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ADVANCED SENSITIVITY ANALYSIS OF DYNAMIC BEHAVIOR AND SPECTRAL TRANSFER IN NUCLEAR CIVIL ENGINEERING STRUCTURES USING PARAMETRIC LUMPED-MASS STICK MODEL

David Johanny Gomez Diaz[1], Ibrahim Bitar[2], David Bouhjiti[2], Ludmila Provost[3], Maria Lancieri[3], Benjamin Richard[2]

[1] 2nd year Master student from ENS Paris-Saclay (internship at IRSN/PSN-EXP/SES/LMAPS)
[2] IRSN/PSN-EXP/SES/LMAPS, B.P. 17 - 92262 Fontenay-aux-Roses Cedex, France (david.bouhjiti@irsn.fr)
[3] IRSN/PSE-ENV/SCAN/BERSSIN, B.P. 17 - 92262 Fontenay-aux-Roses Cedex, France

ABSTRACT

The verification of the behavioral requirements of structures relies increasingly on the use of advanced methods. These methods account for the physical phenomena that are likely to occur when a structure or an equipment is loaded beyond its design level. Although the physics can be described in a proper way, the advanced methods need a vast number of input parameters and require a large computational time (CPU). This makes advanced sensitivity analysis, uncertainties propagation or reverse engineering hard to achieve with complex SSCs models. However, the use of parametric lumped-mass stick model is an option to obtain first estimations of trends before going to more advanced surrogate techniques. When calibrated well for a given purpose, such models can provide representative results at low computational cost. This paper presents a comprehensive strategy to develop such models for a given nuclear building and then use it to achieve advanced sensitivity analyses, uncertainties propagation and reverse engineering methods, especially in the presence of large number of input parameters.

INTRODUCTION

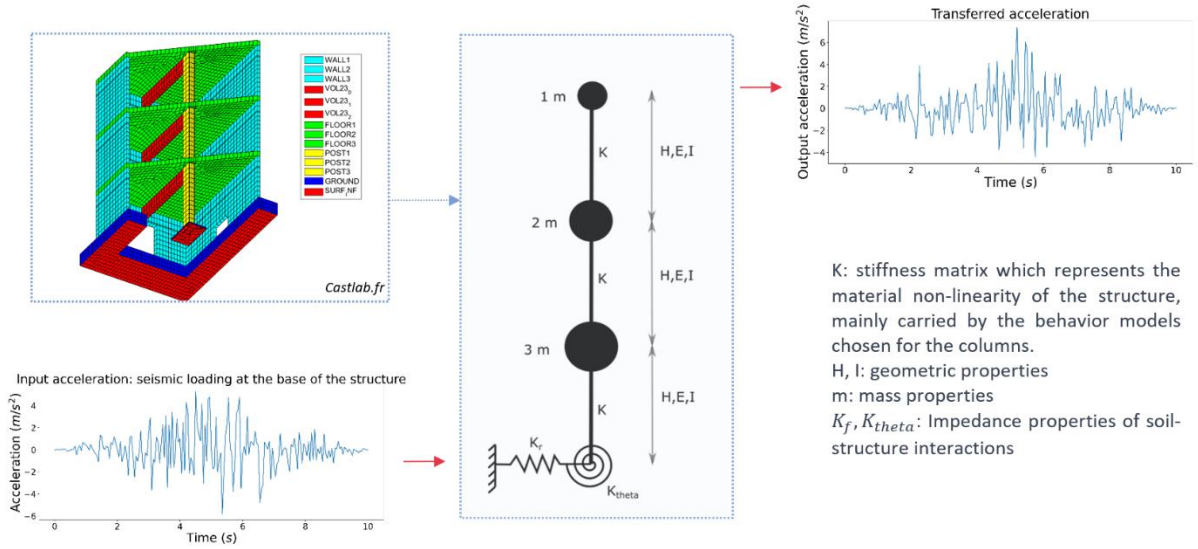
More and more often, the verification of the behavioral requirements of structures relies on the use of advanced methods. These methods account for the physical phenomena that are likely to occur when a structure or equipment is loaded beyond its design level. Although the physics can be described in a proper way, the advanced methods need a vast number of input parameters. The values of these parameters are often difficult to identify based on accompanying tests and their physical meaning can be questioned. Furthermore, variations in these parameters, especially those that control the degradation laws of the constitutive materials, may lead to significant variations in the output quantities of interest. It can therefore be complex to assess the sensitivity of a result with respect to an initial set of hypotheses without having adapted tools.

