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DIFFERENT WAYS TO IMPLEMENT THE CONDITIONAL SPECTRA APPROACH IN NUCLEAR ENGINEERING – COMPUTATIONAL COSTS AND POSSIBLE BENEFITS FOR SEISMIC RISK ASSESSMENT

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ABSTRACT

The ground motion to be considered for seismic safety analysis is generally defined by a Uniform Hazard Spectrum (UHS), evaluated for a certain return period. The UHS provides spectral accelerations as a function of frequency such that all values have same exceedance probability. In nuclear engineering practice, the UHS is used directly to define seismic load- although it does not represent any singular earthquake but an envelope of a great variety of scenarios. This is a conservative approach since it is very unlikely that the response spectrum of recorded (scenario) ground motion does not reach UHS level at all frequencies in one specific event. The use of multiple scenario spectra rather than the UHS avoids exciting a broad frequency 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 analyses is not straightforward. In this presentation, first, we define the different ways to decompose the UHS into scenario spectra, then we illustrate possible applications and benefits for nuclear safety analysis. The hazard consistency of such ground motion is also discussed. Eventually we provide an example application to quantity possible benefits in term margins based on a simple but comprehensive case study.

INTRODUCTION

The Seismic Probabilistic Risk Assessment (SPRA) methodology is the most commonly used approach for the evaluation of seismic risk and is now applied worldwide. In this framework, the ground motion to be used for structural analysis is generally defined by the Uniform Hazard Spectrum (UHS). The UHS is derived from the mean seismic hazard curves by retaining the PSA value for a given probability of exceedance or return period. Then, a set of ground motion time histories is often simulated to comply in its mean with the target UHS and exhibiting peak-to valley variability.

This can be considered as conservative since the UHS constitutes an envelope: it combines various scenarios to yield a target spectrum. Indeed, the UHS provides spectral accelerations as a function of frequency such that all values have same exceedance probability (“same hazard level”). The spectral content of time histories in agreement with such spectra does not correspond to any real earthquake scenario. Moreover, it is generally not possible to find recorded time histories that comply with UHS. In consequence, simulated ground motion is often preferred or spectral matching and scaling is applied to recorded ground motion.

The conditional spectra methodology developed in the US by Baker and coworkers (Baker 2011, Jayaram et al 2011, Lin et al 2013) defines ground motion by multiple scenario spectra obtained by disaggregation rather than the UHS. It allows to define ground motion at design level with realistic spectral shape. Indeed, the use of multiple scenario spectra rather than one UHS avoids exciting a broad frequency range in each single structural analysis. Nevertheless, the choice of earthquake scenario target spectra complying with design requirements and the selection or generation of time histories in agreement with the latter is not straightforward.

There were different attempts to introduce the conditional spectra approach in nuclear safety assessment with limited success. In a more recent communication from Salmon et al 2022, different approaches based on UHS and CS are assessed and compared. The reason was mainly the large amount of time histories and analysis to be conducted, limited cost-benefit, and the difficulties of the integration in existing and approved assessment procedures.

In this paper we introduce and develop different paradigms to decompose target UHS spectra into scenario spectra and discuss possible applications, benefits, and bottlenecks. In particular, we show that the hazard or return period targeted decomposition of the UHS is in agreement with current practice in nuclear safety assessment (margin assessment, safety factor approach, floor spectra) and can be implemented without considerable supplementary effort. On the other hand, the fully hazard consistent decomposition of UHS at different intensity levels is more appropriate when advanced simulation-based computation of fragility curves is adopted in the framework of the multiple stripe analysis (MSA).

