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SIMULATION OF HAZARD CONSISTENT ACCELEROGRAMS COMPATIBLE WITH TARGET UHS FOR SEISMIC RISK ASSESSMENT

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Abstract

The Performance-Based Earthquake Engineering is becoming the state of the art for risk-informed decision making. In the nuclear domain, the Seismic Probabilistic Risk Assessment (SPRA) methodology has become the most commonly used approach for the evaluation of seismic risk and is now applied worldwide. In current practice, a set of ground motion is often simulated to comply in its mean with the target Uniform Hazard Spectrum (UHS). This can be considered as conservative since the UHS constitutes an envelope: it combines various scenarios to yield a target spectrum with uniform annual rate of exceedance for all spectral frequencies (or equivalently periods). Lin, Haselton & Baker recently proposed an innovative ground motion selection procedure that allows to obtain sets of hazard consistent time histories that allow to comply with prescribed UHS target spectra. It is based on the derivation of conditional spectra that not only matches the uniform hazard spectrum (UHS) at a conditioning frequency but also represents the spectral shape associated to a single earthquake scenario more realistically. The present work proposes a new way to obtain a pertinent ground motion set by simulation and combining the conditional spectra at various spectral frequencies. The time histories are simulate for a number of conditional target spectra using a stochastic model. The simulated ground motion possess the advantage that a close fit to target conditional spectra can be obtained, without record scaling. A great number of conditional ground motion can be simulated at low cost. Moreover, the simulation facilitates the definition of 3D motion that comply with the target. The methodology is assessed by the computation of in-structure floor response spectra. The floor spectra are an input used for the evaluation of seismic fragility curves in the framework of SPRA.

Keywords: conditional spectra; UHS; ground motion simulation; floor spectra; probabilistic seismic risk assessment

1. Introduction

The Performance-Based Earthquake Engineering is becoming the state of the art for risk-informed decision making. In the nuclear domain, the Seismic Probabilistic Risk Assessment (SPRA) methodology has become the most commonly used approach for the evaluation of seismic risk and is now applied worldwide. The key elements of SPRA studies are seismic hazard analysis, seismic fragility evaluation for each components and substructures and system analysis including the construction of logical fault tree model. These three elements allow for the safety assessment of the industrial plant [8]. For the structural fragility analysis, a set of hazard consistent ground motion time histories is needed. In current practice, a set of ground motion is often chosen so as to comply in its median with the target Uniform Hazard Spectrum (UHS) [15, 14]. This can be achieved by selecting and modifying natural time histories or by generating synthetic time histories with equivalent features. This approach can be considered as very conservative since the UHS constitutes an envelope. It provides spectral acceleration as a function of frequency such that all spectral acceleration values have same exceedance probability ("same risk"). The spectral content of these time histories does not correspond to any real earthquake scenario. The use of multiple scenario spectra rather than the UHS avoids exciting a broad period range in a single evaluation. However, the definition of target spectra that comply with design requirements while being hazard-consistent for a reduced number of structural analysis is not straightforward.

Lin, Haselton & Baker [11] recently proposed an innovative ground motion selection procedure that allows to obtain sets of hazard consistent time histories that allow to comply with prescribed UHS target spectra in the framework of different settings. In particular, the two different settings described in ATC 2011 [2], risk-based assessment and intensity-based assessment, are considered. The two settings are illustrated by Fig. 1. Loosely speaking, Fig. 1 left corresponds to an intensity based approach (assessment at design level intensity) while Fig. 1 right corresponds to risk-based approach. In both cases, the methods are based on the derivation of Conditional Spectra (CS) that represent the spectral shape associated to single earthquake scenarios more realistically [3]. Sets of time histories that best fit the set of target spectra are then selected in a database, and possibly scaled in order to improve the matching, see Jayaram et al [10]. The intensity-based assessment is the framework for structural analysis that are performed for a given risk target spectrum such as UHS. On Fig. 1a, the Conditional Mean Spectrum (CMS) is determined at various conditioning frequencies for the target UHS such that the UHS is the envelope of the respective CMS (see Fig. 2 for an illustration). The risk-based approach allows to reconstruct the full hazard curves and to obtain sets of fully "hazard-consistent" ground motion. On Fig. 1b, the Conditional Mean Spectrum (CMS) is determined for one conditioning frequency but considering various risk levels such that the ensemble of all conditional spectra yields the hazard curves (this is shown for 2 values of spectral acceleration on Fig. 3). Both approaches are studied for possible use in SPRA. The present work proposes a new way to obtain a pertinent ground motion set by stochastic simulation. Time histories are generated for a number of conditional target spectra using the stochastic model proposed by Zentner 2014 [17]. The simulated ground motion possess the advantage that a close fit to target conditional spectra can be obtained, without record scaling. A great number of conditional ground motion can be simulated at low cost. Indeed, the international databases are indeed growing but they do not always contain sufficient data for all possible scenarios and site conditions. Moreover, the simulation facilitates the definition of 3D motion that comply with the target. In order to assess the mathematical soundness and highlight the concepts, only simple cases of hazard curves are considered. In particular, only one GMPE is considered. This allows to fully check the PSHA simulations against theoretical results. The industrial interest of the methodology is then checked through the evaluation of floor spectra and fragility curves for the Karisma benchmark reactor building [16, 13]. In consequence, the epistemic uncertainty, introduced by logic trees, and involving more than one GMPE, is not accounted for here. This issue is not a simple one, but the use of the CS-approach with multiple scenarios and models has been tackled by several authors (Lin et al [11, 12], Abrahamson 2014 [7]) in the past. The methodology is assessed by the computation of in-structure floor response spectra. The floor spectra are an input used for the evaluation of seismic safety margins or fragility curves, in the framework of SPRA. More precisely, the resulting "probabilistic" In-Structure Response Spectra (ISRS) are compared to the same quantities used for design, which allows to determine a safety margin and associated uncertainty. In the PRA approach, the safety factors and the associated uncertainty are also used to establish lognormal fragility curves [9, 20, 15, 21].

