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DESIGN RESPONSE SPECTRA FOR VERY HARD ROCK BASED IN SWISS SITE-SPECIFIC SEISMIC HAZARD MODEL

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Abstract

Very hard rock sites (V_{S30}> 2500 m/s) can be found in Switzerland, as suggested at some sites from the site-specific seismic hazard assessment of the PEGASO Refinement Project (PRP). Design spectra for engineering practice for such sites are currently not developed. The main impediment of such development is perhaps the lack of observed strong motion data for such as conditions and for relevant earthquake magnitudes (>5). Consequently, the use of observed data for this task is not possible. A good alternative is to rely on synthetic seismograms. In this paper we developed a generic design response spectrum for very hard rock (V_{S30}=2500-3500m/s) based on synthetic seismograms simulated by the stochastic model of Boore (2003) and constrained by the controlling magnitude and distance events derived from the deaggregation of the computed probabilistic seismic hazard assessment (PSHA) of the PRP. The synthetic earthquake scenarios cover magnitude M_W=4.5-7.5, source-site distance 5-100 km and kappa (κ) factor 0.002-0.02 s. The high frequency covered by the proposed normalized design spectra is more or less similar to the Eurocode 8 for hard rock type 2, but amplitude of the spectral plateau is about 8% lower than the Eurocode 8 and also covers a wider high frequency range. The comparison with available data from the NGA-East database for V_{S30}~2000 m/s shows that the proposed spectrum fills the lack of observed data for magnitude larger than 5 and V_{S30} larger than 2000 m/s and consistently cover the observed high frequency region. The application of the proposed design spectrum can be generalized to be used in low to moderate seismic regions in Europe.

Keywords: Design spectra, Very hard rock, Seismic hazard assessment, High frequency ground motion simulation

1. Introduction

Contrary to UHS, design spectra are routinely used in engineering practice, but those design spectra for very hard rock sites are currently not developed in Switzerland and to our knowledge worldwide. The main feature of such type of spectra is the high frequency content, which is not explicitly considered in standard design spectra. The importance for considering high-frequency energy content is because the possibility of affecting components and equipment of critical structures, such as power plants, chemical plants, hospital and others. This issue has been earlier posted in the literature (e.g. [1]) and currently the subject has again been a matter of investigation in the USA to investigate the high-frequency excitations in seismic input to structures, systems and components. For that purpose, the Electric Power Research Institute (EPRI) conducted the High Frequency Program [2, 3, 4] in which shaking table testing on components are performed for seismic risk assessment of nuclear installations. This program does not deal with the consequences of high-frequency content in ground motions, but simply addresses the fact that on certain ground conditions high-frequencies are present in the input motion.

In order to address this issue, a generic design spectrum for very hard rock (characterized by shear-wave velocity from 2000 m/s to 3500 m/s) consistent with low to moderate seismicity area, as it is in Switzerland, is proposed here. But the development of such spectra poses a serious issue; there are no observed strong motion data or they are sparse for all magnitudes and distance, in particular for magnitudes M > 5 and distance to the source 0 – 100 km for stable continents. Consequently, the use of observed data for this task is not possible. A good alternative for spectra developments is to rely on synthetic seismograms. For that purpose, we use the stochastic model of Boore [5]. This model is widely used to predict ground motion accelerations for regions lack of recorded data from damaging earthquakes [e.g. 6, 7].