Over the last few years, researchers have endeavored to develop so-called "reverse engineering" methodologies. These techniques make possible to identify a set of input data compatible with the targeted output values. In other words, these techniques make possible to determine the input parameters of a structural model verifying the objective functions or cost functions that ensure an output quantity reaches a target value with a given precision (Figure 1).

In this work, three major objectives are targeted. Firstly, to have an integrated methodology to assess the relevance of input parameters with respect to an output quantity, the knowledge of which is necessary to verify a behavioural requirement attributed to a structure. Secondly, to have an inverse methodology to identify or adjust a set of input parameters knowing target output quantities. Finally, to be able to carry out a correlation study between seismic intensity measures and engineering demand parameters or damage indicator.

To achieve such goals, one needs to have a computationally efficient and reliable model with reasonable (as lowest as possible) cost in terms of CPU efforts. In this paper, we propose to use a parametric model of a lumped-mass stick type (Roh, et al., 2012) according to the material

characteristics of the reinforced concrete and the conditions related to the soil-structure interaction (SSI). The model is easily modifiable to facilitate the task of initiating sensitivity studies from a seismic database (Haselton et al., 2009). A reflection on the geometrical choices of the model is made as well as their justification. The development is done in Cast3M software (Cast3M, 2022) and the sensitivity studies as well as the reverse engineering methods are carried out using Python open libraries. As a demonstration of the proof of concept, the overall calculation chain is applied to the case of French



double walled nuclear concrete containment buildings (CCBs).

Figure 1: Simplified illustration of the procedure and parametric mode

THE SIMPLIFIED LUMPED-MASS STICK MODEL

The simplified lumped-mass stick model is described hereafter through the example of the French double walled CCB.

Principle of lumped-mass stick models

The lumped-mass stick models consist of modeling structures using concentrated masses at the level of floors or levels with each two successive masses connected using springs (Figure 2):

- the mass modeled at each level represents the mass of the floor, the mass of the upper half-story and that of the lower half-story. This makes it possible to account for the effect of the real inertia forces which appear in the structure during its seismic excitation.
- the translational rigidities of each level are determined with the hypothesis of rigid floors to obtain the stiffness matrix associated with the structure via massless springs.

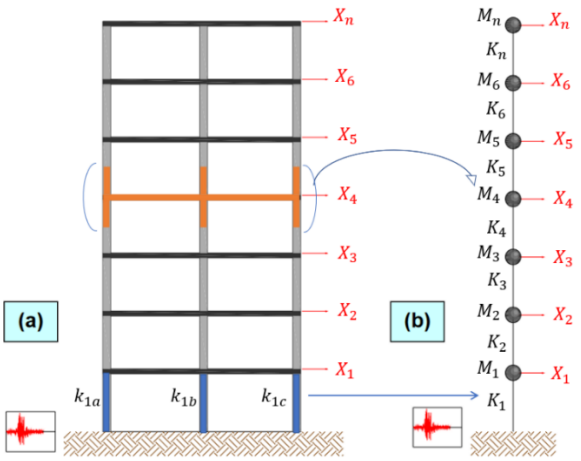


Figure 2: (left) n-floor building (right) n lumped-mass stick models (from A. H. Barbat et al., 2005)

To approach the reel response that one can obtain using a 3D and more refined model, one can calibrate the masses and the stiffnesses according to the algorithm proposed by H. Roh et al., 2013: adaptive frequency method. One should note that such method:

- is mainly adapted for symmetric buildings and strictly aims at getting the same fundamental frequencies, or at least the first three main ones, as in the reference model (of course the reference values can be obtained by experimental means).
- only covers elastic properties of the structure. So, for nonlinear analyses, another calibration step needs to be done to have the same global behavior as the reference one (using 3D models or based on experimental measurements).

Soil Structure Interactions modeling

For most common nuclear buildings, SSI modelling is based on the superposition principle (described in Wolf et al., 1988) of kinematic interaction, inertial interaction and equivalent impedance-based description of the soil beneath the foundation. The damping and stiffness matrixes of soil are calibrated to provide a modal behavior that is be coherent with the structural stiffness and mass.

