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# 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. Two numerical applications are addressed : a semi-industrial application to illustrate the effect of nonlinear soil (the Hujeux law) in seismic soil-structure interaction calculations; and a reinforced concrete arch dam with frictional contact nonlinearities within soil-fluid-structure interaction analysis.

## INTRODUCTION

Large and heavy structures such as power plants or dams have always been designed and constructed to withstand full seismic loading. However, the definition of seismic loading is not absolute and it actually evolves with technology. As a consequence, updated seismic risk assessments have to be continuously provided.

In this framework, performing more accurate simulations that account for new physical phenomena at stake arises as a good way for the assessment of structural seismic resistance. These simulations refer mainly to dynamic soil-structure interaction (SSI) or soil-fluid-structure interaction (SFSI) effects but not only, since numerical models can also be enriched by considering soil nonlinear behavior, uplift of foundation, deformable raft foundation, seismic spatial variability, inclined incidence waves, etc.

The present work deals essentially with nonlinear dynamic soil-structure interaction. This means that the finite stiffness and the damping behavior of the soil are considered in the calculation as well as possibly nonlinear constitutive laws. Indeed, the use of nonlinear material behaviors of structural and nonstructural elements are of great interest to predict the ductility, resistance decay and the ability to dissipate energy through cyclic loading.

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This kind of nonlinear analysis can be straightforwardly performed by using some known spatial discretization approaches such as the Finite Element Method (FEM). However, FEM-based approaches are restricted to finite domains, facing some numerical difficulties to account for the unbound character of the soil. Therefore, the classical procedure to solve nonlinear dynamic SSI problems is usually based on a sub-structuring technique where the soil-structure system is decomposed into two sub-domains (see figure 1): the nonlinear superstructure and the linear (visco)-elastic unbounded soil (J.P. Wolf, 1985). This decomposition allows the use of different numerical techniques for each of the domains enhancing thus the advantages of the FEM while its main drawbacks get reduced. The most popular approach combines a FEM modelling of the bounded superstructure with a Boundary Element Method (BEM) modelling for the linear unbounded domain of soil. The choice of  coupling strategy lies on the fact that BE method implicitly account for the radiation condition that must be satisfied within an unbounded domain.

Nevertheless, the transient formulation of the BE method may be difficult to compute for nonlinear SSI analyses. To overcome this problem, substructuring approaches based on soil impedances can be employed. In particular, the spring method 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 also be done (J.P. Wolf, 1985). In these cases, the nonlinear domain, which includes the structure and the surrounding soil exhibiting nonlinear behaviour (see Figure 1), is formulated in the time domain using a FEM modelling. 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 of the latter frequency coupling strategies, the present work relies on the so-called Hybrid Laplace-Time domain Approach (HLTA) (A. Nieto Ferro et al., 2012), where soil frequency-domain equations are reformulated in the Laplace domain. In order to bring out the main features of this new approach, the present article analyzes two different nonlinear applications. The first one deals with a reinforced concrete building founded on a possibly nonlinear soil (SMART building, 2008). This model has been used for the validation of the HLTA approach by comparison to a full-FEM modelling. The second application deals with a concrete arch-dam under seismic conditions. Frictional-contact joints between the dam constitutive concrete blocks results in nonlinear analysis. This calculation accounts not only for nonlinear SSI but also for added mass effects due to the dam reservoir.

For the numerical implementation of the HLTA, the nonlinear FE code (*Code_Aste*r, 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, developed at Ecole Centrale Paris).