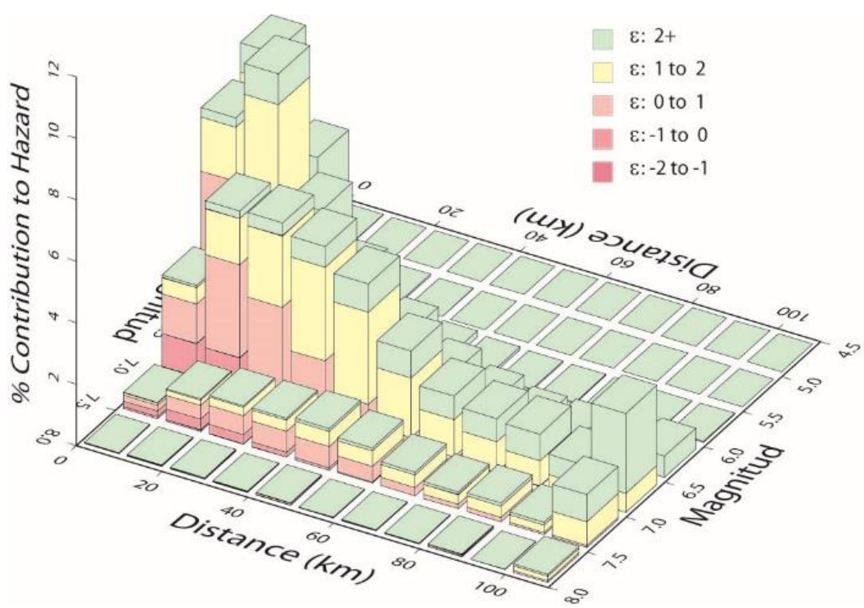

Fig. 1. Deaggregation of controlling magnitude-distance events from the PRP for an annual exceedance probability of 1E-4 at 8 Hz. This frequency has been used as reference values, as it is representative for the geometric mean of 2.5 – 25 Hz, which is the frequency range of engineering relevance.

The controlling magnitude and distance events from the deaggregation (Fig. 1) of the Swiss site-specific PEGASOS Refinement Project (PRP) model [8,9] is used as constraint to the development of the design spectra. Therefore, these controlling events are used as guidance to model earthquake scenarios at the controlling magnitudes and to calculate spectral response accelerations for 5% damping at the controlling distances, as the distribution is typical for low seismicity regions. The generic site itself is characterized by a set of kappa (κ) factor values (parameters that control the spectral acceleration decay at high frequencies) from 0.002 to 0.02 s, which is appropriate for hard rock [e.g. 10, 11, 12] and shear wave velocity (defined as V_{S30}) of 2000, 3000 and 3500 m/s. Each response spectrum is normalized with respect to the peak ground acceleration (PGA) and then, a normalized mean response spectrum is calculated using the probabilistic density functions provided by the PRP project. The construction of the design response spectrum shape is based on the mean spectrum and follows the method presented by Newmark and Hall [13, 14] that defines the spectrum in piecewise-linear regions: acceleration, velocity and displacements, respectively, for high, intermediate and low frequencies regions. A sensitive study of the effects of magnitude, distance, V_{S30} and kappa on the mean spectrum is carried out to evaluate the main controlling parameters. Finally, we present three hard rock design spectra for three combinations of kappa distribution and compare them with the current Eurocode 8 spectra.

2. Set of synthetic response spectra

As mentioned before, there are no observed strong ground motion records on very hard rock (2000 – 3500 m/s). To fill this lack of data, we have simulated a set of synthetic response spectra using the well know stochastic method of Boore [5, 15] assuming a point source and characterized by the ω-square model introduced by Aki [16] with a corner frequency defined by Brune [17]. The stochastic point-source model for strong ground motion simulation was originally developed by Hanks and McGuire [18] and refined by Boore [5, 15]. It has been validated in a comprehensive manner in diverse tectonic environments and is currently very useful for simulating high frequency ground motions [e.g. 6, 7], which are basically random [15]. Though finite-fault simulations that include the rupture process and wave propagations effects would me more realistic [e.g. 19], our target is very high frequency, in which waves are highly incoherent and the source and propagation are poorly understood, then point-source stochastic models are well justified for this purpose.

Guided by the controlling magnitude and distance events obtained from the deaggregation (Fig. 1) of the PSHA of the PRP project, a set of earthquake magnitude-distance scenarios M_W=4.5, 5, 5.5, 6, 6.5, 7, 7.5 and R=5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 km has been considered. The generic site is characterized by V_{S30} and kappa (κ) parameters. The V_{S30} is the average shear-wave velocity between 0 and 30 meters depth. It is widely used as proxy to describe the shallow site profile and for seismic amplification calculations. For generic very hard rocks we assume values of 2000, 3000 and 3500 m/s. The spectral decay factor kappa (κ), introduced by Anderson and Hough [20], controls the Fourier spectral acceleration decay at high frequency. Though the approach to estimate and quantify this parameter as well as its physical interpretation is still in debate in the seismology community, it is a crucial input parameter for describing the high frequency in ground motion simulation. Several authors proposed values for very hard rock that fluctuate from 0.002 to 0.02 s [e.g. 10, 11, 12] being predominate for the lowest values. In this study values of 0.002, 0.006, 0.01, 0.02 s are used.

