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AN INTEGRATED APPROACH FOR THE TRANSFER OF SEISMIC LOAD FROM BEDRCOK TO THE STRUCTURE BASED ON RVT AND CMS

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Abstract

This paper proposes to develop an integrated approach to determine floor spectra and demand parameters combining the conditional spectra approach to the so-called random vibration theory (RVT). The approach allows for the evaluation of floor spectra, including SSI and 1D site effect. More precisely, the RVT allows for the transformation of response spectra into Power Spectral Densities (PSD) and vice versa. This is why it is suitable for the development of an integrated approach where response spectra at bedrock are converted to PSD and then transferred to the ground surface and to the structure and its equipment without conversion to response spectra at the intermediate steps. The ground motion to be considered is defined by a Uniform Hazard Spectrum (UHS), evaluated for a certain return period. 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 the response spectrum of recorded (scenario) ground motion does not reach UHS level at all frequencies for one earthquake. The conditional spectra approach allows for the decomposition of the UHS in a set of conditional mean spectra (CMS) such that the UHS is the envelope of the set of CMS. The CMS can then be conveniently used together with RVT to determine conditional PSD at bedrock level. The latter are driven through soil columns to determine PSD of seismic load on ground surface which is used as input for soil-structure interaction analyses. The output of the analyses are to peak responses at different levels of the building as well as floor spectra. A key for the successful implementation of RVT is the definition of the equivalent stationary duration, a topic that will be discussed thoroughly in this work. This approach is applied here to a NPP containment building. The new analysis procedure allowed for margins around 15% on floor spectra and peak floor displacement.

Keywords: Random vibration theory; floor spectra; conditional mean spectrum; NPP

1. Introduction

The so-called random vibration theory (RVT) allows to establish a like tween the standard-deviation (std) and the statistics of its peak values (maxima) of a stochastic process observed on a given time interval. The underlying hypothesis is that one deals with a Gaussian stationary process. This allows for taking advantage of the fact that any linear transformation of a Gaussian stochastic process yields a Gaussian stochastic process. This topic is more generally known also as the first crossing problem. It has been studied in the literature since the late 60ies by various authors (e.g.[3,17, 18]). The RVT is currently used in engineering in various domains where random processes are involved: wind engineering, earthquake engineering, ocean… It has been used as early as in the 70ies to generate spectrum compatible ground motion (SMQKE developed by Vanmarcke and co-workers). The tools provided by RVT are also used or the introduction of site effect in Probabilistic Seismic Hazard Analysis (PSHA) [11,15]. Eventually, the RVT approach constitutes an interesting alternative to the modal combination rules currently used in seismic engineering. Indeed, given today's computational capabilities, there is no need for approximate modal combinations to compute response quantities. The main computational cost is linked to the computation of the eigenvalues. The computation of modal responses and subsequent projection on physical coordinates are of minor cost and are performed by any FEM code. The RVT-stochastic dynamics approach has the advantage that not only peak responses but the whole (floor) response spectrum is obtained. In contrast to time history analysis, only one analysis is required to obtain the floor spectra.

The RVT approach it allows for the transfer of spectra from bedrock to soil surface, from soil surface to the structure and to the equipment. It is suitable for the development of an integrated approach where response spectra at bedrock are converted to PSD and then transferred to the structure without conversion to response spectra at the intermediate steps.

More generally, the advantages of RVT over time history analysis are

- only one structural analysis required to obtain response statistics, input ground motion variability is accounted for (in the framework of the underlying hypothesis (Gaussian process)
- no need to select or generate ground motion time histories

The conditional spectra approach can be conveniently used together with RVT for the computation of floor response spectra in an integrated approach accounting for uncertainty. For this purpose, the UHS is decomposed in a set of conditional mean spectra (CMS) as shown in Figure 21. The UHS is the envelope of the set of CMS. This procedure is an integrated approach in the sense that the soil surface PSD resulting from 1D site effect analysis is directly used as input for SSI analysis. There is no transfer or conversion to response spectrum necessary at this stage. There are no further approximations due the evaluation and application of site amplification factors. It is then also possible to generate 3 correlated components of time histories from the PSD determined at floor level that can be used for (nonlinear) equipment response analyses.

To simplify the analysis and focus on the overall approach, we neglect uncertainties related to the soil profile. Uncertainties in soil and structure shall be considered in further studies. When considering uncertainty related to the soil profile, then one RVT analysis has to be performed per soil profile.