2. Conditional spectra approach for seismic PRA

2.1 Definition of target spectra from UHS

We can break the UHS down into a suite of CMS at different frequencies whose envelope reproduces the UHS. This is illustrated on Fig. 1a. The use of CMS as a target design spectrum has the advantages of being representative of realistic earthquake scenarios. The analysis conducted in this study showed that a dozen conditioning points allowed to well represent the UHS (Fig. 3). In order to introduce variability predicted by the GMPE, it is necessary to go further and define motion by CS. This is illustrated in Fig. 4 where the blue curve is the target UHS and the red curve is the mean of the CMS anchored to the UHS at various frequencies. Obviously, the median of the CMS or CS does not coincide with the UHS. When considering realistic spectral shape, there is generally a predominant spectral peak at one frequency while other spectral accelerations are below design level. In consequence, the mean or median cannot equal the peaks at the whole range of frequencies. However, the engineering goal is to assure that all predominant structural frequencies are excited at (UHS) design level. This goal is achieved by the UHS-intensity-based (target return period as defined by the regulator) CS or CMS approach

In recent applications to safety analysis of NPP, the choice was rather to consider only one conditioning frequency. In this framework, CMS / CS are considered for a set of UHS at different return periods (for example Renault et al.[14]). This is illustrated on Fig. 1b. This approach is also studied with detail in Lin et al 2013 [11] and called the risk-based approach. It has been further developed by Al Atik & Abrahamson [1] for the framework of seismic PRA where it is important to correctly model a wide range of significant eigenfrequencies related to the complex industrial structures considered. A major difference with the first approach is that each conditional ground motion has an associated occurrence rate, such that the ensemble sums up to one by virtue of the total probability theorem. This has to be considered when computing seismic demand and ISRS. The major drawback of the risk-based approach is the large number of time histories required to fully cover the hazard - and in consequence the increased number of time and CPU consuming mechanical analysis. Besides, a great number of the lower intensity analysis may not lead to considerable structural damage and are of less interest for the structural reliability analysis (cf. section 2.3).

Generally speaking, it is expected that the conditional spectra approach can help to focus on selecting pertinent time histories for structural analysis by reducing the conservatism of the classical approach of UHS matching.