Fig. 2 shows results of a suite of simulated response spectra for all the combined scenarios M, R, V_{S30} and κ. Overall, a total of 924 synthetic data has been generated in a frequency range of 0.1 to 500 Hz. The left hand side of Fig. 2 corresponds to the absolute values of the response spectra and right side is the response spectra normalized with respect to the peak ground acceleration (PGA) at 1 g.

3. Spectra mean calculations and parameter analysis of M, R, V_{S30} and κ

To evaluate statistical expectation from the synthetic data shown in Fig. 2, weights for each parameter (M, R, V_{S30} and κ) need to be assumed, then ensemble mean can be calculated. For the M and R bins (here the used values are considered as representative for bin centers), weights are estimated from the approximation of the probability density functions derived from the PRP project (Fig. 3a, b). Of course any other (more complex) shape of the probability density function could be also justified, but the chosen one is appropriate and broad enough for the development of a generic spectrum. For V_{S30}, a uniform distribution has been assumed, that is, weights are the same for the three values (Fig. 3c). For kappa (κ), three combinations of weight distribution have been considered, assigned as κ-model 1, κ-model 2 and κ-model 3 in Fig. 3d. The reason for considering three distributions for κ is because we do not have a reliable constraint to define weights and the definitions of it may vary substantially between authors [e.g. 12] for very hard rock. For example, if we put too much weight for the lowest value we may introduce too much high frequency content in the resulted response spectra, and vice versa.

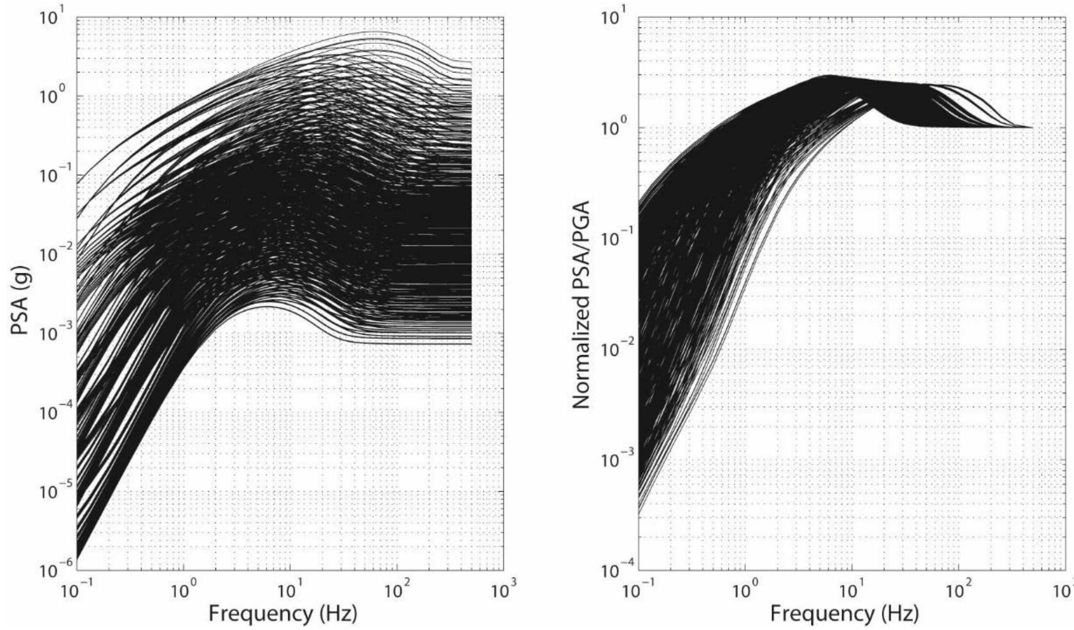

Fig. 2. Response spectra from 924 synthetic seismograms. Left side shows absolute values acceleration. Right side shows the acceleration response spectra normalized with respect to PGA at 1 g.