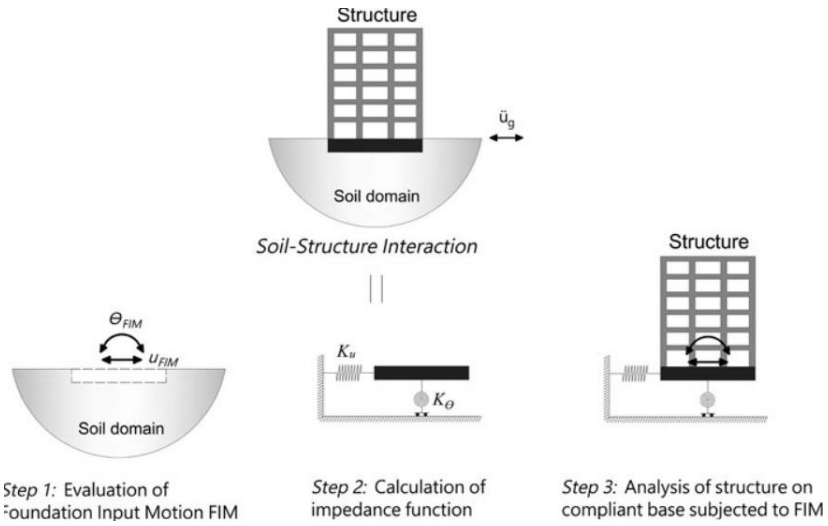


Figure 3: Superposition principle to the analysis of SSI problem

Nonlinear behavior laws

In this work, the nonlinear behavior of the lumped-mass stick model is described using a global law called "Cisail_nl" that is implemented in Cast3m. This model shows a softening linking shear and shear force for the Timoshenko beam elements and the elements modeling a beam section (fiber model) (the law is non-linear in the longitudinal direction of the local frame of the beam). The law is expressed in terms of the shear forces as a function of the distortion strain with a linear phase, a given number of transition phases until plasticity before reaching failure.

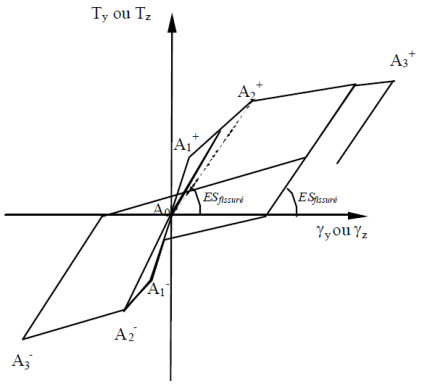


Figure 4: Superposition principle to the analysis of SSI problem

The law accounts for residual strains and includes hysteresis modeling which is relevant for cyclic and dynamic loads. Of course, the law is mostly adapted for relatively slender structural elements subjected primarily shear forces. The law needs the identification of the following parameter:

Table 1: List of parameters of Cisail_nl behavior law

Parameter	Definition	Remark
'DELP'	Elastic distorsion strain (positive direction)	$\gamma_e = \frac{T_{c,e}}{S\,.\,G}$ $and\ G = \frac{E}{2(1+\nu)}$ With S the beam section, E the Young's modulus, ν the Poisson's coefficient, $T_{c,e}$ the elastic shear force threshold
'DELN'	Elastic distorsion strain (negative direction)	
'DMAP'	Maximum damage index during plastic phase (positive direction)	$D_m = \frac{T_{c,p}}{S \cdot G \cdot \gamma_p}$ With $T_{c,p}$ the plastic shear force and γ_p the associated plastic distortion strain.
'DMAN'	Maximum damage index during plastic phase (negative direction)	
'BETA'	Pinching parameter	If Beta is equal to zero, cracks' closure does not induce any stresses (sliding model). Otherwise, cracks' closure induces stresses with an amplitude defined by the value of Beta>0.
'ALFA'	Parameter defining the kinetic of degradation under cyclic loadings	Multiplying degradation factor writes: $Degradation\ factor = \theta + (1-\theta)\, e^{\alpha\,(\gamma_p - \gamma_e)}$
'TETA'	Portion of the residual strength after complete degradation under cyclic loadings	
'MONP'	Evolution of the shear strength as a function of the plastic distortion (positive direction)	User defined piecewise linear function
'MONN'	Evolution of the shear strength as a function of the plastic distortion (negative direction)	

Also, to account for the hysteretic damping in the model, the global Rayleigh formulation is used where the damping matrix is written as a linear function of the mass and stiffness matrix: $\underline{\underline{C}} = \alpha\underline{\underline{M}} + \beta\underline{\underline{K}}$. α and β are defined to obtain a target global damping value within the range of frequencies of interest ($f_1\ and\ f_2$).