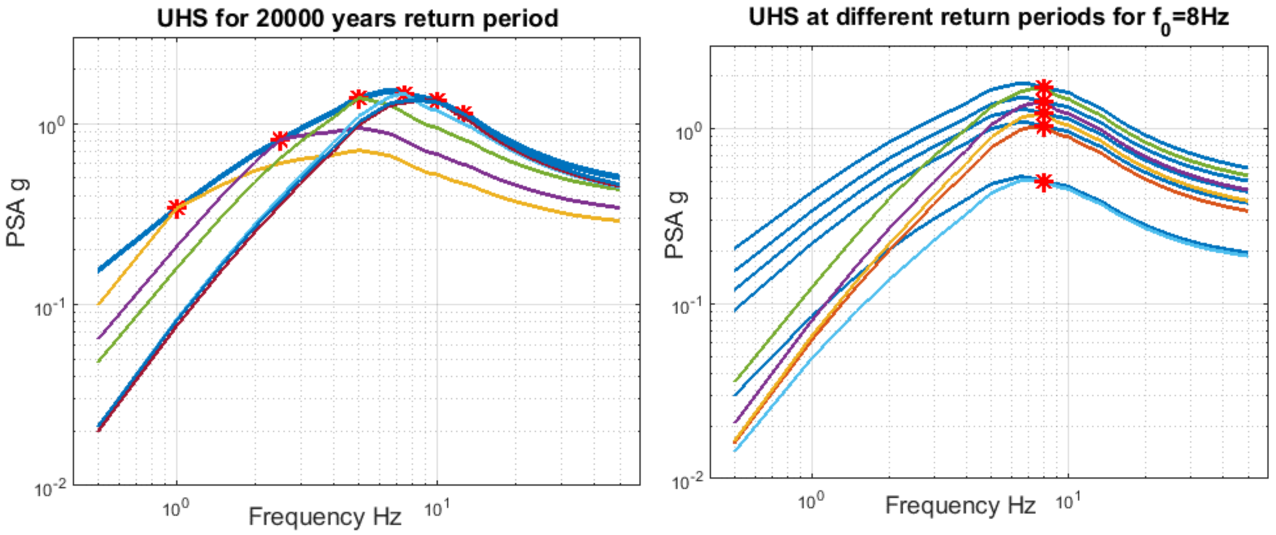

Fig. 1 – a) CMS at multiple conditioning frequencies (red asterisk) for one target spectrum (UHS – dark blue curve, left side) vs b) CMS at one conditioning frequency (red asterisk) for multiple return period target spectra (UHS – dark blue curves, right side).

2.2 Implementation of Risk-based approach

The adequacy and accuracy of the constructed ground motion representation can be checked by comparing it to the hazard curves from PSHA used to define the UHS. This can be done without having to resort to selection or simulation of time histories but simply by using the know probability distribution of the conditional spectra, using the total probability theorem:

$$\lambda(Sa(f) > y) = \int_0^\infty P(Sa(f) > y|Sa(f_0) = x)p(x)dx\ , \tag{1}$$

where $P(Sa(f) > y|Sa(f_0) = x)$ is the probability that a ground motion conditioned on $Sa(f_0) = x$ has spectral acceleration greater than y at frequency f and $p(x)$ is obtained as the derivative of the hazard curve [1]:

$$p(x)dx = -d\lambda(Sa(f_0) > x) \tag{2}$$

Equation (1) is evaluated by numerical integration and by evaluating the exact lognormal cumulative density function of the CS. It is observed that, in order to fully represent the direct hazard curve, it is necessary to account for GM at a wide range of return periods, including very low intensity spectra not relevant for design.

The results for this verification, using Eq. (1), are shown on Fig. 2 for conditional frequencies 2.5 and 5.Hz and the hazard curves described with more detail in section 3.2. Since each conditional ground motion has an associated occurrence rate, the median spectrum is no more a pertinent statistical quantity to define seismic demand. It is however possible to evaluate the distribution of seismic demand in terms of floor spectral acceleration:

$$F(y) = \int_0^\infty P(Sa > y|IM = x)p(x)dx\ , \tag{3}$$

where $P(Sa > y|IM = x)$ is the probability that the seismic demand exceeds a given threshold, given ground motion intensity $IM = x$ (PGA and PSA at frequency f_0 will be considered) and $p(x)$ is obtained as the derivative of the hazard curve as in Eq. (1).

2.3 Implementation of the intensity-based approach

The validation of the intensity-based CS-approach consists in verifying that

- the envelope of the CMS at conditioning frequencies matches the target UHS. This is illustrated for the case study of this paper on Fig. 3.
- The set of CS match CMS and log std at each condition frequency.

As discussed in the preceding section, by construction, the median is not an adequate statistical quantity. Moreover, evaluating the ISRS as the envelope of the whole set of floor spectra is not in agreement with performance-based approach, median not adequate.

A way to overcome this drawback is to evaluate floor spectral acceleration for each conditioning frequency as the median of floor spectral accelerations obtained with CS conditioned on that very frequency. This means that each set of CS corresponding to one particular conditioning frequency f_0, is used to determine the floor spectral acceleration at that frequency, $S_a(f_0)$. The set of these then yields the ISRS. This is the approach adopted in what follows.