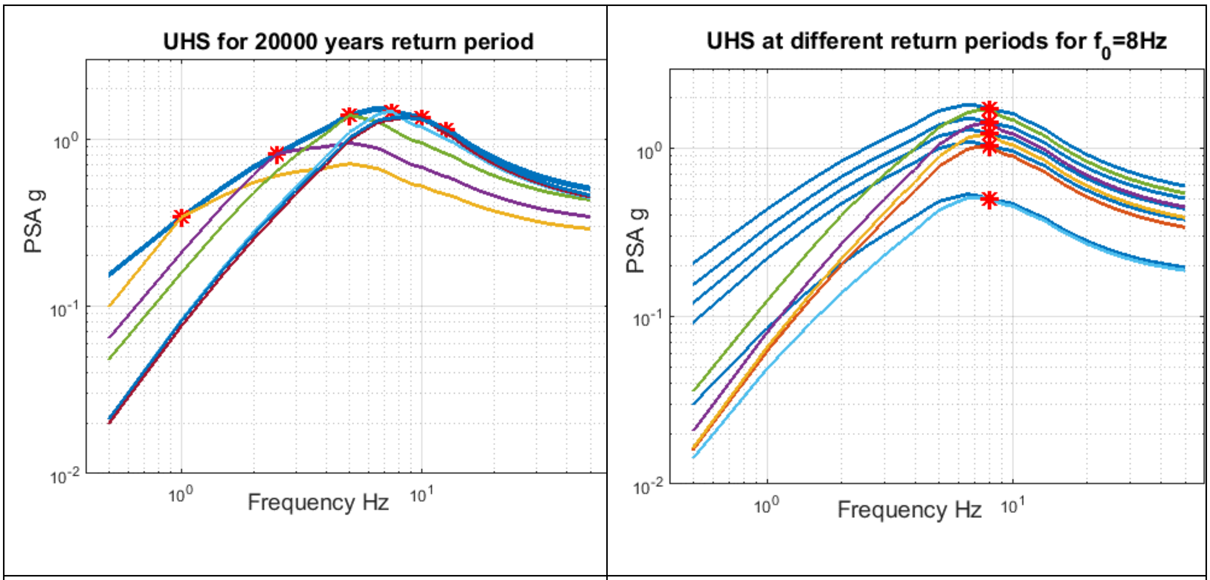
DIFFERENT PARADIGMS TO DECOMPOSE UHS INTO SCENARIO SPECTRA

The UHS is useful because it defines engineering design safety level (eg 10000 years). However, it is not most suitable for best-estimate or performance-based seismic analysis. This is why the conditional spectrum approach has been introduced. It allows to link scenario spectra linked to the design level spectrum.

The two different ways to decompose UHS into scenario are illustrated in **Figure 1**:

- **Left -** The conditional spectra approach allows for the decomposition of the UHS in a set of conditional spectra such that the UHS is the envelope of the set of conditional mean spectra (CMS). This approach is in agreement with the current seismic margin assessment approach and can be readily implemented in nuclear practice.

- **Right –** The conditional spectra approach allows for the decomposition of the UHS such that the resulting ground motion is hazard consistent. In this framework, the conditioning IM (intensity measure, PGA or PSA) is fixed and the CMS is evaluated for a suite of UHS with increasing return period. This approach (eg Lin et al 2013) is most suited for simulation-based fragility/failure probability computations since the ground motion is defined for one conditioning intensity measure (PGA or PSA) at increasing intensity levels. In **Figure 1** right, the conditioning frequency is 8Hz According to literature, the conditioning frequency does not have a major impact on the outcome. This assertion should certainly be analysed and studied in view of practical application of hazard consistent decomposition. On the other hand, when fragility curves are evaluated for PGA, then the PGA is the natural candidate for conditioning.



UHS for 20000 years return period

UHS at different return periods for f_0=8Hz

hazard-targeted

hazard consistent

Figure 1. Left: Target UHS (thick blue line) for 20 000 years return period and CMS anchored at 10 different frequencies (thin lines). Right: Suite of UHS at different return periods (thick blue line) and CMS anchored at fixed conditioning frequency (here 8Hz).

The hazard targeted decomposition can be further simplified by considering only two scenarios, such as one low frequency (generally one near field scenario) and one high frequency scenario (generally one far field scenario) that cover the design envelope defined by the UHS. Then, to make sure that the scenario spectra fully cover the UHS envelope, it is possible to choose two or three conditioning frequencies per conditional spectrum. This is illustrated in **Figure 2** below. Such an approach can be readily applied in deterministic assessment frameworks.