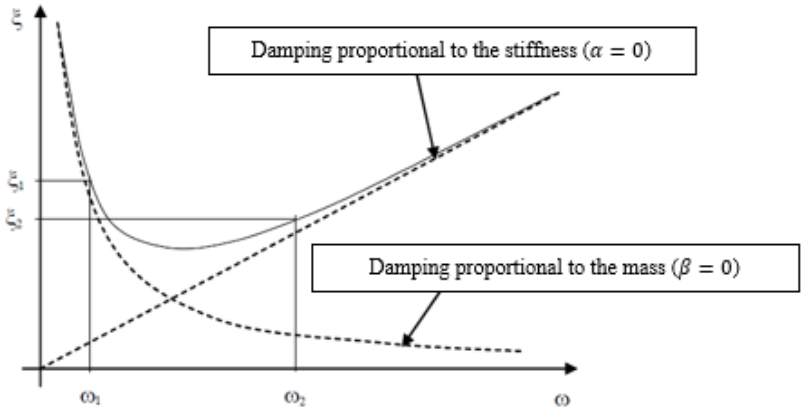


Figure 5: Rayleigh damping principle

LUMPED MASS-STICK MODEL OF FRENCH DOUBLE WALLED CCBs

Lumped-mass stick model calibration

In this work, the model is limited to the inner wall of the double walled CCBs. The definition of masses in the simplified model is set based on the number of lifts during the construction phase (see Figure 6). Then the stiffness and sections of the springs between masses are defined so as to obtain the same eigen frequencies as in a reference full 3D model for a boundary condition with a fixed foundation. In a second time, SSI springs and dampers are added for three translation modes (X, Y and Z directions) and for two rotational modes (along the X and Y axis). The torsional mode of SSI is overlooked.

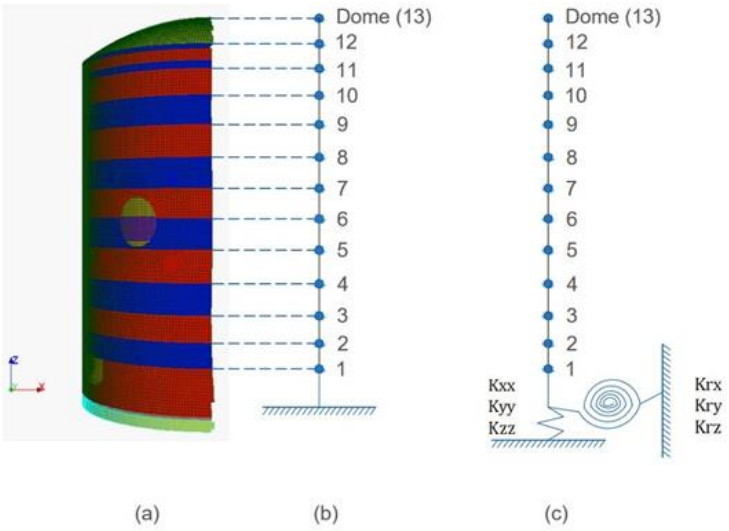


Figure 6: CCB inner wall's (a) 3D model (b) lumped-mass stick model with fixed foundation (c) lumped-mass stick model with SSI

For the nonlinear model's parameters calibration, we consider as a reference a nonlinear pushover curve relating the shear forces at the foundation level to the overall displacement of the dome. This reference pushover analysis is done using the full 3D model where a nonlinear damage-based law for concrete is used (RICBET available in Cast3m as well). The pushover analysis is based only on the first eigenmode that is amplified increasingly to induce damage and plastic strain in steel elements (Figure 7). To simplify calibration, the parameters α=0.5, β=1, θ=1 are fixed to their default values whereas only the 'MONP' and 'MONN' are adjusted to fit the result obtained from the 3D model.