In what follows we give some general concepts and definitions of the quantities used in this report. We then apply the methodology for the computation of floor spectra in an integrated approach.

2. Framework of RVT for site and structural response

The tools provided by RVT allow for:

- determining a PSD in agreement with a given response spectrum by means of the Vanmarcke formula [19],

- the calculation of the response spectrum from a given PSD
- the evaluation of peak response quantities

More details and equations are given [21].

One key element for the application of RVT is the definition of the duration. We consider acceleration time histories $\ddot{x}(t),\ t \in [0, T_d]$, where T_d is the total duration of the non stationary time history. We need to define the strong motion duration where the time histories are considered as stationary signals and during which the peak values are expected to occur. The Arias-intensity based definition of strong motion duration is adopted here for this purpose. More precisely, the strong motion duration T is the interval between 5% and 95% of Arias intensity of the signal: $I_a = \frac{\pi}{2g}\int_0^{T_d} \ddot{x}(t)^2 dt$.

The RVT can also be used to obtain response spectra at different damping levels by determining the response spectra at different damping values from the spectrum-compatible PSD. As a check, we assessed the capability of the methodology to correctly represent different damping ratios for the ideal case where a Gaussian process is considered. For this purpose a set of 50 ground motion time histories generated from the Kanai Tajimi PSD using code_aster. The Jennings and Housner modulating function parameterized to yield a strong ground motion duration (defined as 5% and 95% of Arias intensity) of 10s is applied. Since we consider a Gaussian stochastic process, the theory of RVT applies. We then compute the mean of the response spectra for different damping ratios (1%, 2%, 5%, 10% and 30%). The 5% spectrum is the target spectrum to which RVT is applied in order to determine the corresponding PSD. Then the inverse RVT approach is used to determine response spectra at 1%, 2%, 5%, 10% and 30% damping ratio. The latter are compared to the reference value in Fig.1. The results fit well.

The RVT soil-column analysis can be used to determine the strain dependant soil profiles used in the framework of the linear equivalent approach. Instead of distinct time histories, the ground motion is defined by its response spectrum. The latter is transformed into an equivalent PSD. Let us consider $S_X(\omega) \in \mathcal{R}$, the scalar PSD of the outcropping bedrock motion, $h(\omega)$ is the complex transfer function and $S_Y(\omega) \in \mathcal{R}$ is the surface motion PSD:

$$S_Y(\omega) = |h(\omega)|^2 S_X(\omega) \quad (1)$$

Instead of computing the response time histories we have to calculate:

$$\sqrt{S_Y(\omega)} = |h(\omega)|\sqrt{S_X(\omega)} \quad (2)$$

where $|h(\omega)|$ is the amplitude of the transfer function. The response spectra and peak strains in the layers are then evaluated by using the RVT tools described in Zentner (2018). The RVT-based soil column analysis has been implemented in code_aster. The PSD obtained at ground surface level are then used in the soil-structure interaction (SSI) analyses to compute PSD and response spectra at floor level. This is carried out using the FEM-BEM approach available with code_aster.

If uncertainty of structure or soil profiles has to be accounted for, then the RVT approach requires on analysis per structure or soil profiles. This can be obtained by random sampling and in particular Latin Hypercube Sampling (LHS), where the latter allows to reduce the number of required analysis. The RVT based transfer of spectra does account for aleatory (peak-to-valley) variability of the input ground motion. The RVT provides median peak responses together with confidence intervals. The variability of the input motion is the one of the assumed stochastic process defined by the PSD identified from the response spectrum. The standard-deviation of the stochastic process is given by the square root of the integral of the PSD function. The RVT approach is based on linear filtering in the frequency domain. In consequence, it is not possible to account for nonlinear structural or soil behaviour.

