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ACCOUNTING FOR NONLINEAR DYNAMIC SOIL-STRUCTURE INTERACTION IN EARTHQUAKE ENGINEERING

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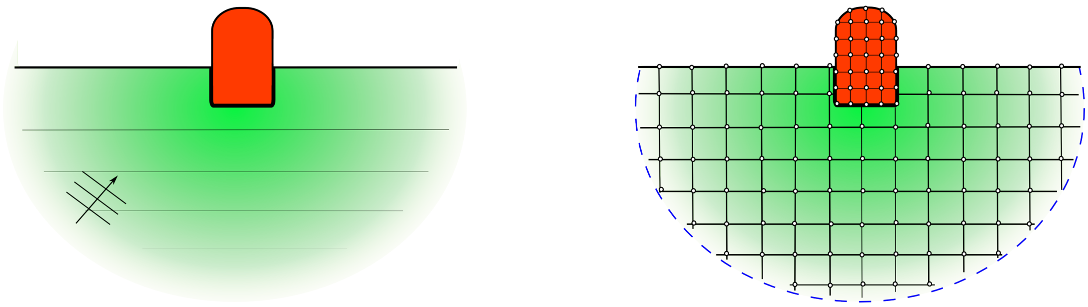
Abstract. *Dynamic soil-structure interaction problems are usually solved by a sub-structuring technique where the soil-structure system is decomposed into two sub-domains: the nonlinear superstructure and the linear visco-elastic unbounded soil. The superstructure might include, in addition to the actual structure, a part of soil showing a nonlinear behaviour. To address this problem, a BEM-FEM coupling strategy is adopted in this work. On one hand, the superstructure is modelled by a FE method which allows to take into account nonlinear constitutive laws as well as complex geometries in a straightforward way. Besides, the problem within the superstructure is formulated in the time domain. On the other hand, the interaction forces coming from the linear unbounded soil are represented by means of an impedance operator defined on the soil-superstructure interface and computed with a Laplace-domain BE method. A semi-industrial application is used to illustrate the effect of nonlinear soil (the Hujeux law) in soil-structure interaction analysis.*

1 INTRODUCTION

Given the recent new insight on seismic hazard in France and other countries, Électricité de France (EDF), the main electricity operator in France and the principal funder of this research work, needs to provide new seismic risk assessment of the entire power production sites. In this framework, the Research and Development (R&D) division of EDF is interested in the development of efficient procedures to solve three-dimensional nonlinear dynamic soil-structure interaction (SSI) problems in the time domain.

Dynamic SSI problems in earthquake engineering can be commonly summarized by Fig. 1a where the soil-structure system is subjected to an incident field displacement that represents the seismic waves. To solve these problems, the most predominant numerical methods in the literature can be divided into two categories. The first category deals with the so-called direct method. This method classically uses spatial discretization techniques based on finite elements (FE). The FE method is well-adapted to bounded domains showing complex nonlinear behaviour and geometry but for the modelling of unbounded domains, artificial boundaries (AB) satisfying transmitting conditions are also required (see Fig. 1b). Different types of AB are used in wave propagation problems such as Lysmer elements, Perfectly Matched Layers or paraxial elements [1, 2, 3]. However, the main disadvantage of these methods are not only the imperfection of the absorbing boundaries but also the considerable computational requirements of such calculations.



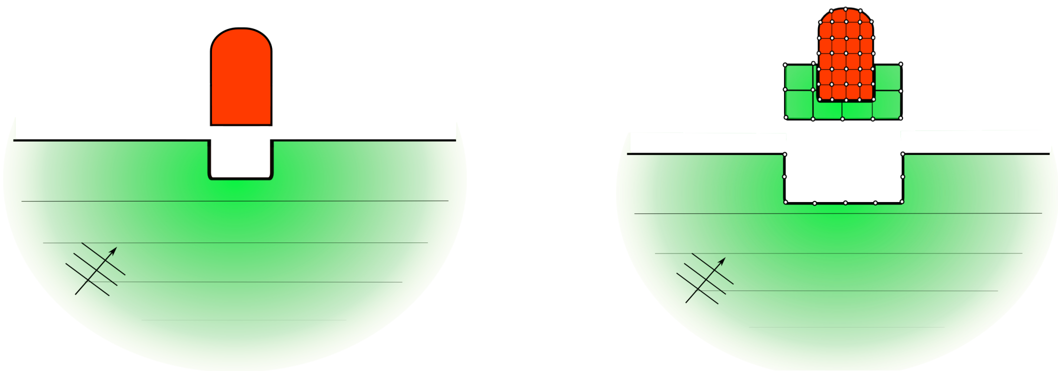
(a) (b)