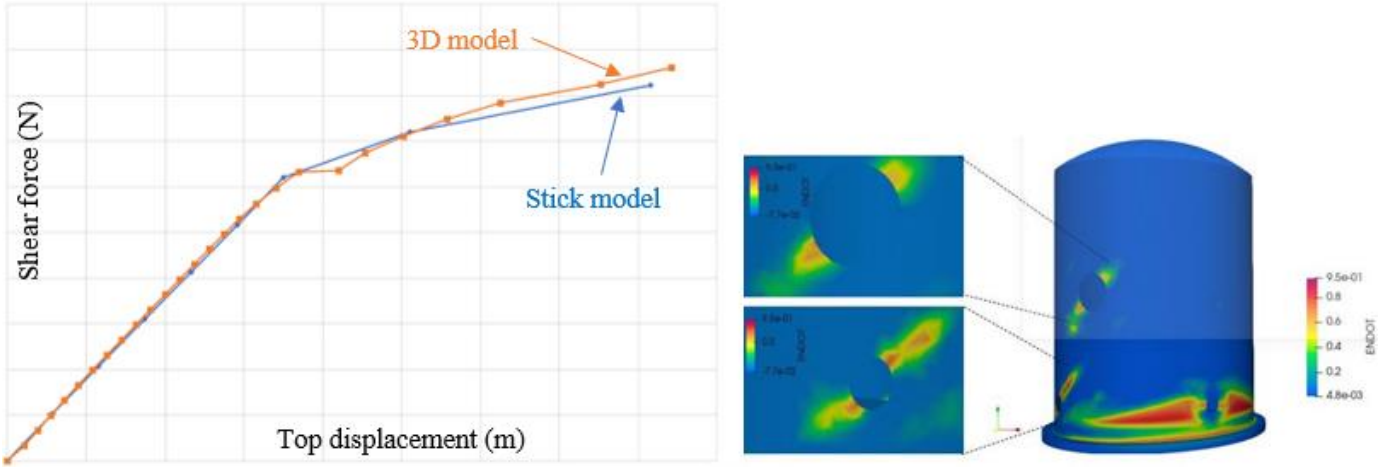


Figure 6: (left) lumped-mass stick model nonlinear parameters calibration based on the pushover analysis (numerical values are deliberately censored) (right) damage profile at the end of the pushover analysis

One can see that, provided an accurate fitting, the simplified model (requiring few seconds) reproduces accurately the nonlinear behavior of the CCB based on the first eigenmode loading (3D model requiring few hours to be solved). Of course, for advanced fitting, one needs to achieve cyclic loading paths and fits the default parameters as well (α, β, θ). This is not done in the present work for the sake of simplicity within the overall chain of calculations.

Model verification

One should note that, by definition, the simplified lumped-mass stick model only allows for the description of the global behavior of the CCB (getting localized strains and stresses is out of the scope of the present work). This global response includes displacements, velocities and accelerations at each nodal position, forces at the foundation level and at each nodal position and finally energy balance terms (input energy, kinetic energy, deformation energy, dissipated energy in the soil and in the structure). For the energy terms, they are all calculated using time integration over time as the seismic motion is applied (Ghavamian, 1998).

Here the goal is to make sure that all these outputs can be calculated accurately, and that the implementation is deprived of errors. For that, and for the sake of illustration, we use the 07/09/1999 Greek seismic accelerograms at bed rock with a magnitude of 5.9. This input motion is applied at the foundation level of the lumped-mass stick model with and without SSI and within linear and nonlinear framework. The numerical solving over time is done using classical Newmark scheme. As outputs, we look at transferred spectra at the heights of 7.6m (P1) and 26m (P2) and at the global energy balance.

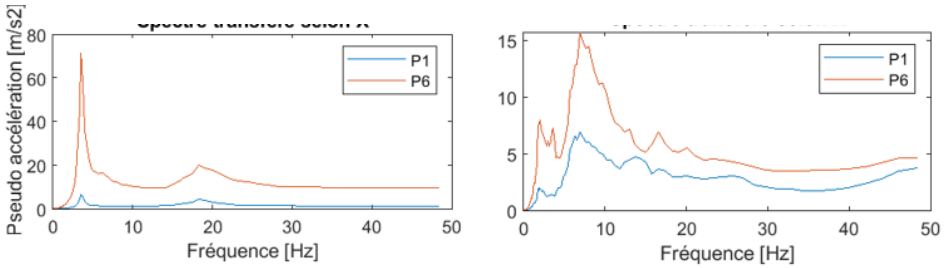


Figure 7: Transferred spectra (left) linear model (right) nonlinear model

One verifies the equality between the total and input energies, the negligeable hysteretic energy and the non-negligible viscous energy within soil dampers and the structure.