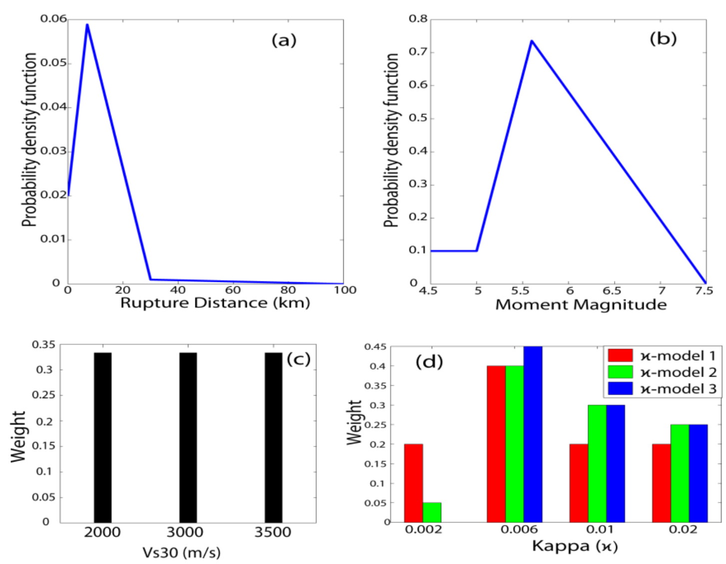

Fig. 3. Probabilistic density function for magnitude M and distance R (top) and weight assignment for V_{S30} and kappa (κ) factor (bottom).

Before developing the design spectra, we first develop a parameter study of M, R, V_{S30} and κ to understand the effects of these parameters and controlling features on the final weighted mean acceleration response spectrum and its mean normalized spectral shape, respectively. For that purpose, we have calculated a final reference mean spectrum considering the probability distributions of M, R and V_{S30} and κ-model 1 distribution only (Fig. 3). This final weighted mean is named as Model 1 because it is linked to the κ-model 1. Then we calculate mean spectrum for each parameter bin (M, R, V_{S30} and κ), that is, for example the mean spectrum for the V_{S30}=2500 m/s would correspond to the mean over all scenarios assuming a weight of one for this V_{S30}, and for the other bins M, R and κ their corresponding distributions shown in Fig. 3. Fig. 4, 5, 6 and 7 show respectively the mean spectra for M, R, V_{S30} and kappa (κ). The left hand side of each Figure corresponds to the absolute values of the mean response spectra and right side are the spectra normalized with respect to the peak ground acceleration (PGA). The red dashed line in all Figures is the reference final mean Model 1 as explained above. The effects of M and R (Fig. 4, 5) are as expected. Magnitude and distance impact the amplitude of the mean spectrum. The magnitude effect on the shape is apparent from the normalized spectrum. The shape visibly deviates starting from around 10 Hz toward lower frequency. Larger magnitude covers larger range of low frequency than smaller magnitude. The distance effect on the normalized shape is also noticeable. As increasing the distance, the shape is shifted toward the lower frequency. The flat area of the PGA starts at around 50 Hz for 100 km distance and at around 300 Hz for the shortest distance (5 km). These results suggest that the definitions of the controlling M–R events to calculate mean spectrum and normalized shape need to be well constrained, from for example seismic hazard assessments, for a reliable representation of spectral design in the area of interest. This evaluation justifies the use of the probabilistic density function from a representative deaggregation of the PRP project, which can be considered as good representation of site-specific PSHA for NPPs in low to moderate seismic regions of Europe, because geographically Switzerland is located in an area between low and moderate seismicity countries. The V_{S30} effects (Fig. 6) is practically negligible on the mean and normalized shape of the spectrum for such high shear-wave velocity values. Though some past studies suggest correlation between kappa and V_{S30} [e.g. 12, 21, 22], as such, the assumption of varying V_{S30} without changing kappa may appear as inconsistent, nevertheless recent observations show that kappa tends to saturate at high V_{S30} [e.g. 23]. Therefore, the assumptions for the sensitivity study of V_{S30} (shown in Fig. 6) are justified by recent studies, beside the large uncertainty observed in the kappa-V_{S30} correlations, see [24] for discussion on it. The kappa effects (Fig. 7) are dominating the high frequency region. The high frequency amplitude of the mean spectrum increases for lower kappa. The normalized shape is shifted toward the low frequency for higher kappa. The flat PGA starts around 60 Hz and 300 Hz respectively for the κ=0.02 s and κ=0.002 s. The definition of κ is therefore fundamental for reliable definition of high frequency regions in the spectral design for generic rock conditions.