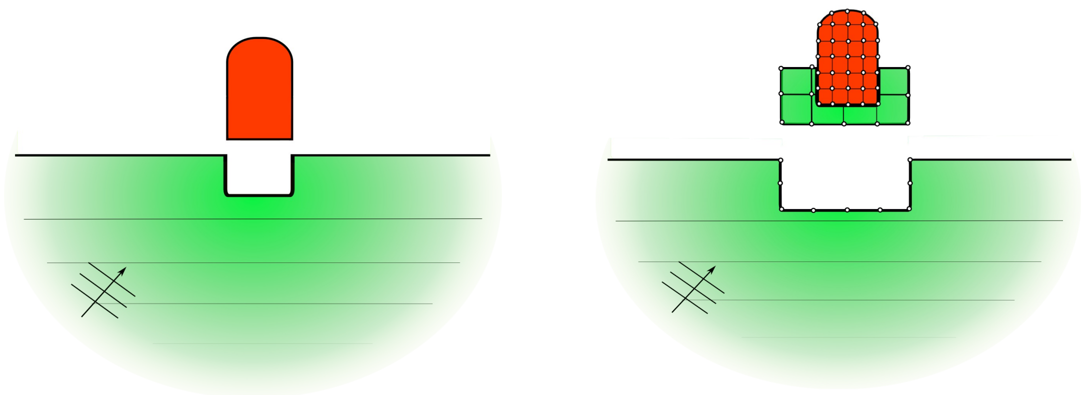


Figure 1. Numerical model used for the validation of the approach adopted in this work.

## NONLINEAR SOIL-STRUCTURE INTERACTION (SSI) APPLICATION

This section gives some insight on how much nonlinear phenomena, as well as soil-structure interaction (SSI) effects, can modify the dynamic response of RC structures. In particular, the numerical model elaborated for the SMART-2008 benchmark (EDF and CEA, 2007) is used in the present discussion (see Figure 2).

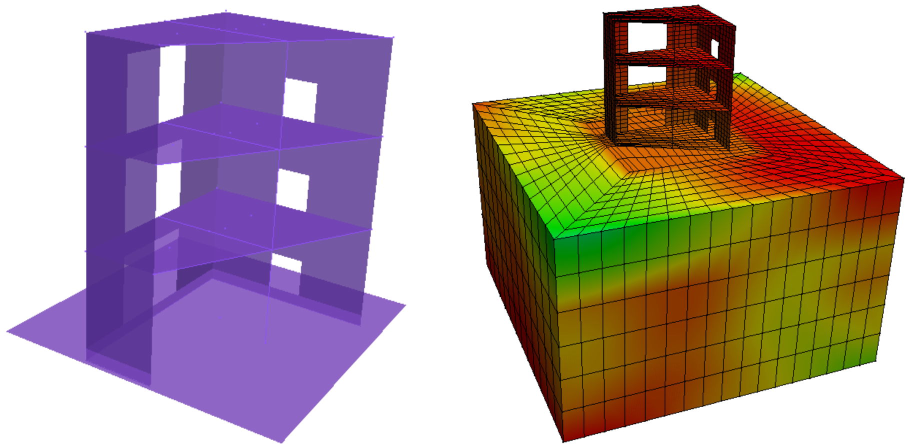


Figure 2. Numerical model used for the validation of the approach adopted in this work.

The nonlinear behavior is taking into account through a macroscopic damaging constitutive model developed for reinforced concrete (RC) plates elements. It is written according to the theory of generalized standard materials and named GLRC_DM (Markovic *et Al*, 2007). In this model, it is assumed that the softening steps due to concrete degradation are avoided considering the reinforcement bars role. It is leading to computing efficiency and robustness.

In order to highlight the effects of material nonlinearities in the SMART building, the linear solution is first compared to the nonlinear case. In both analyses, zero-displacement conditions are assumed at the base of the building so that no SSI effects are accounted for and an unconditionally stable Newmark's time integration scheme is used for the resolution of the FE equations. Figure 3 shows the corresponding pseudo-spectral accelerations (PSA) at the top of the SMART building under a seismic loading in X, Y, Z directions. For further details on the accelerograms, material properties of the structure and the soil, the reader is encouraged to refer to the doctoral thesis of A. Nieto Ferro (2012).