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[1] The hazard curve of the simple example with one point source is expressed as

$$\lambda(Y > y) = v(m \geq m_{min}) \int_{m_{min}}^{m_{max}} P_i(Y > y|m)\, f_i(m) dm$$

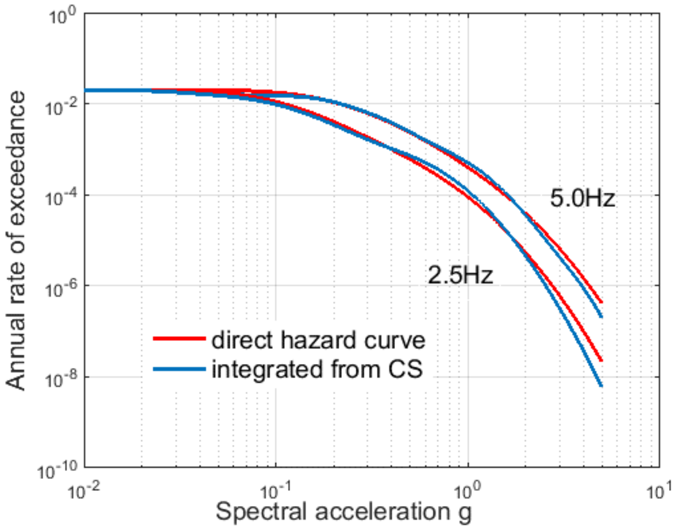

Fig. 2 – Comparison of hazard curves for *Sa*(2.5Hz) and *Sa*(5Hz) to those obtained from CS by integration using Eq. (1).

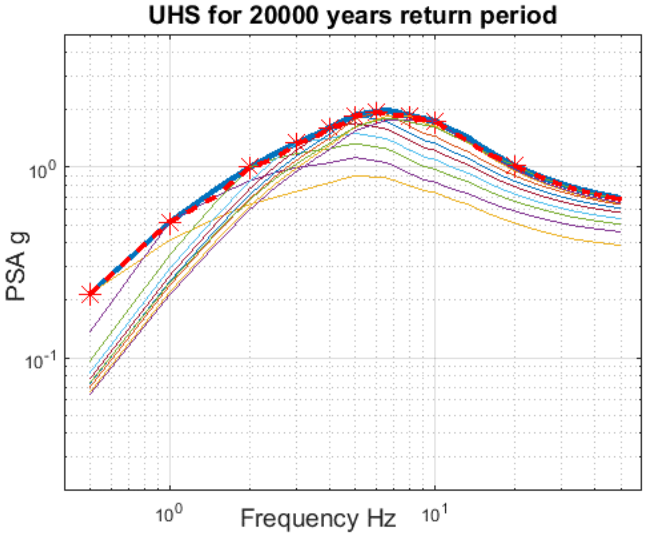

Fig. 3 – Comparison of UHS (blue) to envelope (red dashed) of intensity-based CMS anchored at various frequencies (red stars).

3. Stochastic ground motion simulation procedure

According to the Ground Motion Prediction Equations (GMPE), the response spectra are lognormal stochastic process defined by its median, log standard deviation and correlation coefficients. This property is used in the ground motion selection algorithm of Baker and co-workers, [10, 3], who propose to simulate sets of target CS and then select natural accelerograms that best match these spectra. The matching is verified one-by-one, which means that for each simulated response spectrum the best matching natural accelerogram is chosen. Moreover, the recorded accelerograms can be scaled in order to improve matching. The procedure is illustrated on Fig.4 for the case of intensity-based assessment. The ground motion simulation methodology used in this work follows the general ideas of the record selection procedure proposed by Baker and co-workers but uses spectrum compatible stochastic models instead of recorded accelerograms. Indeed, the constructions of spectrum-compatible power spectral density model allows to simulate synthetic accelerograms matching various spectral shapes. It is used here for the simulation of accelerograms that fit a set of CS one by one. That means that each synthetic accelerogram corresponds to one CS, as shown on Fig. 6 for the study case of section 4. It is well known that not all of the information on site specific and hazard consistent motion is included in the spectra. The proposed ground motion simulation procedure allows to introduce supplementary information linked to the transient characteristics. In particular, the strong motion duration and evolution of frequency content with time can be tuned according to information available from PSHA and GMPE. Eventually, former studies showed that the stochastic ground motion model produces time histories having PGV, CAV etc in agreement with physics and seismological models [17, 18].

The ground motion simulation procedure used here can be summarized as follows:

- For chosen conditioning frequency and return period, obtain dominant scenario spectra by disaggregation
- Simulate sets of the conditional target spectra matching CMS and ± 1σ CS using dominant scenario and GMPE
- Simulate time histories in agreement with the sets of conditional target spectra

The stochastic ground motion simulation methodology is described with more detail in reference [17].