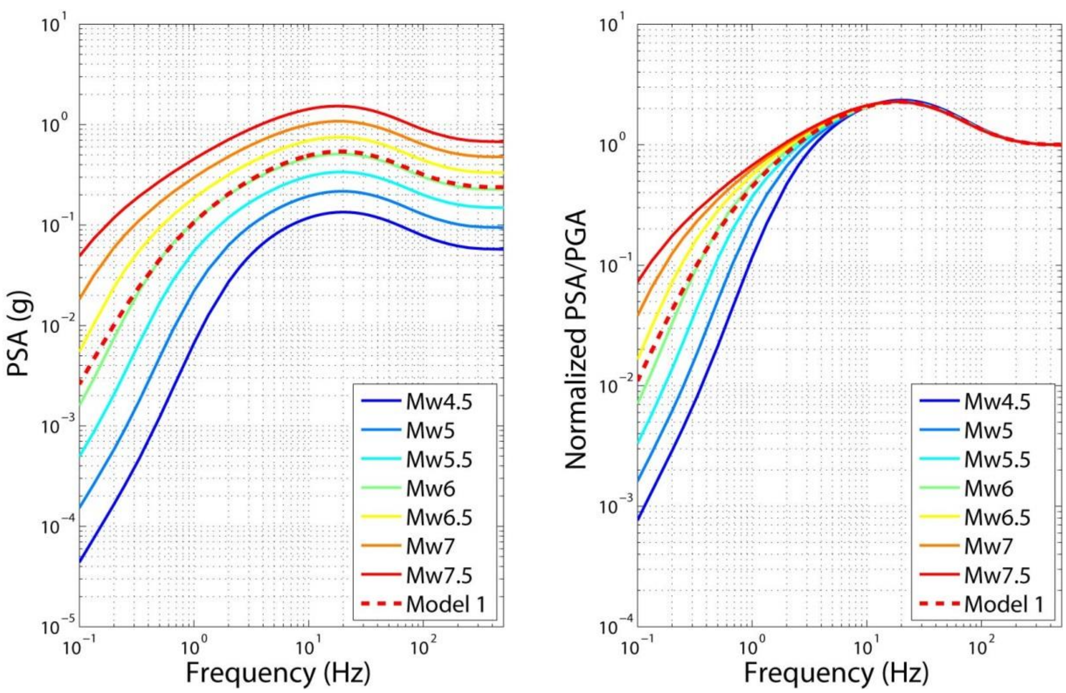

Fig. 4 Mean response spectra (left) and normalized with respect to PGA (right) for magnitude Mw bins. Each Mw bin has a weight of one, the other parameters follow distributions from Fig. 3 and 3d. Red dashed line corresponds to the total mean using kappa Model 1 from Fig. 3d.