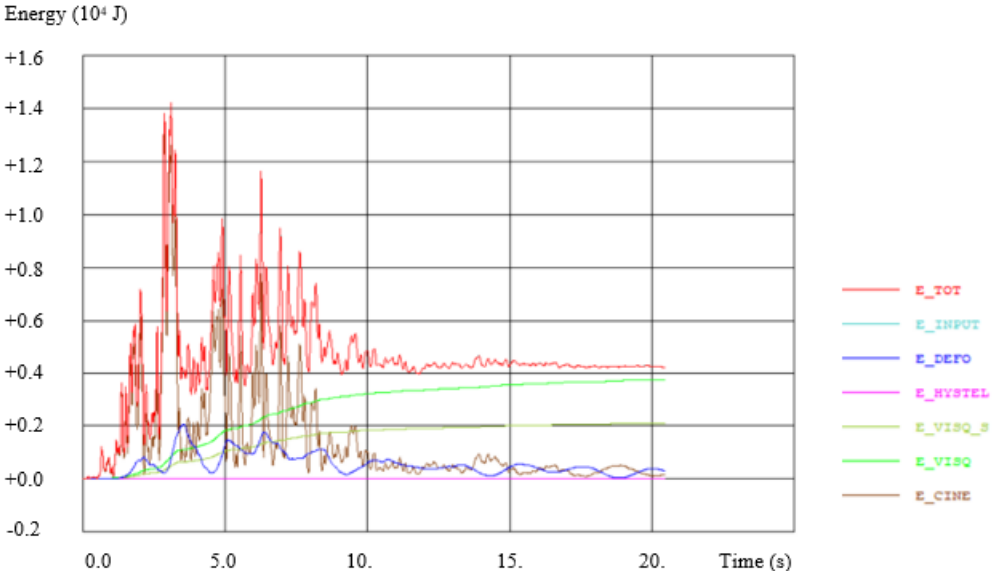


Figure 8: Energy balance terms with SSI: Total energy (E_tot), input energy (E_input), deformation energy (E_defo), hysteretic energy (E_hyst), viscous energy in soil (E_VISQ_S), total viscous energy (E_visq), kinetic energy (E_cine)

CORRELATION AND SENSITIVITY ANALYSIS

As the model implementation is now verified (and the model is validated to some extent based on the modal analysis and pushover analysis using a full 3D nonlinear model), one can use it to achieve advanced sensitivity analyses at low cost. The results of such analyses can be used for the purpose of reverse engineering amongst others.

For our analyses, we use natural seismic signals at bed rock with magnitudes ranging from 3.7 to 6.4 that have occurred between 1997 and 2013 in Greece, Italy, and France (Table 2). For each seismic signal, several Intensity Measures are studied (Table 3). Then transient dynamic calculations are achieved to analyze the correlation between the outputs of interest and the same intensity measures.

Table 2: Short data base of natural seismic signals

	event_id	event_time	ev_nation_code	station	epi_dist_km	ev_depth_km	hypo_km	Mw
1	GR-1999-0001	07/09/1999 11:56	GR	ATH4	19,7	9,4	21,82773465	5,9
2	GR-1993-0006	05/03/1993 06:55	GR	KYPA	17,8	38,8	42,68817166	5,2
3	GR-1997-0019	18/11/1997 13:07	GR	KYPA	90,2	10	90,75263082	6,4
4	IT-2009-0102	07/04/2009 17:47	IT	AQP	12	13,5	18,06239187	5,5
5	IT-2009-0121	09/04/2009 00:52	IT	AQP	12,9	8,3	15,33949152	5,4
6	IT-2009-0140	09/04/2009 19:38	IT	AQP	13,9	7,2	15,65407295	5,2
7	IT-2009-0264	23/06/2009 00:41	IT	AQP	7	10,4	12,53634716	3,7
8	IT-2009-0279	03/07/2009 11:03	IT	AQP	2,7	4	4,825971405	4,1
9	IT-2013-0019	29/12/2013 17:08	IT	MCN	20,2	20,4	28,70888364	5
10	IT-1995-0003	30/09/1995 10:14	IT	VSD	23,8	22,111	32,48594036	5,2
11	EMSC-20080716_0000056	16/07/2008 20:33	FR	PYAD	1,3	9,7	9,786725704	3,55
12	EMSC-20061117_0000084	17/11/2006 18:19	FR	PYBB	14	7,2	15,74293492	5,3
13	TK-1999-0294	13/09/1999 11:55	TR	4101		10,4		5,8