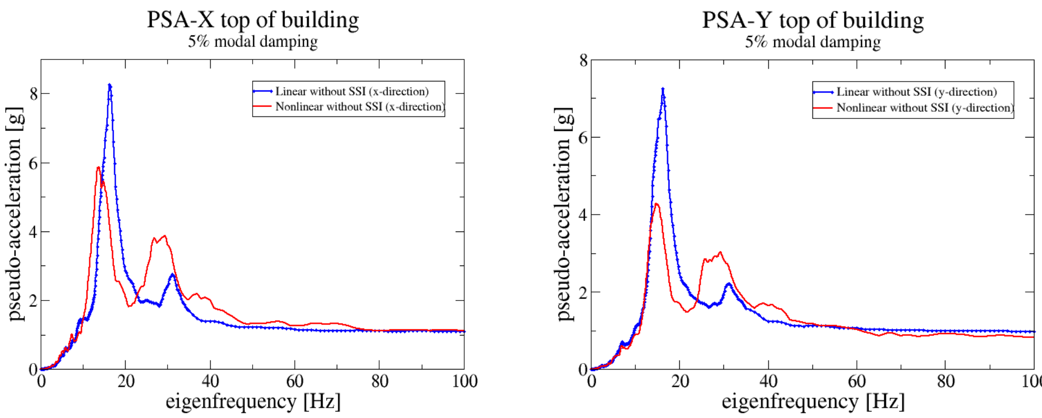



Figure 3. Linear and nonlinear SMART building responses without SSI effects (x and y directions).

Differences are observed between X and Y directions because of the non-symmetric character of the building. Even if no significant differences are observed in terms of Peak Ground Acceleration (PGA), eigenfrequencies are slightly shifted to a lower frequency range and the overall impression is that more energy dissipation is introduced in the model.

When SSI is accounted for, similar statements can also be concluded if the PSA are compared at the top of the building (see figure 4) within a linear analysis. However, besides the observed frequency shifting, the present case shows important levels of attenuation not only in terms of amplitude but also in terms of PGA.

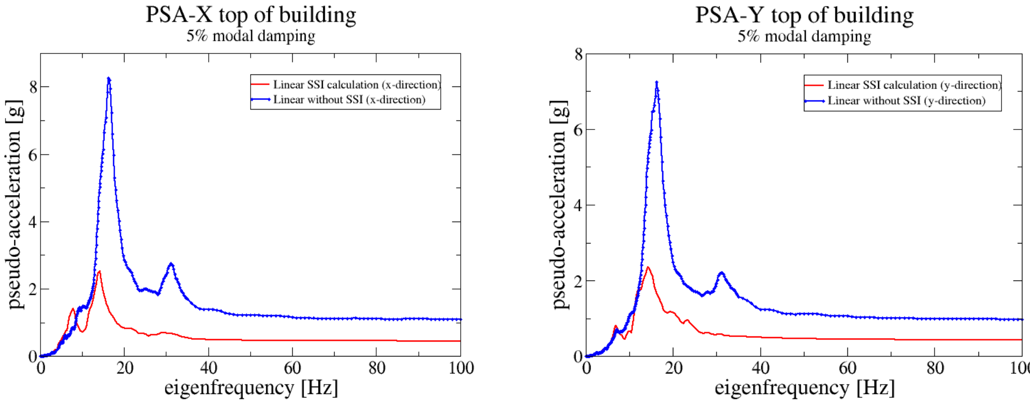



Figure 4. Linear SMART building responses with and without SSI effects (x and y directions).

If, in addition to SSI effects, nonlinear analysis is performed, the structural response can still be modified. In the following, two nonlinear cases are considered and compared. The first one deals with material nonlinearities only within the SMART building whereas the second case includes nonlinear phenomena also in the soil surrounding the structure.

The first case has been studied in previous works (Nieto Ferro *et Al.*, 2013) by coupling *Code_Aster* and MISS3D within a Hybrid Laplace-Time domain Approach (Nieto Ferro *et Al.*, 2012). Some results involving ultimate damage levels and response spectra are given in Figure 5 in order to illustrate the obtained overall agreement when compared to a full-FEM solution.