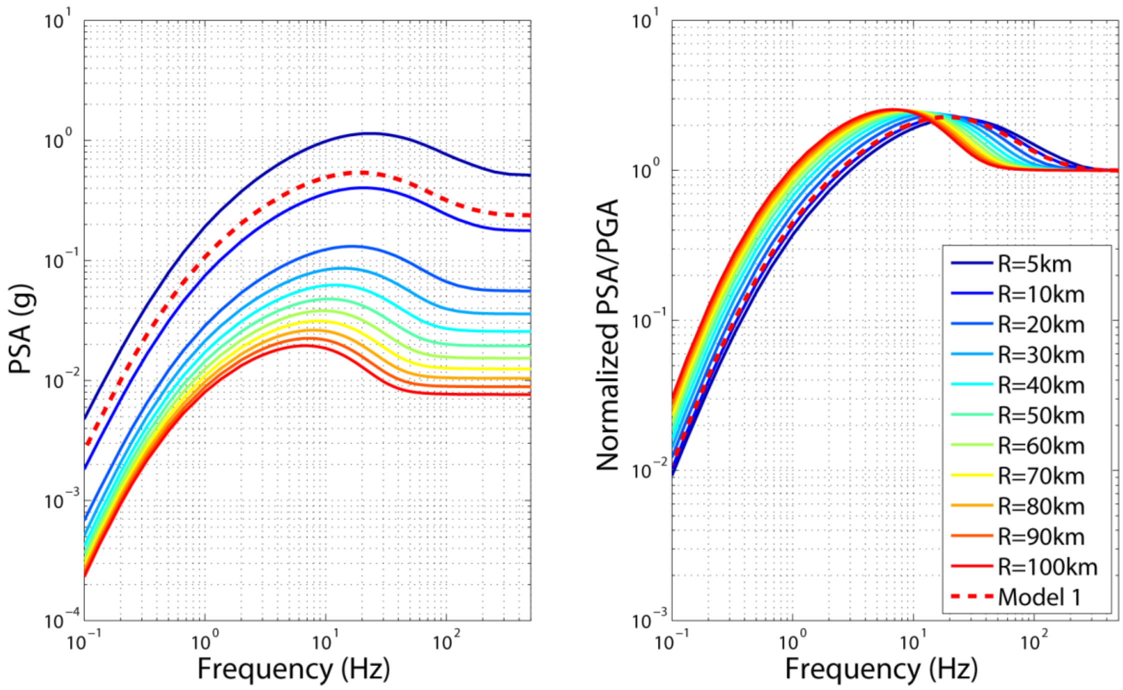

Fig. 5 Mean response spectra (left) and normalized with respect to PGA (right) for distance R bins. Each R bin has a weight of one, the other parameters follow distributions from Fig. 3 and 3d. Red dashed line corresponds to the total mean using kappa Model 1 from Fig. 3d.

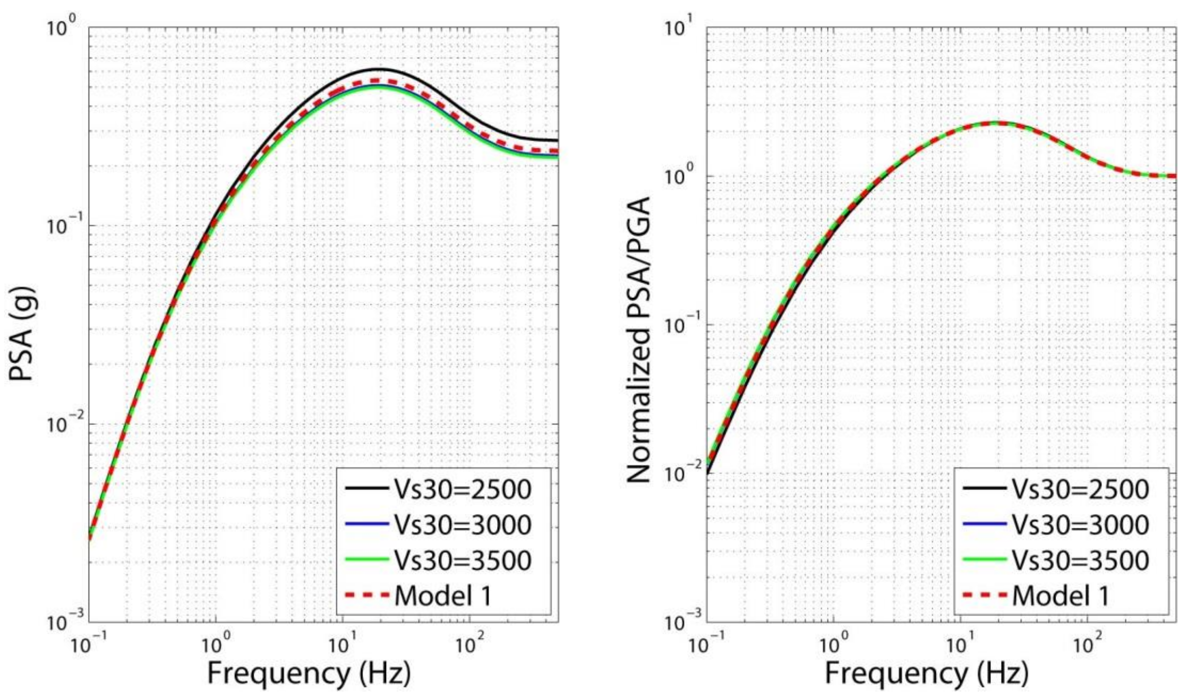

Fig. 6 Mean response spectra (left) and normalized with respect to PGA (right) for V_{S30} bins. Each V_{S30} bin has a weight of one, the other parameters follow distributions from Fig. 3 and 3d. Red dashed line corresponds to the total mean using kappa Model 1 from Fig. 3d.