Table 3: List of considered Intensity Measures

IM	Description	Expression
$V_{s,30}$	Shear waves velocity at a depth of 30m	-
X_{PGA}	Pseudo-acceleration in the X direction	$max\left\|\ddot{u_g}(t)\right\|$
X_{PGV}	Pseudo-velocity in the X direction	$max\left\|\int_{t_0}^{t_{duration}} \ddot{u_g}\,(t)dt\right.$
X_{PGD}	Pseudo-displacement in the X direction	$max\left\|\int_{t_0}^{t_d}\int_{t_0}^{t_d} \ddot{u_g}\,(t)dtdt\right.$
X_{IA}	Arias intensity in the X direction	$\frac{\pi}{2g}\int_0^{t_d} \ddot{u_g}^2(t)dt$
$X_{Housner}$	Housner intensity in the X direction	$\int_{0.1}^{2.5} PSV(T,\xi)dT$
X_{CAV}	Cumulated absolute velocity in the X direction	$CAV = \int_t^{tmax}\left\|\ddot{u}_g(t)\right\|dt$
X_{T90}	Husid period: time interval during which Arias Intensity varies from 5% to 95% of its final value in the X direction	$D = T\ verifying\ \frac{U_{IA}}{U_{IA\,fin}} = 95\%$

PSV= Pseudo-Velocity Spectrum – X is one of three main directions of the cartesian frame.

Intensity measures (IMs) correlation analysis

Considering the 13 seismic signals in Table 2, the Pearson correlation analysis reveals some strong correlation between the following IMs: PGA, PGV and PGD in the horizontal directions. The vertical components of these intensity measures are less correlated to the rest of them. A strong correlation is also observed between Housner intensity measures in the three directions. The same can be said regarding the cumulated absolute velocity. Finally, horizontal Arias intensities seem strongly correlated (not the case of the vertical component). That allows eventually to reduce the list of representative IMs from 22 to 11 only (the other 11 are correlated to the ones retained hereafter).

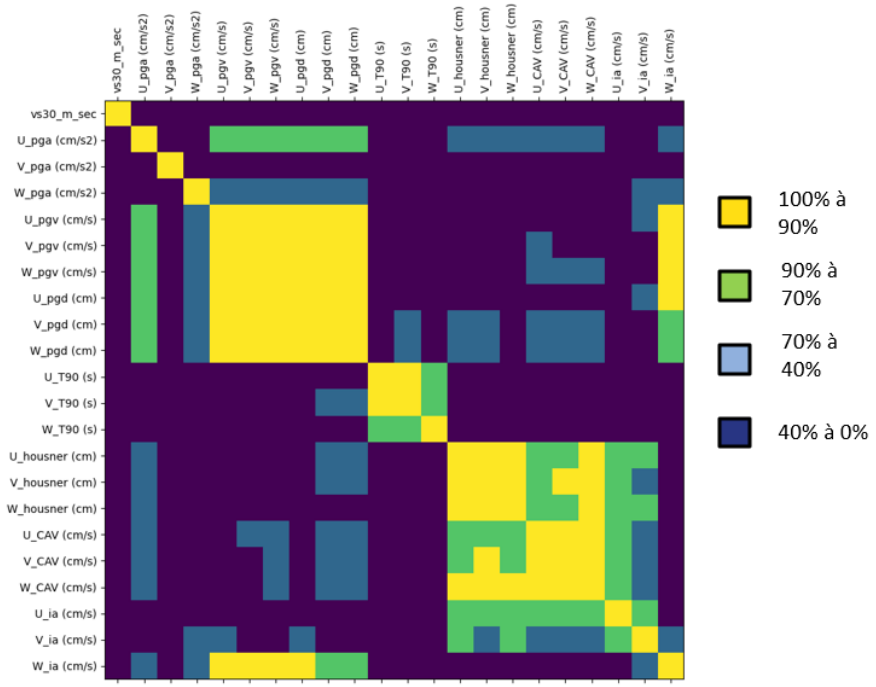


Figure 9: Pearson correlation matrix of the considered Intensity Measures

Correlation between Intensity measures (IMs) and Engineering Demand Parameters (EDPs)