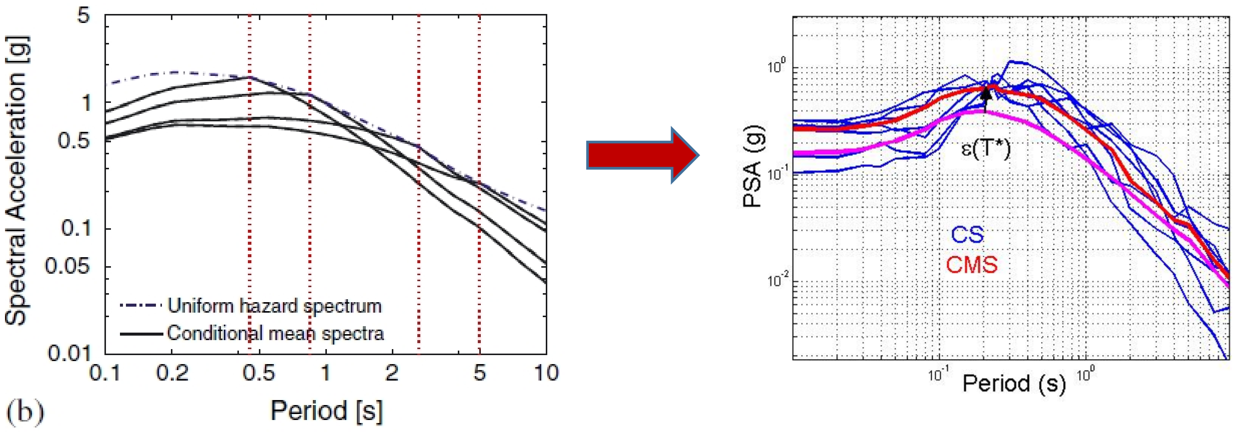

Fig. 4 – Approach: a) definition of sets of target CMS and b) simulation of sets of CS for each disaggregation period

4. Application to KARISMA benchmark study

The methodologies described in the preceding sections are assessed through application to a case study. The structural model is the Kashiwazaki Kariwa nuclear power plant that withstood a strong earthquake on July 16th 2007, and was the object of the international benchmark KARISMA (Kashiwazaki-Kariwa Research Initiative for Seismic Margin Assessment) in 2012, see e.g. [16, 13].

Three cases will be considered in what follows:

1) Classical approach with target UHS (conservative intensity based assessment): set of time histories with median matching the UHS at design RP
2) Conditional UHS approach (intensity based assessment): sets of time histories matching CS for a set of conditioning frequencies

3) Full probabilistic approach using CS (risk-based assessment): sets of time histories matching CS at one, fixed, conditioning frequency but increasing intensity (target UHS at a number of return periods)

The response quantities considered for comparison of these methods are the in-structure response spectra (floor spectra). For all cases, synthetic ground motion are used since they allow to obtain time histories in agreement with the target spectra and other seismological properties without having to resort to ground motion modification and scaling. Once the conditional target spectra are defined, as many time histories as required can be simulated at very low cost by the stochastic approach. The procedure used to obtain these time histories is explained with more detail in section 3.

All of the mechanical analysis are performed using SalomeMeca simulation platform featuring multipurpose FEM code Code_Aster. The input spectra from PSHA were computed using Matlab.

4.1 Structural model

More details on the numerical model used by EDF in the framework of KARISMA benchmark can be found in reference [16]. The mesh of the reactor building is represented on Fig. 5 on the right side. Here, soil-structure interaction is accounted for through a coupled FEM-BEM approach, where the soil is modelled by Boundary Element Method (BEM) while the structure and the foundation are modelled by Finite Element Method (FEM). The coupled problem is resolved in the frequency domain by dynamic sub-structuring. The layering and the (low-strain) shear velocities of the soil domain are also shown on Fig. 5 (left).

