhibit considerable spatial variability even within apparently homogeneous soil deposits [16]. This variability is mainly attributed to the physical processes involved in the formation of the soil layers but also to man-made activities that may perturb the properties of virgin land. Even though geotechnical and geophysical investigations allow us to identify this variability, the spatial resolution of the information on the properties of the soil remains limited. Since the soil directly beneath a structure can have a dominant role on the structural response, the aim of this paper is to assess the influence of imperfectly known local subsoil conditions on the prediction of the response of buildings to environmental ground-borne vibration.

The dynamic SSI problem has been treated in a probabilistic setting considering parametric and non-parametric sources of uncertainty in the literature. The models focusing on parametric sources of uncertainty predate those that adopt non-parametric sources and have been mostly considering the frequency range of interest for seismic SSI problems [17,18]. This approach requires the uncertain parameters of the model to be described by means of random variables and/or fields [19]. Subsequently, the uncertainty on the parameters of the model is propagated to the structural response with simulation methods. The models that consider non-parametric sources of uncertainty rely on the random matrix theory [20] and have been used in both seismic analyses [21] and problems of environmental vibration [22,23]. In these models, the uncertainty is controlled by few dispersion parameters which need to be calibrated based on experimental observations.

In the present paper, the imperfectly known subsoil properties are modeled as conditional random fields following the parametric probabilistic approach formerly introduced in Ref. [24]. The parametric approach is favored over the non-parametric as it can provide insight on how the statistical and physical properties of the subsoil affect the structural response. The stochastic dynamic SSI problem is formulated based on the finite element method which provides great flexibility in incorporating any type of heterogeneity in the imperfectly known subsoil. The unbounded soil is modeled by means of perfectly matched layers [11]. An external incident wave field is incorporated in the FE-PML model by exploiting a subdomain formulation originally conceived for FE-BE formulations [13].

The remainder of this paper is organized as follows. Section 2 introduces the dynamic SSI problem and its subdomain formulation. Section 3 discusses the formulation of the dynamic SSI by means of a FE-PML model. Next, section 4 addresses the problem of statistically characterizing the uncertain local subsoil properties and the construction of the corresponding random fields. Finally, section 5 presents the results of a case study where the response of a building to ground-borne vibration is computed and the influence of the spatial correlation length of the subsoil's shear modulus and the foundation type of the building is investigated.

## 2. The dynamic soil-structure interaction problem

Fig. 2 depicts the stochastic dynamic SSI problem where a building $\Omega_b$ is founded in a soil with imperfectly known properties.