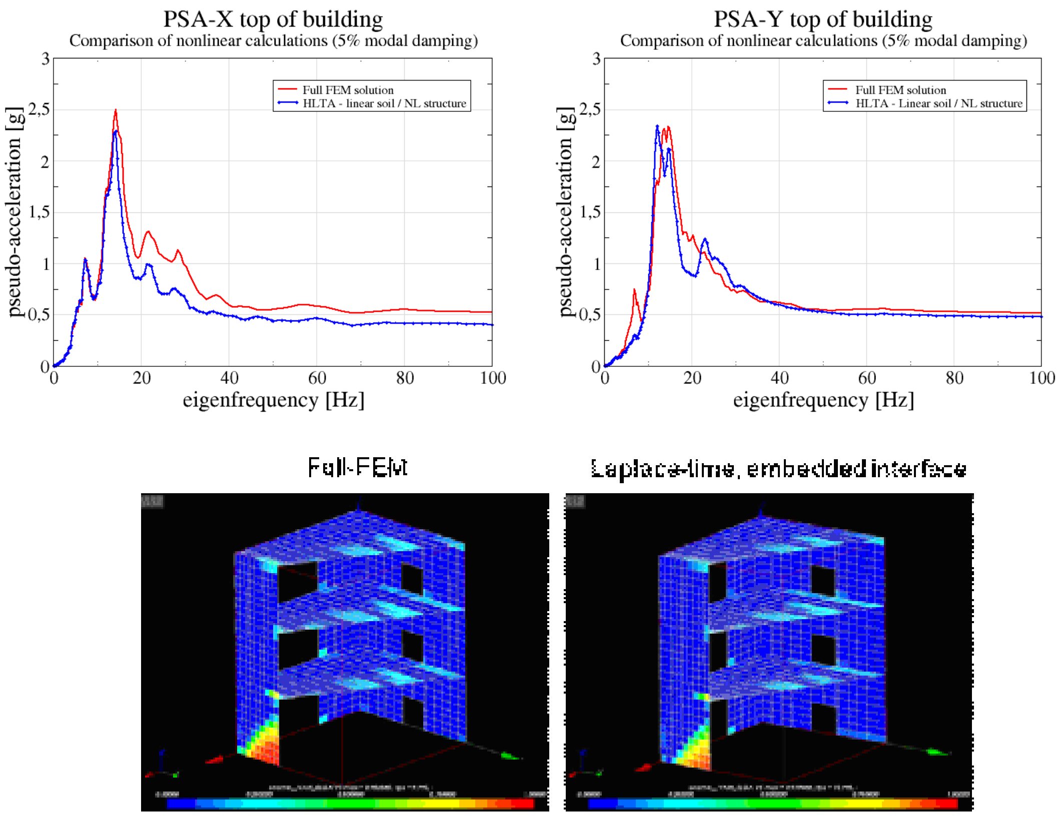



Figure 5. Nonlinear SMART building responses obtained using the HLTA and a full-FEM approach.

The second case, where also the soil exhibits nonlinear behavior, is briefly addressed in figure 6. The nonlinear law of Hujeux (1985) is assumed for the region of soil close to the structural foundations. The HLTA has been used for this calculation so the rest of the soil, extending to infinity, is assumed to behave linearly.