Figure 1: (a) Simplified model of a SSI system in earthquake engineering. (b) The whole SSI system, bounded by an artificial boundary (dashed blue line), is discretized using a FE-based method.

The second category deals with domain decomposition techniques. In this case, the problem is decomposed into two sub-domains: the nonlinear superstructure and the linear (visco)-elastic unbounded soil (see Fig. 2a). This decomposition allows the use of different numerical techniques for each of the domains enhancing thus the advantages of the FE method while its main drawbacks get reduced. The most popular approach combines the FE method for the modelling of the bounded superstructure with the Boundary Element (BE) method for the unbounded –but linear– domain of soil. Indeed, the BE method relies on the use of Green's functions which implicitly satisfy radiation conditions at infinity. However, when nonlinear analysis is carried out, the coupled problem must be solved in the time domain but transient Green's functions are not always available or difficult to compute.

To overcome last problem, substructuring approaches based on soil impedances can be employed. In particular, the spring method [4] where the soil impedance, assumed as a set of frequency-independent spring and dashpots, is assembled to the structural domain. Although this approach may result attractive from a computational point of view, it does not perform well neither for embedded foundations nor for complex soils with relevant frequency dependency.

Alternatively to the spring method, frequency-time domain couplings can be done [5, 6]. In these cases, the nonlinear domain, which includes the structure and the surrounding soil exhibiting nonlinear behaviour (see Fig. 2b), is formulated in the time domain using FE. The far-field soil is assumed linear and thus, it can be solve in the frequency domain by means, for instance, of a BE method. Following the same principle, recent works have employed Laplace-time domain couplings [7, 8, 9].



(a) (b)

Figure 2: (a) Domain decomposition technique: the bounded superstructure and the unbounded domain of soil. (b) The superstructure, which also includes a surrounding part of nonlinear soil, is modelled with FE whereas the rest of the soil is solved with a BE method.

The present work relies on the so-called Hybrid Laplace-Time domain Approach (HLTA) [10, 11]. To address this problem, the nonlinear FE code (*Code_Aster* [12], developed at EDF R&D) is coupled in the time domain to a BE formulation of the soil impedance matrix in the Laplace domain (computed using code MISS3D [13], developed at École Centrale Paris).

Within the framework of a linear soil and a nonlinear structure, previous research works [11] showed that the use of HLTA leads to satisfactory results when compared to a full-FE solution, at least in terms of spectra responses and damage assessments. The effect of nonlinearities in the soil, in addition to those in the structure, is thus the scope of the present study.

2 NUMERICAL MODEL

The numerical nonlinear model chosen for the structure is the one used in the international SMART-2008 project [14], where it was compared to experimental results obtained on the CEA/EMSI shaking table Azalée. In order to build up a dynamic SSI system, this structure has been completed with a concrete slab and a bounded domain of soil (see Fig. 3) modelled in *Code_Aster*. As a result, the HLTA applies on the boundary of this FE domain of soil, allowing the rest of the unbounded domain of soil to be accounted for by a BE impedance matrix computed by MISS3D. In the following, the building is assumed to be nonlinear. However, two types of calculation are considered and compared in Sec. 3: one where the FE region of soil exhibits a nonlinear behaviour and the other, where the soil behaves entirely linear.

Some properties of the considered numerical model are briefly reviewed in next subsections but the reader can refer to [11] for further details.