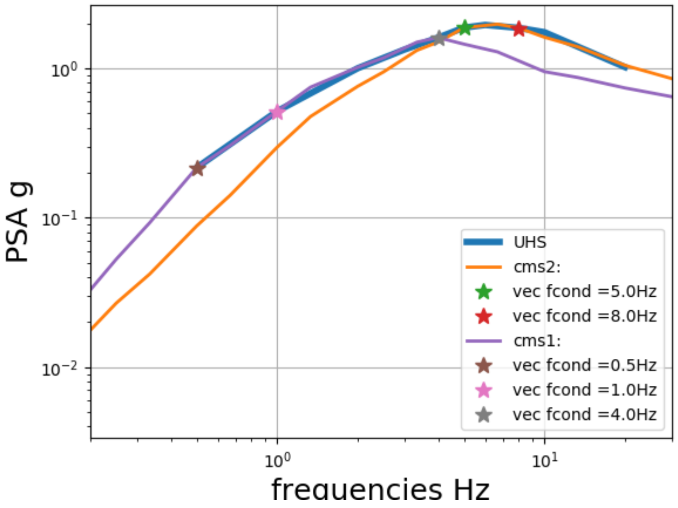


Figure 2: Alternative hazard targeted decomposition into two scenarios by multiple conditioning

- **What is hazard consistency?**

The ground motion time histories (GMTH) selected in agreement with CS at a set of intensity levels (right side of **Figure 1**) are termed “hazard-consistent” in the literature because it is theoretically possible to reconstruct the hazard curves from the resulting ground motion set. This is expressed as:

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

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:

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

However, to guarantee “hazard-consistency” it is important to check the number of ground motion (time histories or spectra) required to fully estimate the hazard curves within acceptable error range. If the number of ground motion per intensity level is too small, then the ensemble cannot be called “hazard-consistent”.

A few example applications highlighted that a large range of intensity levels (starting from low return periods generally not of interest) as well as a larger number of time histories per intensity level is required to achieve hazard consistency and thus a full representation of the hazard curves. This is a key issue for successful implementation of the hazard consistent decomposition but often neglected when the CS ground motion is developed.

- **Variability and uncertainty**

Once the decomposition strategy chosen, i.e. hazard targeted or hazard consistent as illustrated in **Figure 1** above, the dispersion and variability for the representation of ground motion needs to be determined.

- Only the mean value is considered. In this case the target spectrum is the Conditional Mean Spectrum (CMS)
- The full distribution, characterized by the mean and standard deviation is considered. This is generally simply termed CS-approach. When this approach is adopted, one important point is to agree on the uncertainty that should and needs to be represented in the adopted analysis framework. For example, the CS should not carry the epistemic uncertainty when the latter is propagated in risk the computation through the hazard curves, otherwise this leads to double counting of epistemic uncertainty in the seismic PRA.

CODES AND CURRENT GUIDELINES

The conditional mean spectrum approach has been introduced in the building code in ASCE 7-16 with the goal to reduce conservatism and possible bias in ground motion selection. To simplify the implementation of conditional mean spectra, ASCE 7-22 proposes an alterntive hazard targeted method that requires only two target spectra (Bassman et al 2021) conditioned on two frequencies (periods) selected based on the dynamic properties of the structure under consideration. In contrast to nuclear, it is accepted that the envelope of the CMS falls below the target UHS, as long as it satisfies a lower bound within a specified period range, which prevents from multiple conditioning as illustrated in **Figure 2**.

Interestingly, the two settings of **Figure 1** have been introduced in ATC (2011).

In nuclear engineering, the hazard consistent conditional spectrum approach has been studied by a few authors (Talaat et al 2015, Renault et al 2015) in the past. Moreover, it has been assessed within PEGASOS project and applied in a pilot study by EPRI (2016). However, the huge computational burden associated to the hazard consistent decomposition and unclear benefits prevented it from larger practical implementation except a few pilot studies (Salmon et al 2022).