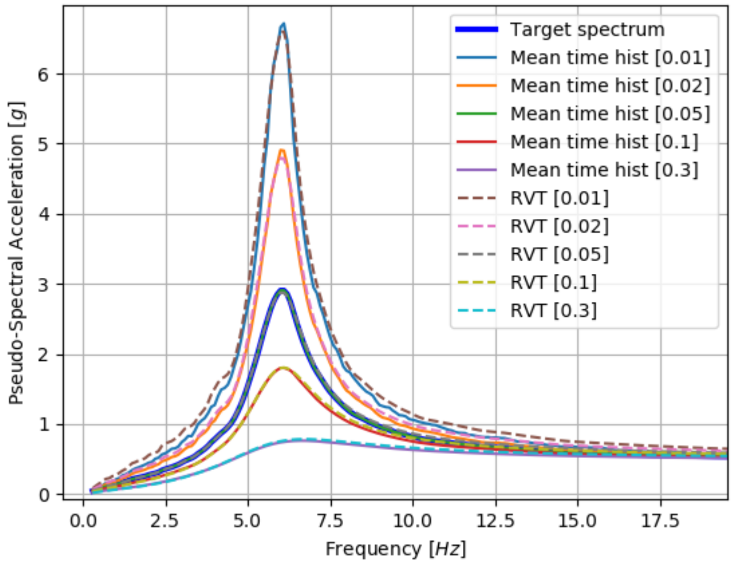

Fig. 1 – Comparison of spectra obtained for different damping ratios by RVT with the target spectra.

The method can, however, be extended to nonlinear soil and structures by assuming linear equivalent model. Linear equivalent approaches are quite common for soil. Equivalent linear structural analyses are proposed e.g. in [8]. In this reference, nonlinear behaviour of structure and associated damping are estimated from Nonlinear Static Pushover Analysis. Another approach to this issue makes use of stochastic linearization such as proposed in [6].

2. Application to a simple study case

For this feasibility analysis we consider a very simple PSHA model representing mainly the NCOE event. It includes one near fault source with Rrup = 16km, RJB = 0 and δ=36°. The engineering bedrock shear wave velocity Vs =720m/s is used as outcropping bedrock condition. Moreover, only one GMPE model, Campbell & Bozorgnia 2008 [1], is used. The design target UHS is defined on "engineering" bedrock for a 20 000 years return period (Figure 1). The 10 conditioning frequencies used for the definition of the CMS 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 (the magnitude of NCOE was indeed Mw=6.6). The UHS target spectrum together with the 10 CMS are shown in Figure 1. In agreement with [10], the median strong motion duration of the time histories was chosen as T=10s. The soil column is the one assumed for unit 5 of the Kashiwazaki-Kariwa (KK) nuclear power plant in the Karisma benchmark where the upper sand layers are removed.

Figure 2 shows the initial (low-strain) properties of the soil profile. These data were provided in the Karisma benchmark (IAEA, 2014) together with the G/Gmax and D curves. The bedrock level is assumed at -167m with respect to ground surface level.

Attitude T.M.S.L. (m)	Geological Layer	Soil type (Sand, clay or rock)	Shear Wave Velocity Vs (m/s)	Primary Wave Velocity Vp (m/s)	Unit Weight γ (kN/m3)	Poisson's Ratio ν	Elastic Shear Modulus G0 (kN/m2)
(+12.0)	Sand	Sand	150	310	16.1	0.347	36 000
+8.0		Sand	200	380	16.1	0.308	65 700
+4.0	Yasuda	Clay	330	1240	17.3	0.462	192 000
-6.0	Nishiyama	Rock	490	1640	17.0	0.451	416 000
-33.0		Rock	530	1700	16.6	0.446	475 000
-90.0		Rock	590	1710	17.3	0.432	614 000
-136.0		Rock	650	1790	19.3	0.424	832 000
-155.0 The free surface of ∞	Nishiyama	Rock	720	1900	19.9	0.416	1 050 000

Fig. 2 – Low strain soil profile

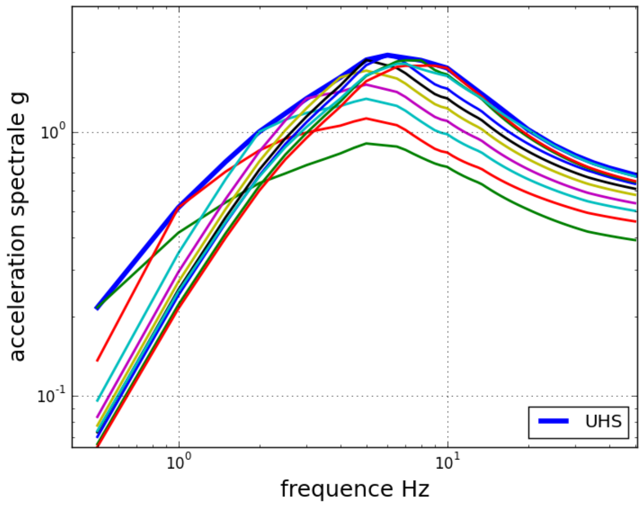

Fig. 3 – Target UHS (thick blue line) and CMS anchored at 10 different frequencies (thin lines).