2.1 The structural domain

The building is modelled in *Code_Aster* using shell elements (floors and walls) except for a multi-fiber beam going from the bottom to the top the structure. The corresponding FE model

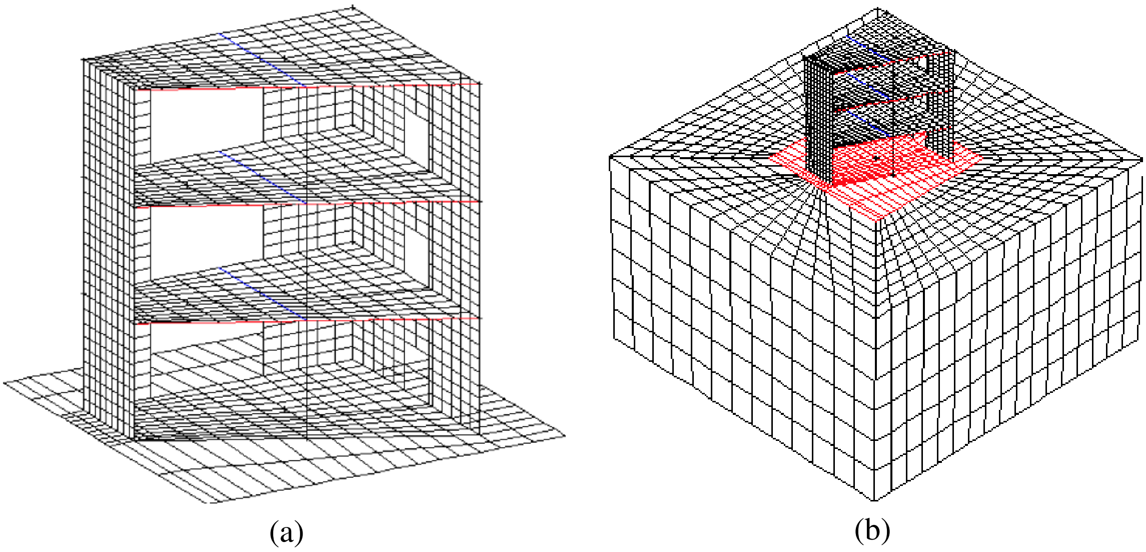


Figure 3: FE model of the SMART building with an additional (a) base-slab and (b) a bounded domain of soil.

consists of $1\,500$ nodes and thus $9\,000$ degrees-of-freedom. For shell elements, reinforced concrete showing a global damage law known as GLRC-DM [15] is used. The squared base-slab, which shows a side length of 4m, is also modelled with shell elements and introduces 332 nodes.

	Bending 1	Bending 2	Torsional	Pumping
Eigenfrequencies [Hz]	9.0	15.9	31.6	32.3

Table 1: First eigenfrequencies of the base-clamped SMART building.

The first eigenfrequencies corresponding to the structure satisfying zero displacement at the base, which are given in Tab. 1, provide some insight on dynamic properties of the SMART building. A modal damping of 2% over frequencies $5\,Hz$ and $15\,Hz$ has been used in order to calibrate the equivalent Rayleigh damping model used for the structure domain.

2.2 The soil domain

The unbounded domain of soil is assumed to be horizontally stratified, in particular, seven layers of soil are considered over the bedrock. However, the bounded domain of soil modelled in FE, which measures 10 m of side length and 6 m of depth, remains within only the first layer of soil. The interface between the unbounded soil has $3\,500$ degrees-of-freedom and hence, a modal reduction technique [16] is recommended. In the present study, the kinematics of the SSI interface are represented by means of 240 interface eigenmodes, a sufficient number of modes to ensure the convergence of the solution.

The unbounded soil, since it is accounted by a BE method in the frequency domain, is assumed to be modelled with hysteretic damping. Nevertheless, a hysteretic damping does not ensure causality properties in the time domain and hence, it cannot be used for nonlinear transient analysis. As a consequence, an equivalent Rayleigh model has been calibrated for the FE region of nonlinear soil.