IMPLEMENTATION IN RISK ASSESSMENT FRAMEWORK

A first step in the practical implementation of the CS approach is the definition of target ground motion and the selection of ground motion time histories if nonlinear time histories analysis is to be performed.

According to the Ground Motion Prediction Equations (GMPE) now called Ground Motion Models (GMM), the response spectral accelerations are lognormal random vectors defined by their median, log standard deviation and correlation coefficients. This property is used in the ground motion selection algorithm of Baker and co-workers, 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 natural accelerograms generally need to be scaled by factors ranging from as low as 0.1 up to 10 to satisfactorily match the target. In summary, both recorded and synthetic ground motion can be selected or simulated to obtain sets of ground motion in agreement with conditional spectra defined in Figure 1 and the chosen variability:

1. Recorded scaled ground motion (Jayaram et al 2011) or simulated scenario ground motion (Alvarez 2024)
2. Stochastic ground motion simulation, spectrum-compatible ground motion can be simulated directly tailored to the target in terms of spectral acceleration, duration and other intensity measures (Zentner 2014, 2015)

Secondly, the definition of target spectra and ground motion selection should agree with the intended use for margin and fragility computation. This is highlighted in what follows.

A simple implementation of conditional spectra approach, that builds on current practice and generally approved assessment procedures, is to decompose UHS for a given return period for the computation of seismic margins. Such an implementation together with RVT approach is illustrated in **Figure 3** below and detailed in the last section of this paper. This is the hazard targeted decomposition in **Figure 1.** The hazard consistent CS approach develops suites of target ground motion for increasing intensity levels (return periods). For each intensity level a suite of ground motion (spectra and time histories) is defined as described above and shown on **Figure 4**. Then for each intensity level, the failure probability is computed as a point estimate and a lognormal fragility curve can be fitted. This approach is generally called Multiple Stripes Approach (MSA). In **Figure 4**, each point on the fragility curve corresponds to a set of conditional spectra defined for a given intensity level (not all levels are shown in Figure 4 left, figures for illustration only).

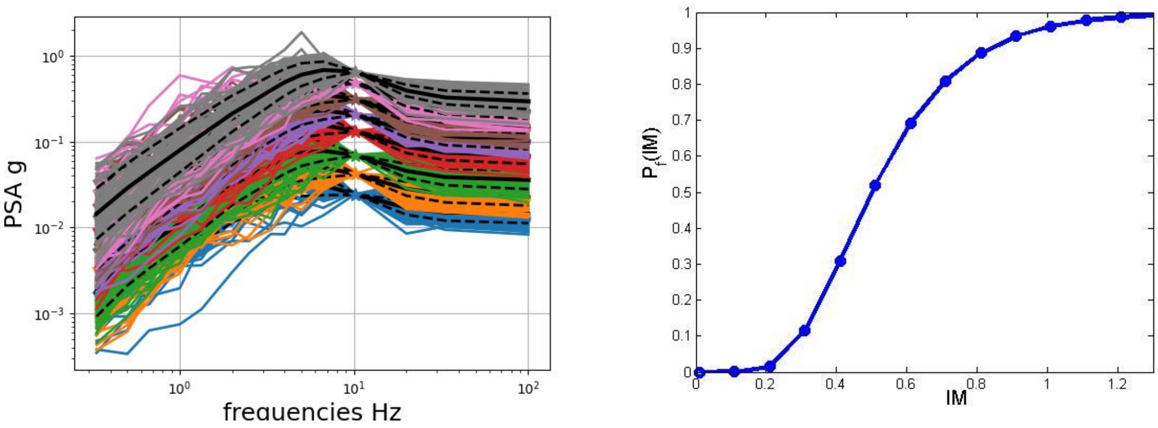


Figure 3: Set of CS simulated according to the hazard-consistent decomposition, mean values are solid black lines and ±1sigma curves are dashed black lines (left) and failure probabilities computed for the conditioning levels (right) – figures for illustration only.