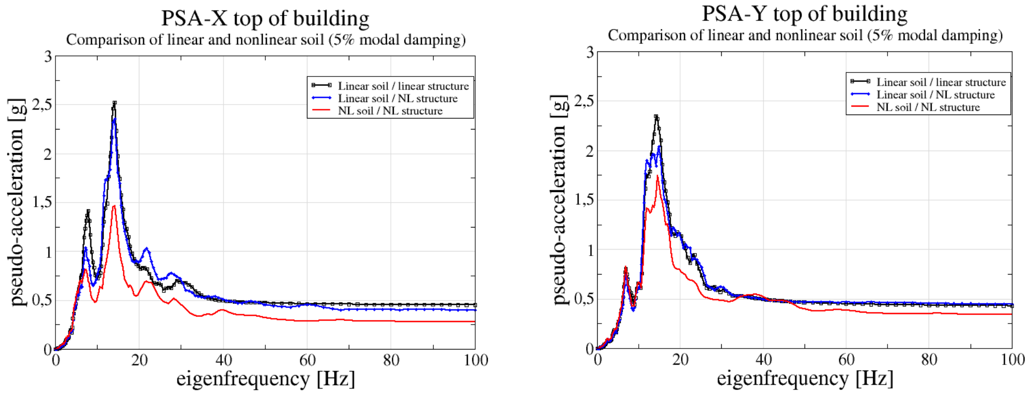



Figure 6. Fully linear response with SSI effects and nonlinear SSI responses with a near-field soil exhibiting linear and nonlinear behavior.

It is interesting to remark 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. This may be explained by the fact that when the Hujeux model is used, plastic deformation appears already in dead weight conditions. 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.

Therefore, it can be concluded that accounting for SSI as well as for nonlinearities in both, structure and near-field soil, can significantly modify the RC building response (at least for the SMART soil-structure interaction system) and it is thus recommended to be taken into account if best-estimate assessments have to be carried out.

## NONLINEAR SOIL-FLUIDE-STRUCTURE INTERACTION (SFSI) APPLICATION

The following numerical application addresses the case of a reinforced concrete arch dam. These kind of structures are usually built by the concatenation of trapezoidal concrete blocks that progressively fit the canyon valley (see for instance the case of the Hoover dam in Fig. 7). The joints between the plots are then filled with concrete in order to obtain a single structure. Nonlinear behaviour may arise within concrete block joints for many reasons (temperature variations, increasing or decreasing level of water reservoir, seismic loading …).

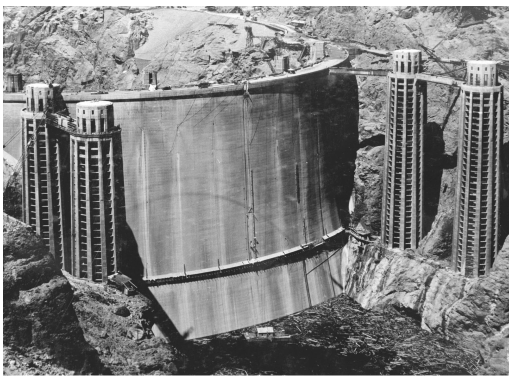


Figure 7. Example of RC dam to illustrate the block-based technique of construction (Hoover Dam).

The present application assumes a contact frictional constitutive law between the concrete blocks. For specific details on this law, which has been implemented in *Code_Aster*, the reader may refer to *Code_Aster* Manual (*R7.01.25)*. As in the previous numerical application, the rock foundation is considered an infinite domain and is modelled by means of the Laplace domain-BE formulation implemented in MISS3D. Assuming incompressibility conditions, mass added effects coming from the water reservoir are also taken into account. Particularly, ponctual masses are fixed on the upperstream dam wall. The value of theses masses is estimated considering both the pressure of water and the surface of the FE elements. More details on this approach can be found in *Code_Aster* Manual (*U4.42.02)*.

As for the previous application, modal reduction techniques (Balmes, 1996) has been employed for the kinematic representation of the foundation-structure interface. After some calculations, it seems that the choice of 48 modes gives satisfying results in terms of CPU time and memory requirements.

Rayleigh damping has been considered for the reinforced concrete elements of the dam and hysteretic damping has been used within the rock foundation. In order to avoid high frequency components due to shocks between concrete blocks, small additional viscous damping has been added in the form of simple dashpots linking pairs of facing nodes. Although this type of damping is not the most proper way to model impact damping, this approach has been adopted at least in this primary study. Further dissipation comes only from the nonlinear character of frictional joint elements. Because of confidential issues, exact damping levels and other material properties cannot be provided.