It has already been mentioned that the case of both linear and nonlinear soils are considered in the following. The Hujeux model of soil [17], which allows to take into account nonlinear ground-borne phenomena, is assumed for the nonlinear case whereas a visco-elastic constitutive law is alternatively used.

3 NONLINEAR TRANSIENT ANALYSES

The response of the building accounting for nonlinear soil-structure interaction under seismic loading is addressed in this section. Three different accelerograms, in x, y and z directions, are applied to the model. Within the HLTA, an unconditionally stable Newmark's time integration scheme is used for the resolution of the FE equations. Two SSI models are considered: one where the soil domain behaviour is modelled by the Hujeux law and the other, where the soil remains fully linear during the whole calculation. Recall that in both cases, the GLRC_DM damage law is used for the building. The comparison is made in terms of response spectra, in particular, the pseudo-acceleration in x and y directions are plotted in Fig. 4.

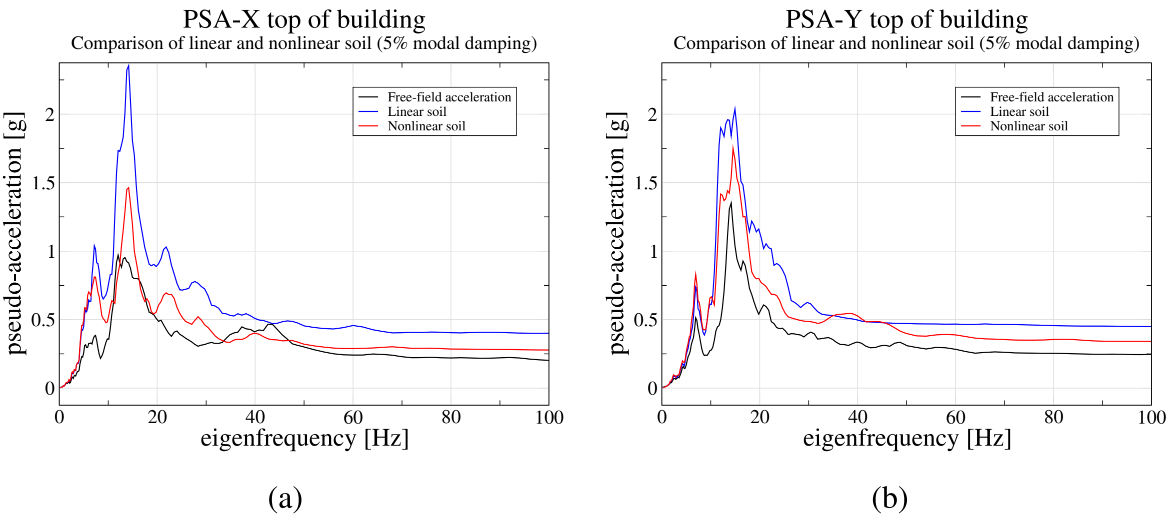
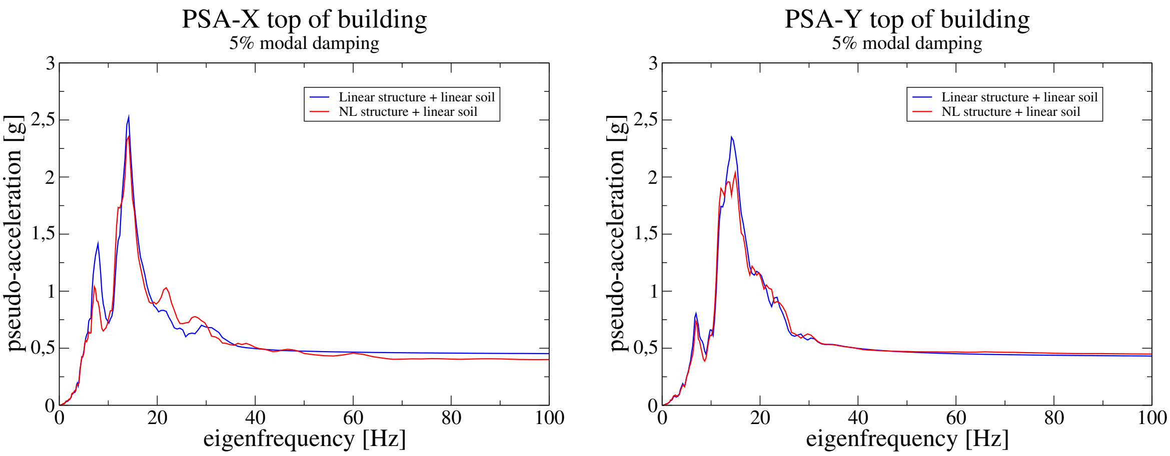