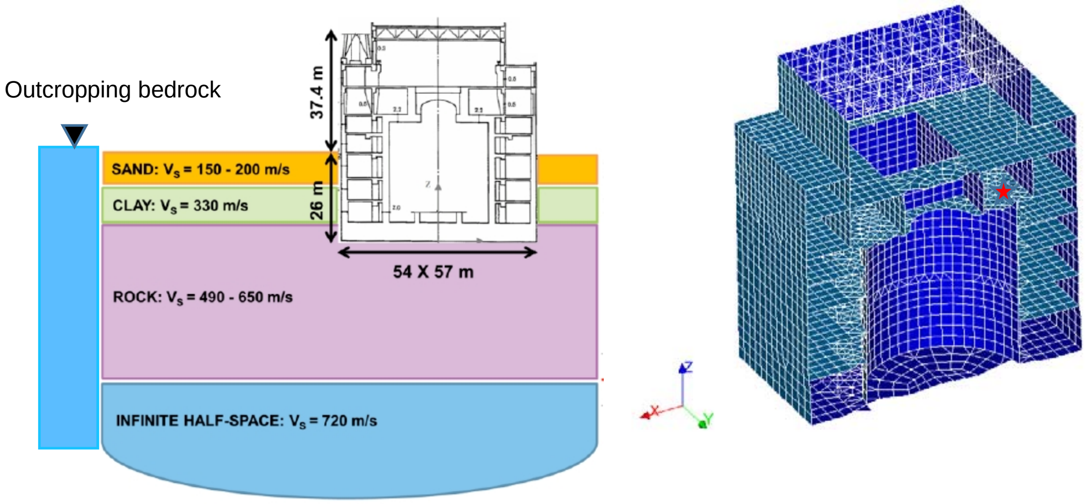

Fig. 5 – Schematic representation of configuration modified from [13] (left) and FEM mesh used here with ISRS location (right).

4.2 Computation of probabilistic floor spectra

Uncertainty on Young's modulus E_c, modal damping δ and density of concrete ρ_c is accounted for and propagated by LHS. Lognormal distributions are assumed with COV in agreement with ASCE4 (0.3, 0.35, 0.1 for E_c, δ, ρ_c respectively, see also [19]). Correlation between E_c and δ is accounted for by a negative correlation coefficient of -0.4. Ground motion is defined on bedrock. Equivalent linear soil properties are used and surface motion is obtained by reconvolution through soil column analysis. The target UHS on the bedrock is the red curve on Fig.5a.

The blue spectra on the same figure represent the family of bedrock motion spectra used for the UHS-based “classical” approach together with the median curve (magenta). The blue curves on Fig. 5b represent the respective soil ground surface spectra together with the median in magenta.

4.3 Simple PSHA model used for this study

For simplicity’s sake, a simple, a generic PSHA with one near fault source R_{rup} = 16km, R_{JB} = 0, and Gutenberg-Richter occurrence rates is considered here. Moreover, only one GMPE model is considered. This means that epistemic uncertainty due to other possible models is neglected. Doing so allows to focus on the major goals of this study which are: 1) demonstration of feasibility of the CS approach with a stochastic ground motion simulation procedure and 2) highlighting possible advantages and drawbacks of either of the approaches analyzed and, eventually, 3) providing comprehensive verified results.

The design target UHS is defined on “engineering” bedrock (see Fig.5, left) for 20000 years return period. In consequence, the GMPE is defined for “outcropping” bedrock conditions as illustrated on Fig. 5 (left side). The Campbell & Bozorgnia (C&B) 2008 GMPE [6] with Vs30 =720m/s, δ=36° together with the correlation coefficients defined by Baker et al [3] are used. The conditioning frequencies used for the intensity-based CS approach are 0.5Hz, 1Hz, 2Hz, 3Hz, 4Hz, 5Hz, 6Hz, 8Hz, 10Hz, 20Hz. Disaggregation reveals that magnitude 6.5 events are predominant for all of the conditioning frequencies except for 0.5Hz where magnitude 7.2 is the controlling event. Time histories are generated at bedrock level. The median strong motion duration of the time histories was chosen as T_{SM}=8s which is a reasonable value according to studies reported in literature [5]. A correlation coefficient of 0.2 is assumed for the horizontal components of ground motion. The same spectral shape is assumed for horizontal and vertical motion, but a factor of 2/3 is applied to the vertical component. The respective time histories on ground surface, used as an input for the SSI analysis, are obtained by soil column analysis. The reduced shear modulus for the “equivalent linear” soil profiles are obtained by the same means. In order to save computational time, 4 degraded soil profiles are retained for SSI analysis. These profiles are related to PGA of the input motion on bedrock. Preliminary analysis allowed to define 4 classes of PGA on bedrock leading to similar shear modulus reduction. Each of the resulting 4 PGA bins {<0.5g; 0.5g≤PGA<1.0g; 1.0g≤PGA<1.5g; PGA≥1.5g} is associated to one equivalent linear soil profile.