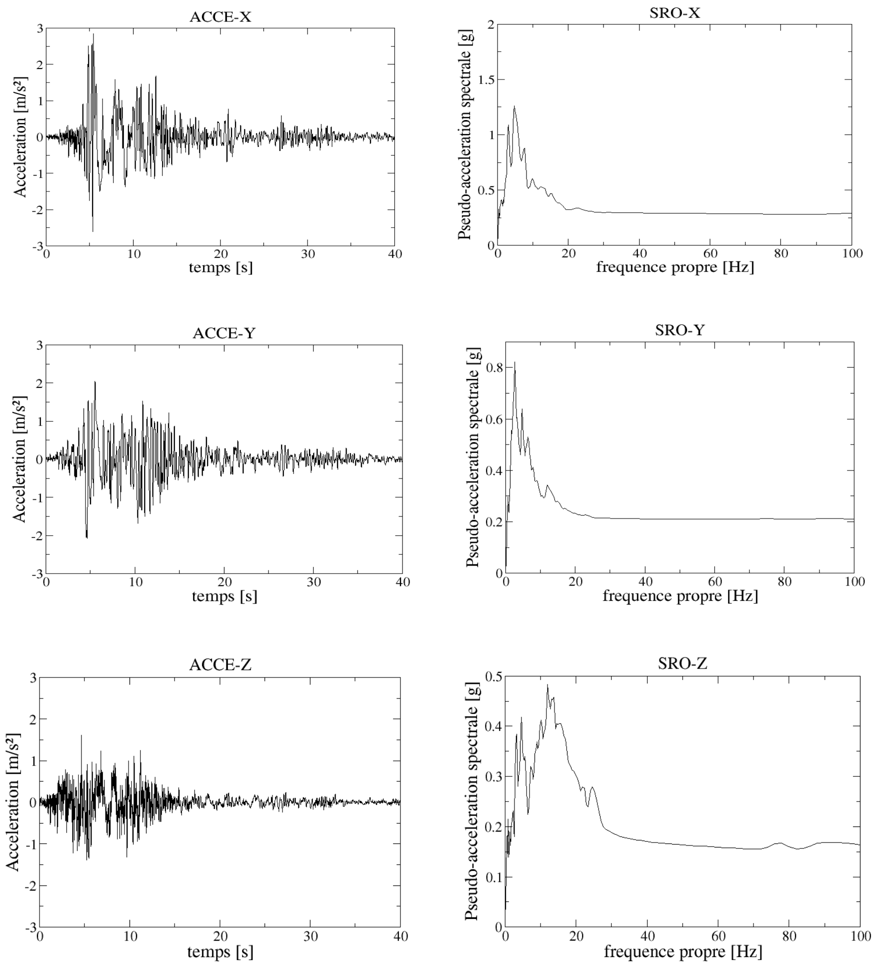
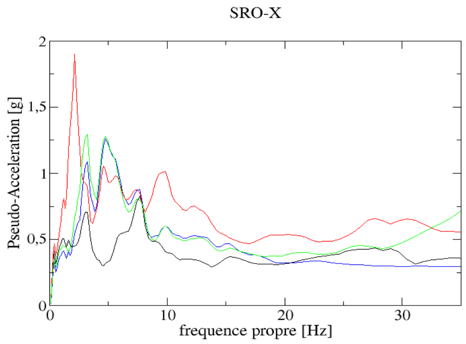



Figure 8. Seismic accelerograms in X, Y, Z directions.

Real rock-outcrop seismic accelerograms in X, Y and Z directions have been used for this calculation. These accelerograms may not be representative for this kind of structures and they have been chosen with only illustrative purposes. Figure 8 shows the resulting accelerograms after basic baseline correction. These signals have been evaluated in each point of the dam foundation by simple deconvolution procedures. In particular a 1D soil column of rock material has been used. This approach allows to partially account for the spatial variability of the seismic incident field. Other sources of spatial variability, such as incoherency, has been neglected for this analysis.

