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Square block foundation resting on an unbounded soil layer: Long-term prediction of vertical displacement using a time homogenization technique for dynamic loading

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ABSTRACT

In this contribution, the structural long-term response of a square block foundation resting on a soil layer over rigid bedrock is investigated in the time domain. To efficiently predict the vertical displacement of the square block foundation at periodic loading, a time homogenization technique is employed to deal with different time scales in the response of the soil-foundation system and its long-term evolution due to the foundation's inelastic and nonlinear material behavior (continuous damage, discontinuous damage, viscoelastic, elastoplastic). To correctly represent the laterally unbounded soil layer over rigid bedrock, the stiffness of the linear elastic soil is first computed in the frequency domain via the modified scaled boundary finite element method. The soil stiffness in the frequency domain is then transferred to the time domain via a lumped-parameter model representation. Subsequently, the time homogenization technique including dynamic effects is developed and applied to obtain the response of the foundation-soil system in the time domain. Consolidation of the soil layer (linear elastic) is not addressed in this contribution.

1. Introduction

Dynamic analyses are commonly carried out in the time or frequency domain. While the frequency domain is attractive to easily deal with periodic (including steady state) loading conditions with a characteristic frequency pattern, restrictions apply regarding the superposition of nonlinear structural responses. Time domain analysis is the more general approach to deal with arbitrary load patterns, material and structural nonlinearities as well as topological changes over time. However, the fine time resolution of load pattern characteristics (e.g. impact loads) and the structural response (e.g. eigenmodes) contradict an efficient and fast computation of the long-term evolution of the structure subjected to repetitive loading.

In case of soil-structure interaction (SSI), the geometry of the soil (commonly regarded as partially unbounded) including wave propagation and energy absorption due to radiation damping in the far field has to be considered as well to set up a physically consistent model for a numerical analysis of the coupled system (soil and superstructure). In the past, different techniques have been developed to deal with SSI problems. Often, the substructuring technique (introduction of a near field and a far field – definition of several subsystems) is employed to decompose the system into smaller subdomains, which are geometrically and physically described by different, appropriate numerical methods. For geometrically and physically nonlinear structural parts of the system, the finite element method (FEM) in the time domain is used, whereas for geometrically and physically linear domains with partially unbounded extension, boundary-oriented finite element methods are employed to derive dynamic stiffness properties of a common interface between near and far field, e.g. in the form of impedance functions for different soil-foundation configurations, see e.g. [1,2]. Numerical methods applied here are the scaled boundary finite element method (SBFEM) [3], the boundary element method (BEM) [4], the thin layer method (TLM) [5,6] and others. Infinite elements [7,8] in terms of transmitting boundaries [9] regarding wave propagation are also used. For a recent overview on numerical techniques, see also [10].

Via the latter methods, expressions are commonly developed in the frequency domain (superposition of solution parts for specific excitation frequencies). To establish the link to the FEM in the time domain analysis of the coupled system, a frequency to time domain transformation (e.g. Fast Fourier Transform (FFT) algorithm) is required, since the dynamic stiffness of the unbounded media is obtained in the frequency domain.

Another possibility to accomplish the frequency to time domain

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transformation is given by lumped-parameter models as representation of unbounded media in the frequency and time domain. Lumped-parameter models are based on the idea to find a rheological interpretation of the frequency-dependent complex stiffness of the unbounded media (engineering approach) by additionally introducing internal variables to the degrees of freedom of the external force-acting node (e.g. reference node of the foundation) and to obtain a system of differential equations of first order, which can be directly transferred from the frequency domain to the time domain. In this case, basic rheological elements (linear springs, dashpots, point masses) are assembled in parallel, in series or in the form of different combinations to represent the complex stiffness spectrum (so-called impedance functions) in the frequency domain of one degree of freedom (DOF) or several DOF of the interface for which the dynamic stiffness has been obtained in the frequency domain. This is especially of interest for engineering applications, where the modeling of the material behavior via rheological elements is standard [11] (phenomenological approach to represent the material behavior, see also [12]). Via the rheology of these lumped-parameter models, the geometry and inhomogeneities (e.g. layering) of the unbounded soil domain are included. Furthermore, simplified so-called optimal equivalent models [13] using an even more simplified rheology (single DOF oscillator: spring, dasphot and point mass) to best fit the half-space solution enable their application for engineering tasks, see also [14].