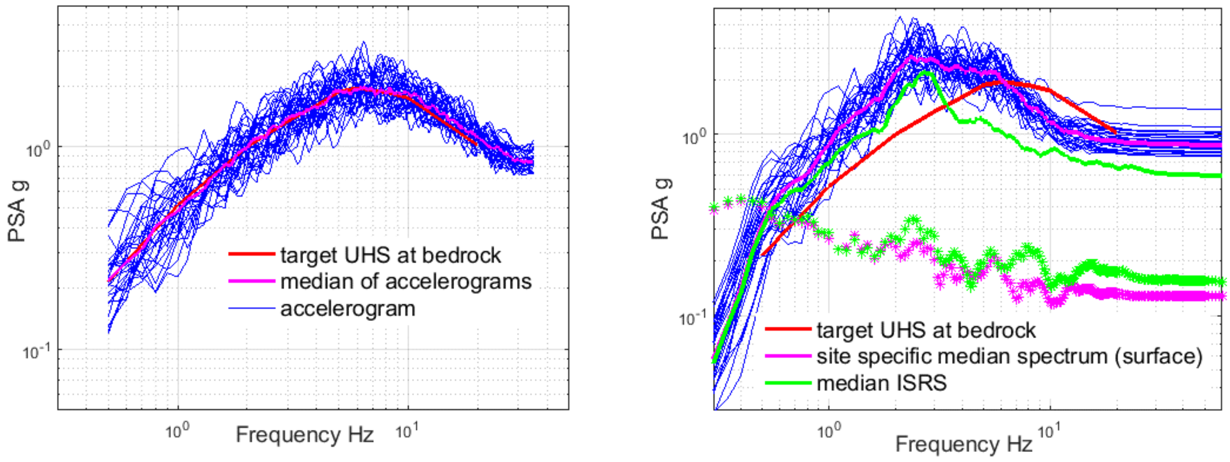

Fig. 5 – Results for “classical” UHS-based approach: a) Input Spectra on bedrock together with target UHS (red, left side) and b) Soil spectra on ground surface (blue) and their median (magenta), and median ISRS (green, right side), the log std of the latter is represented by the asterisks.