Let's take the example of the maximal displacement at the top of the CCB as the EDP of interest. We find that such quantity is correlated to PGA terms (totaling 15% correlation factor), PGV terms (showing higher correlation around 17%) and Arias Intensity (with a cumulated correlation factor around 35%). Though the PGA is most widely used as a ''universal'' IM to describe seismic motion, one sees through this analysis that this is not always the best choice; here for instance the Arias Intensity IM is better suited, though not sufficient, to describe the drift of the building than the PGA. For other EDPs of interest, we find that Husid period shows a cumulated correlation of 50% with the spectral acceleration in the structure, as much as the one calculated for the PGA IMs. Hence, one concludes that one IM might not be sufficient to describe all EDPs and the PGA is not always the best IM candidate.

OFAT based sensitivity analysis

In this section, we aim at identifying the most influential parameters of the behavior law "Cisail_nl" especially the ones that are defined by default. For this, we use the OFAT approach (one-factor-at-a-time) applied to the Young's modulus (with a coefficient of variation of 10%), the alpha (varying between 0 and 1), beta (varying between 0 and 1) and theta parameters (varying between 0 and 1). Applied to all seismic signals, this leads to a total number of calculations equal to 13 signals * (1 reference calculation + 4 parameters * 2 bounding values)=117 calculations. We find that, for seismic loads inducing low level of nonlinearities, the most influential parameter is naturally the Young's modulus. However, as the seismic load increases:

- the parameter "theta" (portion of the residual strength after complete degradation under cyclic loadings) becomes more influential in terms of the maximal displacement at the dome position (drift).
- the parameter ''beta'' (pinching parameter) becomes equally influential as the Young's modulus in terms of the spectral accelerations.

So, these default parameters should be defined carefully especially at high seismic levels.

CONCLUSIONS AND PERSPECTIVES

The actions carried out in this paper resulted in the development of a simplified lumped-mass stick model for the analysis of the dynamic behavior of reinforced concrete structures. The model is based on the use of a generalized force/displacement behavior law (called “cisail_nl”) implemented in Cast3M and its parameters are calibrated based on results provided by non-linear full 3D calculation subjected to progressive pushover loading. The fitting aims at finding the correct main eigen frequencies as well as the pushover global curve expressed in terms of shear forces vs. displacement at a given control point. Once well calibrated, the lumped-mass stick model calibrated (modal analysis, ISS calibration, post-processing of spectra and energy balance) can be used to carry out sensitivity analyzes at low cost.

In terms of applications, the approach was applied to the case of the inner wall CCB subjected to 13 natural seismic signals with increasing amplitudes. The results of the study show:

- a complex correlation between the IMs (intensity measures) associated with earthquakes and the EDPs (engineering demand parameters) of interest. Indeed, although seismic signals are usually described by their PGA, the latter is not sufficient to describe the entire dynamic behavior of structures, especially in the range of low frequencies. That is why other IMs can be more representative depending on the studied quantity of interest (spectral acceleration at a period of interest, drift, energy, etc.). For instance, the Arias intensity and Husid period can be better suited.
- a high sensitivity of the dynamic response (spectral acceleration, drift, energies, etc.) to the Young's modulus of the concrete then to the parameters of the cisail_nl law: the pinching parameter as well as the parameter defining the fraction of the residual resistance after complete degradation under cyclic loading show increasing influence as the magnitude rises.

Several ongoing tasks shall cover (a) the extension of the calculation chain to include soil degradation through impedances functions before continuing with the modal calculation then the non-linear transient analysis, (b) the enrichment of the digital experiment plan in order to carry out advanced sensitivity analyzes such as the Sobol’ or Morris analysis, (c) the application of the approach to several nuclear buildings of interest (other than CCBs) and (d) the definition of the response surfaces (for each building and site) associated with each EDP of interest according to the IM but also the properties of the materials.

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