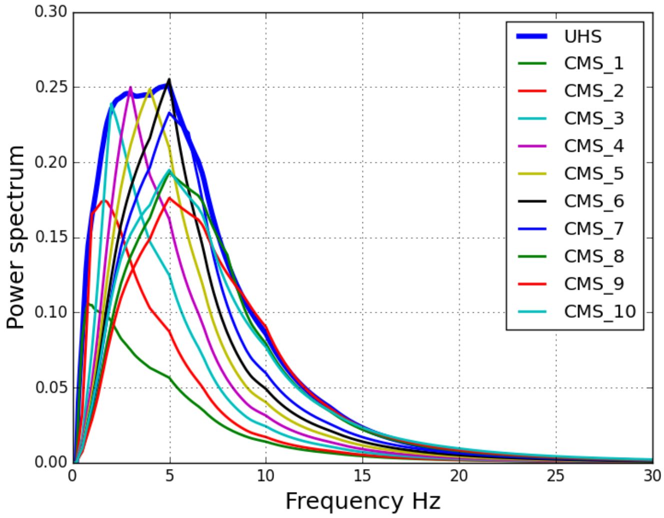

Fig. 4 – Power Spectral Densities on bedrock.

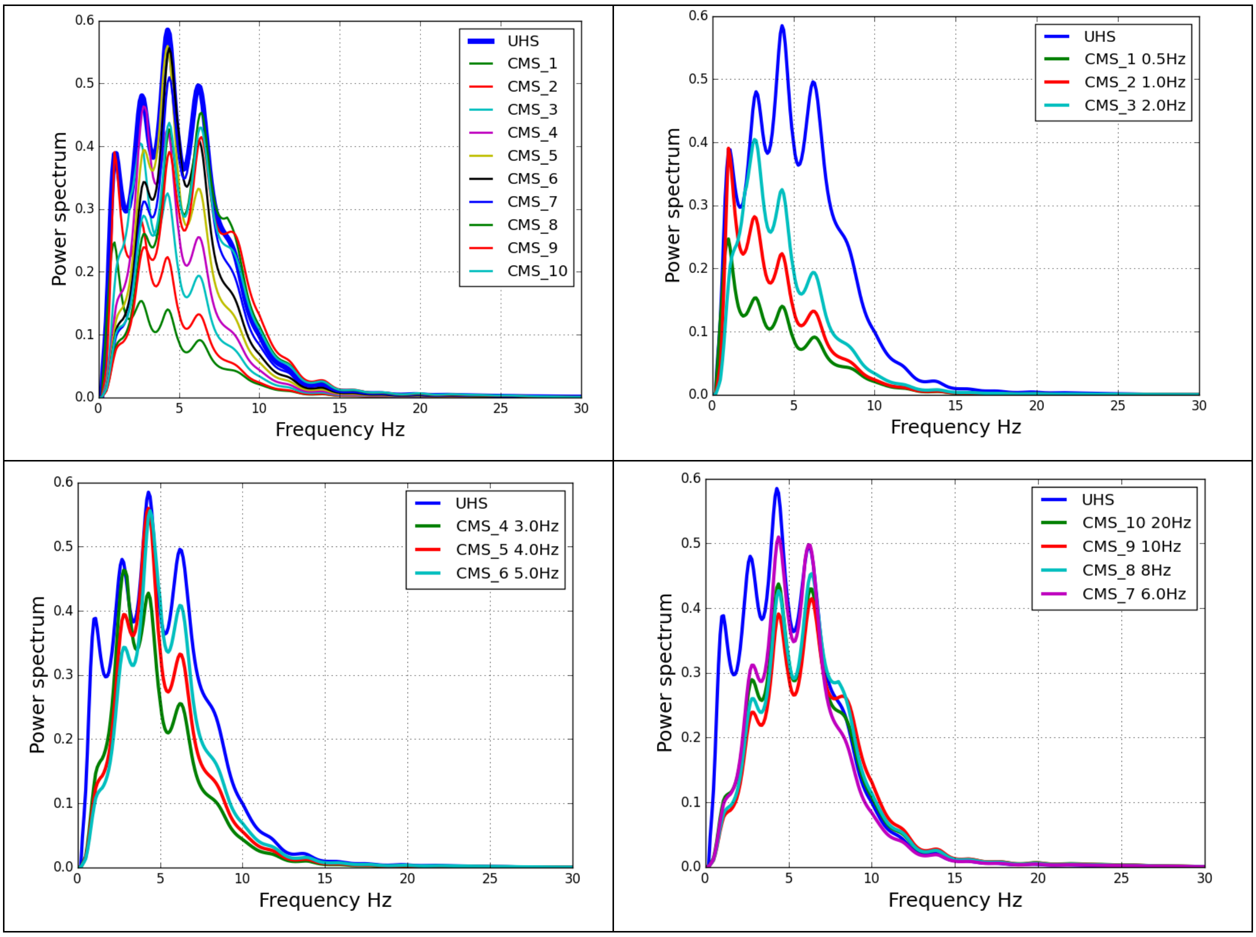

Fig. 5 – PSD at free surface obtained by 1D site response analysis from UHS and 10 CMS (upper left) and extracts: UHS and 3 lower frequency CMS (upper right), UHS and 3 mid-frequency CMS (lower right), UHS and 4 higher frequency CMS (lower right)

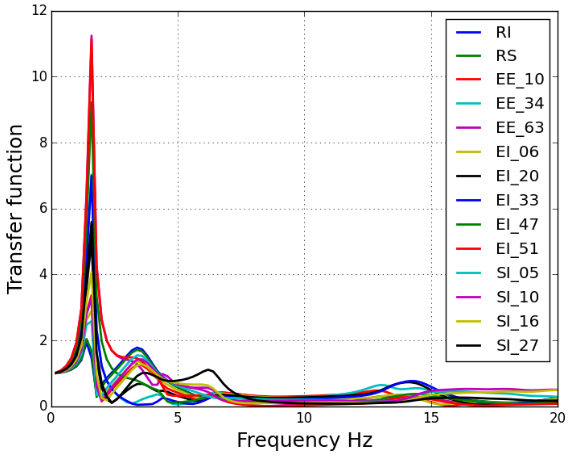

Fig. 6 – Transfer functions for simplified reactor building with reference soil profile

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 analysis are conducted in the frequency range 0-50Hz. Fig.3 shows the set of PSD identified from the response spectra at bedrock level (UHS and CMS). Fig.4 shows the respective PSD on ground surface (CL) obtained by 1D equivalent linear site response.

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). It is supposed to have superficial foundation resting on the modified KK-soil profile. With this input, the FEM-BEM SSI analysis are conducted in order 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). For example, « EE_63 » designs the floor at 63 m of EE. Fig.6 shows the transfer functions between the floor response and the seismic excitation on ground surface (free field). The Tab.1 and Tab.2 compare the maximum relative displacements and absolute accelerations of the UHS approach to the CMS. For the CMS, the tables provide both the maximum value of the 10 CMS and the anchoring frequency. The CMS approach leads to reductions of around 10% for the max displacement and from 13% up to 20% for the max acceleration. In Fig.7, the floor response spectra obtained with UHS input (thick blue line) and the set of CMS is shown for the lower basemat (RI) and different levels of the external and internal confinement and the internal structures (EE10, EI06 SI24).

Table 1 – Relative maximal displacement (DMAX) (m) at different locations for UHS, margin and max value from CMS, the maxima occurred at conditioning frequency 1Hz.

Location	UHS	CMS		Margin
	DMAX m	DMAX m	Cond. Freq Hz	
Upper basemat (RS)	0.096	0.084	1	12%
EE_10	0.861	0.760	1	12%
EE_34	2.473	2.183	1	12%
EE_63	4.038	3.634	1	10%
EI_06	0.651	0.574	1	12%
EI_20	1.612	1.426	1	12%
EI_33	2.470	2.176	1	12%
EI_47	3.247	2.900	1	11%
EI_51	3.978	3.584	1	10%
SI_05	0.495	0.439	1	11%
SI_10	0.795	0.704	1	11%
SI_16	1.157	1.024	1	11%
SI_27	1.833	1.619	1	12%

Table 1 – Peak acceleration (g) at different locations for UHS and max value from CMS.