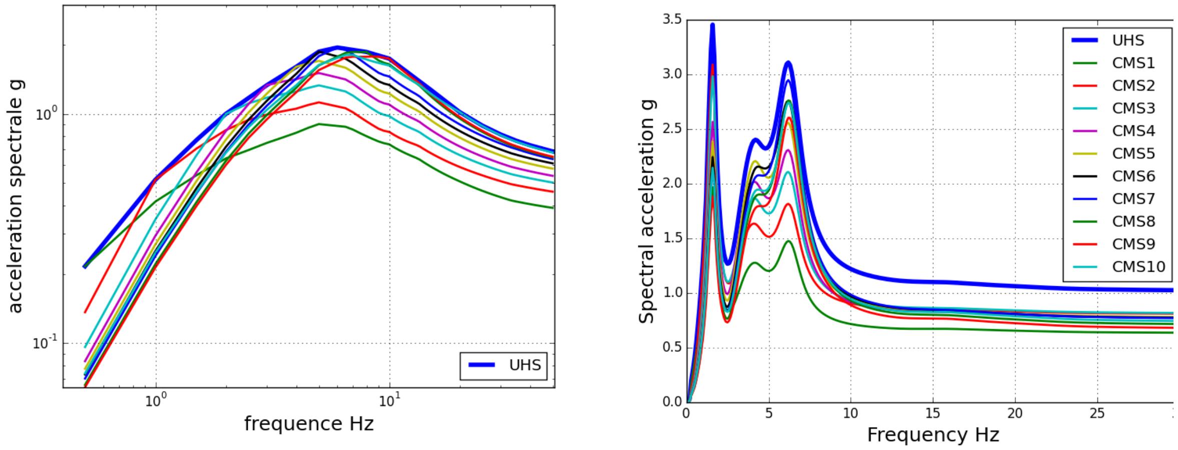


Figure 4 Set of CMS together with enveloping UHS (left) and corresponding conditional floor spectra and UHS-based floor spectrum (right)

EXAMPLE APPLICATION OF CMS TO FLOOR SPECTRA COMPUTATION

For this illustrative example we compute floor spectra using the RVT approach (Zentner, 2018) together with the conditional spectra for computing the floor spectra for a reactor building including 1D site effects and SSI. This case study is described with more detail in Zentner et al (2020). It is not necessary to perform conversion from PSD to response spectra or vice versa at ground surface level.

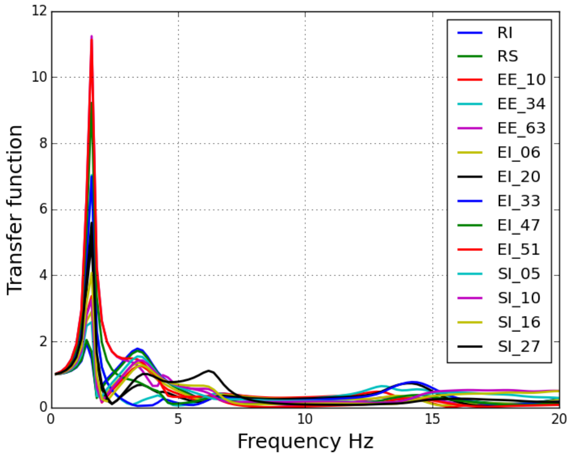


Figure 5 Transfer functions for simplified reactor building with reference soil profile

Here we used CMS together with RVT to determine conditional seismic motion at bedrock level. The latter is driven through soil columns using the classical equivalent linear approach to determine seismic motion on ground surface and strain dependant soil profiles which are the input for soil-structure interaction analyses.