Figure 4: Pseudo-acceleration at the top of the building in x and y directions, for the free-field accelerogram (black) and for models showing a linear (blue) and nonlinear soil (red).

Because of the asymmetry of the SMART building, differences are observed between x and y responses. Nevertheless, the overall impression is that accounting for nonlinear phenomena in the soil results in lower Peak Ground Accelerations (PGA) at the top of the building. In fact, the PGA in the y-direction is almost lowered of 19% and for x-direction, the reduction rises to almost 32%. Also the amplitude of the pseudo-acceleration at lower frequencies decreases when a nonlinear soil is considered. In fact, the peak around $15\,Hz$ is reduced in both directions, particularly, in the x-direction where the amplitude descends from $23.4\,m.s^{-2}$ to $14.6\,m.s^{-2}$. On the other hand, the peak around $8\,Hz$ is slightly amplified in the y-direction. Other local amplifications can be observed in this direction around $40\,Hz$. These amplifications, even if not significant, are probably the reason of getting lower PGA reductions in the y-direction than in the x-direction when comparing to the PGA of a linear soil model.

It is interesting to remark that when the Hujeux model is used, plastic deformation appears by just applying the weight of the structure. Indeed the nonlinear character that the soil exhibits from the beginning of the calculation, increases the amount of seismic energy dissipated before reaching the building, yielding thus to more attenuated responses at the top of the structure. This argument can still be reinforced by observing Fig. 5, where pseudo-accelerations corresponding to a linear soil model and a fully linear model (i.e. not only the soil but also the structure shows an elastic behaviour) are plotted. Notice that the use of the GLRC_DM law reduces indeed global pseudo-acceleration levels but not as much as when soil nonlinearities are modelled in the surroundings of the structure.



(a) (b)

Figure 5: Pseudo-acceleration at the top of the building in x and y directions, for the case of a fully linear model (blue) and a model showing nonlinear behaviour within the structural domain but not within the soil (red).

Regarding the dynamic properties of the coupled system, it may be concluded that the inelastic deformation considered in the soil is not enough to introduce important differences on the resonant frequencies of the dynamic SSI system.

4 CONCLUSIONS AND PERSPECTIVES

This work presents the numerical results obtained when nonlinear soil-structure interaction analysis is performed using an efficient BE-FE coupling based on the Hybrid Laplace-Time domain Approach (HLTA). The SMART building numerical model has been chosen for this application, where the FE code of *Code_Aster* is used for modelling nonlinear domains and the BE code of MISS3D, for the computation of the impedance matrix that accounts for the linear unbounded domain of soil.

It has been observed that inelastic deformation (Hujeux model) arising in the soil attenuates acceleration responses at the top of the building, significantly more than only with a damage model (GLRC_DM law) in the structure. It has to be noticed that this conclusion is particular to the SMART model considered and should not be generalized.

The obtained results have been presented from a qualitative point of view. Further research has to be done in order to validate these results. In particular, a reference solution should be obtained when the Hujeux soil model is used, this is for instance a full-FE solution.

In addition to this, different nonlinear constitutive laws of the soil should be tested in order to evaluate their influence on the structural response. Also the size of the volume of soil that has to be meshed using FE should be studied so that SSI modelling criteria could be identified.

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