Since the (linear) evolution laws of the basic rheological elements (spring, dashpot, point mass) are well known in the frequency and time domain, the transition from the frequency domain to the time domain can be easily accomplished. Different approaches to derive a rheological interpretation of the frequency-dependent complex stiffness of unbounded media exist: approximation of stiffness [9,15–17] (in parallel lumped-parameter models) or approximation of flexibility (compliance) [18,19] (in series lumped-parameter models). Other approaches focus on rational approximation [20] by using a combination of stiffness and flexibility expressions for the additional internal variables in terms of displacement and force DOF (mixed variable formulation), see e.g. [21,22]. The continued-fraction expansion results in a system of fractional differential equations with respect to time. Note that the corresponding continued-fraction expansion only results in a system of fractional differential equations for particular applications, such as diffusion. In general, it leads to a set of first order differential equations. An efficient algorithm based on approximating the fractional integral by a series of partial fractions in the frequency domain is discussed in [23–25] with a numerically more robust formulation in the frequency domain and in the time domain for arbitrarily high orders of approximation and large-scale systems.

For a computational implementation, a systematic procedure for identification of constant (frequency-independent) coefficients is of interest since the parameters often lack a physical interpretation, e.g. no unique rheological representation of the frequency-dependent stiffness exists since additional information (internal DOF) are introduced for which the solution in the frequency domain does not provide a unique choice.

Accurate lumped-parameter models exist for the homogeneous half-space solution. For layered soil, radiation damping is zero below the fundamental frequency of the layers. Hence, the imaginary part of the complex stiffness in the frequency domain is zero too, which can only be approximately incorporated into the lumped-parameter models (approximation). In [26], the quality of consistent lumped-parameter models for rigid footings is discussed focusing especially on the maximum response during excitation and the geometrical damping related to free vibrations as well as the optimal order of a lumped-parameter model. SSI for a foundation on soil is studied in [27] for unbounded and layered soil [28]. In [29], the example of a rotor start on a pile foundation is discussed using time domain analysis. Other examples focus on the analysis of wind turbines [30] and related topics on resonance and maximum amplitude [31].

Once the time domain representation of the SSI problem has been obtained, an efficient time stepping algorithm has to be employed to predict the long-term response of the coupled system to repetitive loading.

In this contribution, the time homogenization technique is addressed as a method of computational homogenization, which is based on the separation of the problem into two or more different time scales (e.g. micro- and macro-time scale). The different time scales can be identified from the loading and the structural response to the loading. Homogenization methods make use of a model reduction on the macro-time scale (loss of information during micro-to-macro transition) to reduce the computational cost required to resolve a cycle-by-cycle simulation in the time domain. The varying macro-time step size (to ensure an imposed quality of the simulation result regarding spatial and temporal resolution) depends on the

- time function of the excitation,
- time-dependent material behavior (short-term),
- time-dependent material behavior (long-term), and
- topological or structural changes of the structure.

Therefore, criteria are introduced to control the choice of the macro-time step size.

In case of constant loads, the features of the structural response are predominating. Periodic excitation occurs e.g. in case of fatigue analyses (high cycle fatigue) or lifetime estimations of the system. In engineering practice, normally empirical relations are employed for lifetime predictions using the information of highly stressed regions of the body which might be subjected to initial failure, see e.g. [32]. Obviously, this procedure belongs to the type of model reduction (reduction of the spatial information of the body considered). Furthermore, the initial failure regions might not be correctly tracked due to topological changes over time or failure initiation at other points of the structure.

Another technique consists in the iterative computation of the stabilized cycle state (steady state response) of inelastic material as an iterative method. This method requires the existence of a steady state solution, i.e. a stabilization of the structural response due to constant cyclic loading must exist. Hence, this method is not applicable for the evolution of structures with different short-term and long-term behaviors until ultimate failure.

To cope with different evolutions of phenomena, a decoupling seems promising, see e.g. [33]. In [34], a linear extrapolation-based method using the evolution of internal variables of one cycle to a multicycle (cycle jump method) is proposed. However, quality loss is expected by loosing solution information (compared to a cycle-by-cycle simulation) and the averaging of local quantities in time. The linear extrapolation method is shown in [34] for the example of an elastic fatigue-damage case. Other strategies focus on higher-order extrapolation (e.g. second-order) or the extrapolation of both, internal variables and displacement field, to arrive closer to the new equilibrium state of the solution. In [35], corrective nodal forces computed from the evolution of the internal variables are additionally used. Piecewise polynomials are proposed in [36] with application to second- and third-order extrapolations only since higher-order polynomials show oscillations for larger extrapolation times. In [37], state variables (stress, strain) and displacements are extrapolated to find a new equilibrium state. It was pointed out that the new equilibrium state might not correspond to the correct equilibrium state in terms of the full simulation of cycles. To control the structural evolution during the computation, the jump size has to be restricted.

The time homogenization technique focuses on multiple scales, which can be identified regarding the spatial and temporal resolution of a system. Spatial homogenization has been widely employed to obtain a spatially homogenized material response on the macroscale from a representative structure, the so-called representative volume element