We consider a reactor building represented by a stick model. It represents the external confinement (EE), the internal confinement (EI) and the internal structures (SI)). The reactor building is supposed to have superficial foundation resting on a layered soil profile. With this input, the FEM-BEM SSI analysis are conducted to obtain peak displacements and floor response spectra (internal structure). The locations for post-processing are located at different floor levels of EE -enceinte externe), EI (enceinte interne) and SI (Structure Interne). The transfer functions are shown on **Figure 5**. The output of the analyses are the peak responses at different levels of the building as well as floor spectra. The 10 conditioning frequencies used for the definition of the CMS are 0.5Hz, 1Hz, 2Hz, 3Hz, 4Hz, 5Hz, 6Hz, 8Hz, 10Hz, 20Hz The UHS target spectrum together with the 10 CMS are shown in **Figure 4 (left)** and the corresponding conditional PSD identified by RVT are shown in **Figure 6**.

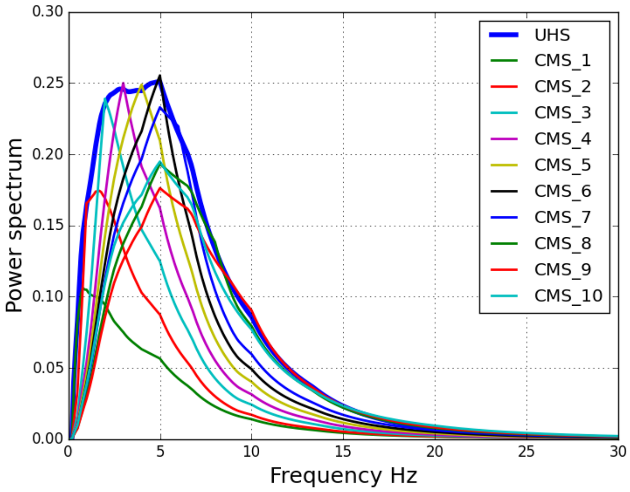


Figure 6: Power Spectral Densities on bedrock determined from target UHS (thick blue line) and CMS anchored at 10 different frequencies (thin lines), the respective UHS and CMS are shown on **Figure 4** (left)

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Table 1 – Peak acceleration (g) at different locations for UHS-based analysis and peak values from CMS. Also shown in column 4 is the conditioning frequency of the CMS that led to the peak acceleration.

Location	**UHS**	**CMS**		**Margin**
	ZPA g	**ZPA g**	**Cond. Freq Hz**	
Lower basemat (RI)	0.79	0.68	4	13%
Upper basemat (RS)	0.77	0.67	4	14%
EE_10	0.76	0.60	2	20%
EE_34	1.00	0.85	1	14%
EE_63	1.58	1.36	2	14%
EI_06	0.74	0.60	4	19%
EI_20	0.80	0.68	1	16%
EI_33	0.97	0.84	1	14%
EI_47	1.24	1.07	1	14%
EI_51	1.53	1.33	2	13%
SI_05	0.78	0.65	4	16%
SI_10	0.80	0.65	4	18%
SI_16	0.84	0.68	2	20%
SI_27	1.01	0.81	2	20%

In agreement with Kempton & Steward (2006), the median strong motion duration of the time histories was chosen as T=10s. For simplicity's sake, only horizontal excitation is considered for the structural analysis. Results with the CMS approach are compared to the more common approach where the UHS is used to define the ground motion for engineering analysis.

The CMS approach leads to reductions of around 10% for the max displacement and from 13% up to 20% for the max acceleration as illustrated in the **table 1**.

CONCLUSIONS

The implementation of conditional spectra allowing to decompose the UHS into a series of target spectra constitutes a promising approach for more realistic ground motion and for improving risk assessment.

In this paper, we discuss different ways to decompose the target UHS and possible benefits for seismic assessment of nuclear installations. More research and applications are required to fully benefit from recent advances in the definition of scenario spectra in the nuclear sector. This part of the high-level objectives of METIS project (https://metis-h2020.eu/).

Here we highlight how the RVT can be used together with the conditional spectra for an integrated approach for seismic response analysis. This approach allows for the computation of floor and equipment responses in the framework of an integrated approach, where the spectra are transferred from bedrock to floor level. The case study conducted here highlighted margins of around 10% for peak displacement and peak acceleration when considering the CMS instead of the UHS to describe seismic excitation.

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