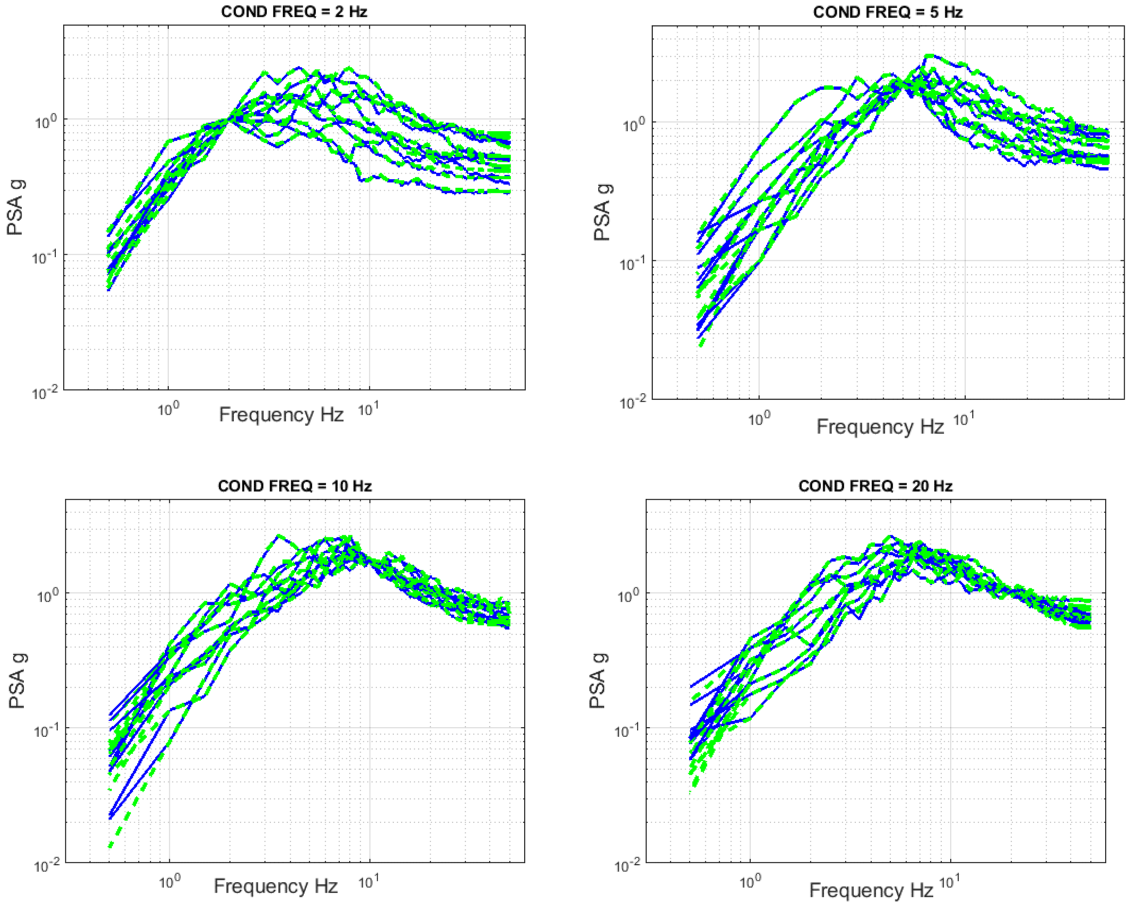

Fig. 6 – Target CS at frequencies 2Hz, 5Hz, 10Hz and 20Hz (blue) and spectra of accelerograms (green)

4.4 Case studies and Results obtained

The results obtained for the following configurations are shown on Fig. 5-7:

- UHS matching: The time histories are generated with *Code_Aster* to match UHS at bedrock using a classical approach for the generation of spectrum compatible time histories. “Natural” peak-to-valley variability is accounted for in the ground motion simulation procedure (see Fig.5a). A total of 30 triplets of 3D ground motion is generated where the horizontal components are correlated and vertical motion is obtained by applying the factor 2/3. Ns= 30 structural analysis are carried out. The resulting input soil spectra on ground surface and the floor spectra are shown on Fig.5b. The log standard deviation (std) of the obtained soil input spectra is given by the asterisks (magenta) on Fig.5b, it takes values around 0.2.

- Intensity-based CS approach: 10 time histories are generated for each of the 10 conditioning frequencies: 0.5Hz, 1Hz, 2Hz, 3Hz, 4Hz, 5Hz, 6Hz, 8Hz, 10Hz, 20Hz. Each time history matches one CS. This is illustrated for 2Hz, 6Hz, 10Hz and 20Hz on Fig.6 where the target CS in in blue and the corresponding response spectra of the simulated time history are in green (dashed curve). The 3D motion (x,y,z) for structural analysis is obtained by permutation of the latter and application of factor 2/3 to the vertical motion. Ns= 100 structural analysis are carried out. The resulting input soil spectra on ground surface and the floor spectra are shown on Fig.7a.

Risk-based approach: The analysis for the risk-based approach (case 3) are in progress and are not shown here.

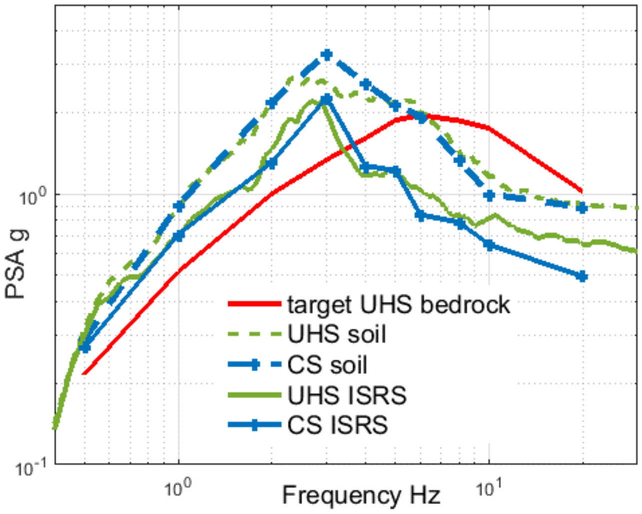

Fig. 7 – Comparison of (surface) soil spectra and ISRS obtained with UHS and intensity-based CS approach

5. Conclusion and further work

This work allowed to assess the feasibility of an intensity-based CS approach combined with a stochastic ground motion model. It allows to obtain ground motion time histories without having to resort to scaling and modification. Moreover, there is no limitation in the number of available appropriate time histories, matching various criteria such as spectral shape, strong motion duration and other ground motion proxies since the latter can be generated at low cost.

The simple case study presented here, however, did not exhibit reduction of ISRS with intensity-based CS approach. Further analyses and post-processing have to be performed. Further studies are necessary in order to fully assess the conditional spectra approach for probabilistic structural analysis in the framework of SPRA.

In particular, work is in progress in order to

- Assess the risk-based approach and comparison of methodologies and results
- Implement more complex PSHA case studies with multiple sources and models
- Evaluate the impact of CS-approaches on SPRA in terms of plant failure probabilities (by convolution with hazard)

4. Acknowledgements

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5. Copyrights

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