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%

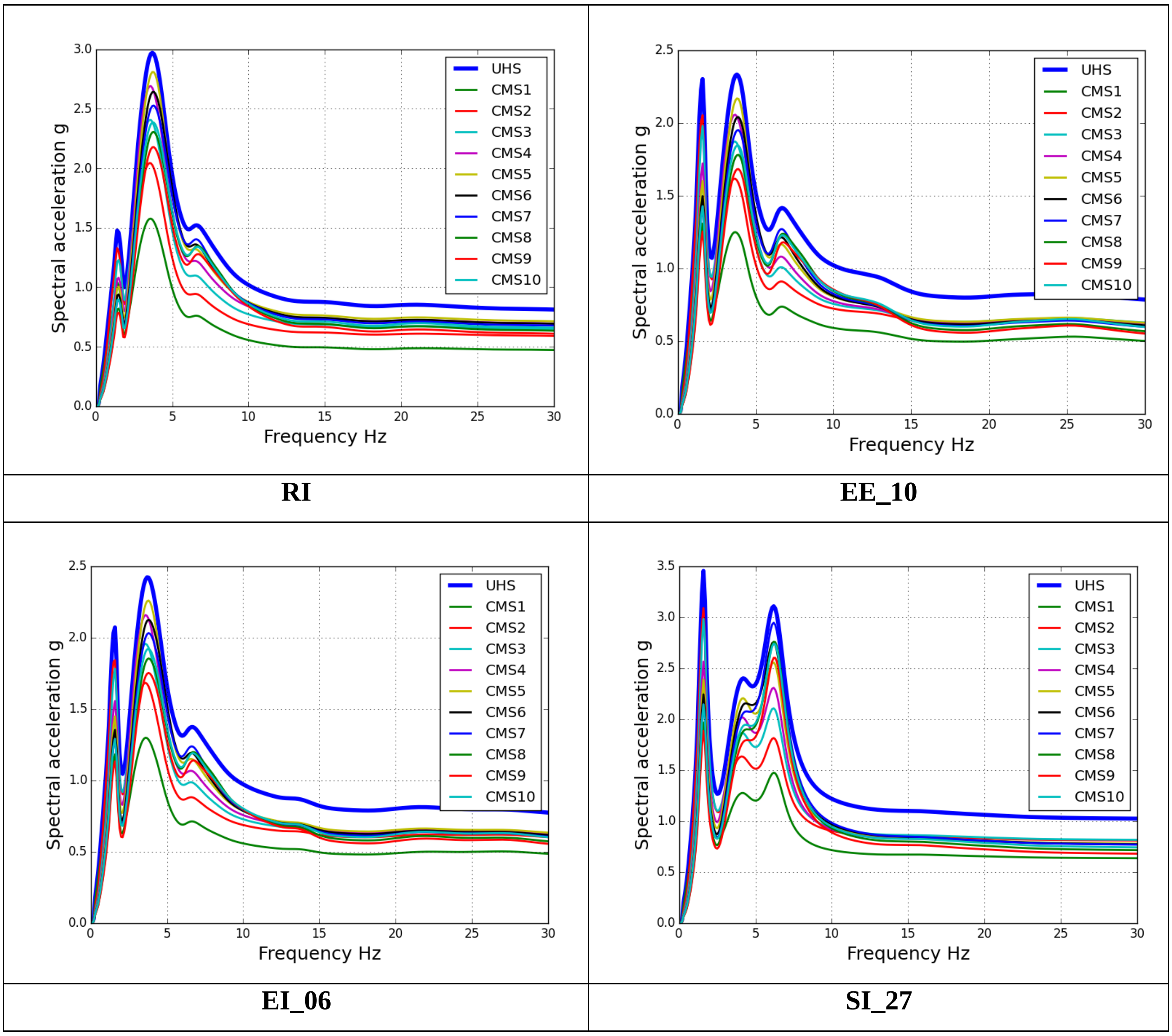

Fig. 7 – Floor spectra at 4 different locations from UHS and CMS bedrock motion

3. Discussion and conclusions

The goal of this work was to highlight how the RVT can be used together with the conditional spectra for an integrated approach for seismic response analysis of industrial installations. It has been shown that the RVT approach allows for addressing multi-modal behaviour and can be used to evaluate response spectra at different damping values. Differences between time history and RVT based site response reported in literature seem to be often rather due to discrepancies between the time histories selected for the soil column analysis and the input response spectrum as well as inadequate assumptions in the RVT approach (definition of signal duration, spectral content, computation of peak factor).

The RVT approach allows for aleatory peak-to-valley variability (according to the underlying assumptions of the RVT approach) of ground motion. The respective confidence intervals can be computed thanks to the peak factor by choosing appropriate parameter values. The RVT approach does indeed provide a full (even if approximate, see section 1) statistical description of the distribution of the maximum (median and quantiles).

Combined with the conditional spectra approach, it 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. It is not necessary to perform conversion from PSD to response spectra or vice versa at ground surface 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.

4. Acknowledgements

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5. Copyrights

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