Again, the Hybrid Laplace-Time domain Approach (HLTA) is used to couple BE and FE formulations within a nonlinear SFSI analysis. The first goal of this application is to test the HLTA with a nonlinearities of different nature and with more complex numerical models. Indeed, this model contains more than 30 000 degrees-of-freedom and also accounts for added mass effects. The second goal of this analysis is to show the nonlinear SFSI effects on the structural response and to put into relief the importance of these phenomena within seismic based-performance analysis. This conclusions can be briefly summarised in Figure 9 and 10, where colours correspond to responses measured at the points indicated in Figure 11.



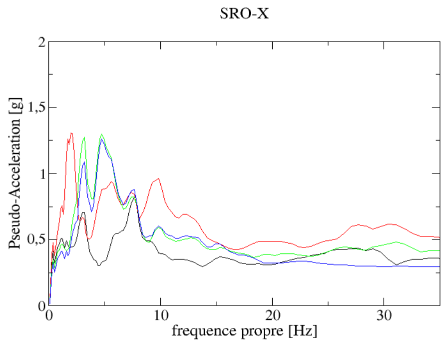
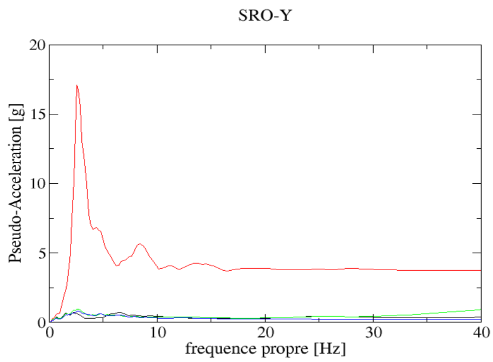




Figure 9. Linear (on the left) and nonlinear (on the right) responses for x-direction (perpendicular to concrete blocks).



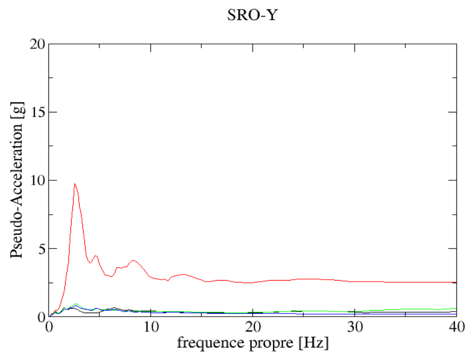




Figure 10. Linear (on the left) and nonlinear (on the right) responses in the y-direction (upstream-downstream direction).

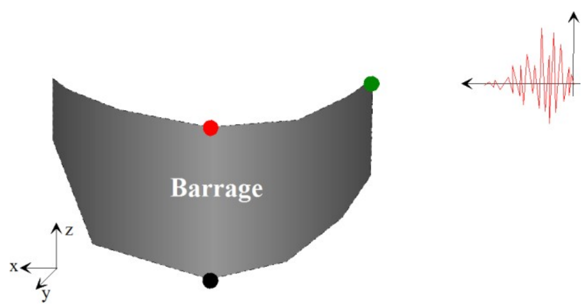



Figure 11. Schematic view of the concrete dam. Colours correspond to point of post-processed responses.

## CONCLUSIONS

This work presents the numerical results obtained when either nonlinear SSI or SFSI analysis is performed using an efficient BE-FE coupling based on the Hybrid Laplace-Time domain Approach (HLTA). Two numerical applications have been discussed: the SMART building numerical model and the case of reinforced concrete arch dam. For both applications the FE code of *Code_Aster* has been 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.

For the first application, 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.

Concerning the SFSI application, it has been shown that frictional and contact nonlinearities between concrete blocks can significantly modify the structural dynamics under seismic loading. Therefore, the initial nonlinear state of the joints due to possibly temperature loading or other effects should not be neglected.

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. Regarding the second application, compressible and damping effects within the water reservoir should be accounted for. In addition, an improved way of modelling impact damping should be adopted in future works.

## ACKNOWLEDGEMENTS

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