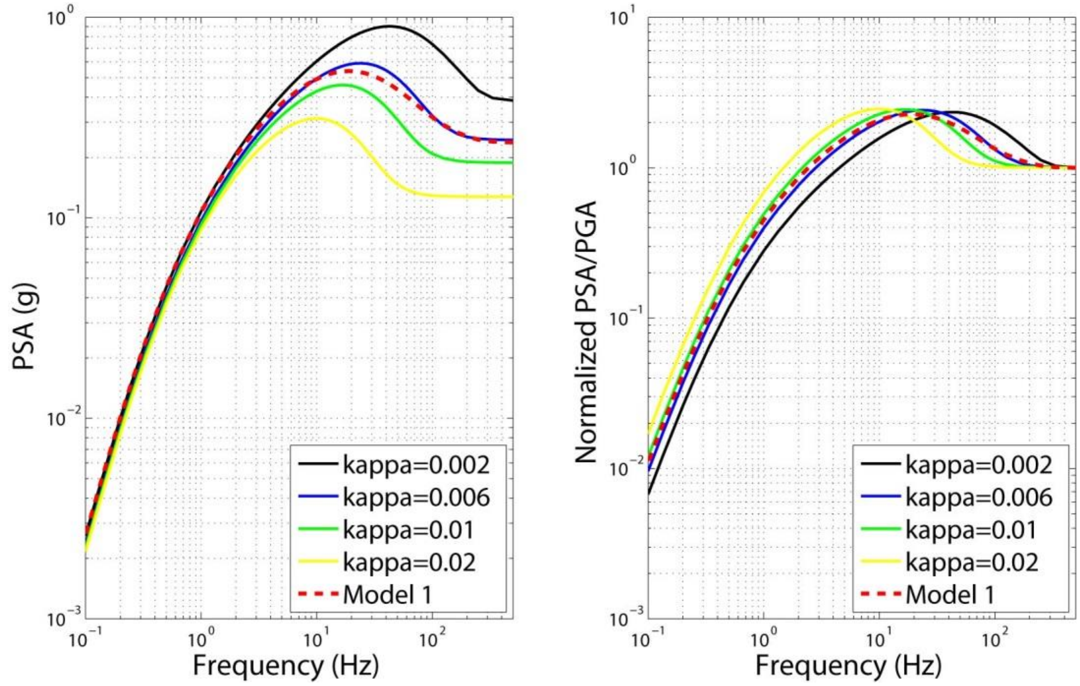

Fig. 7 Mean response spectra (left) and normalized with respect to PGA (right) for kappa bins. Each kappa bin has a weight of one, the other parameters follow distributions from Fig. 3. Red dashed line corresponds to the total mean using kappa model 1 from Fig. 3d.

4. Deriving a design response spectrum

A design spectrum differs conceptually from a response spectrum of a real earthquake. In the latter, the peak ground response of the SDOF system at all frequencies are calculated, therefore it is a description of a particular ground motion. On the other hand, the design spectrum is based on statistical analysis of response spectra for the ensemble of ground motion generated from different earthquake faults and M–R scenarios. The mean spectrum value resulted from the statistical analysis can provide the basis for a procedure to construct design spectra, which is illustrated in Fig. 8. In this Figure, the design spectrum is constructed from the pseudo spectral velocity (PSV) that is estimated from the mean normalized acceleration spectrum that assumes PGA=1 g. Based on observation from the response spectrum of real earthquakes, the response spectrum is subdivided in three spectral regions [25]: *i)* acceleration sensitive region, where structural response is related mostly to ground acceleration and PGA (high frequency region); *ii)* velocity sensitive region, where structural response is better related to ground velocity and peak ground velocity (PGV) (intermediate frequency region); *iii)* displacement sensitive region, where structural response is most related to ground displacement and peak ground displacement (PGD) (low frequency region). Then straight segments (in log scale) are defined for the acceleration, velocity and displacement regions. The corner periods T_a, T_b, T_c and T_d are identified for the three spectral regions to construct the spectrum. This procedure for constructing a piecewise linear design spectrum from the PSV has been already presented by Newmark and Hall [13, 14]. The basis of this idealization comes from the observation that the smoothed response spectrum curves are essentially scalar amplifications of the maximum values of ground displacement, velocity and acceleration in their respective frequency region. Once the PSV design spectrum has been developed, the pseudo acceleration (PSA) design spectrum as well as spectral displacement (SD) can be determined using the standard formulas that relate PSA, PSV and SD.

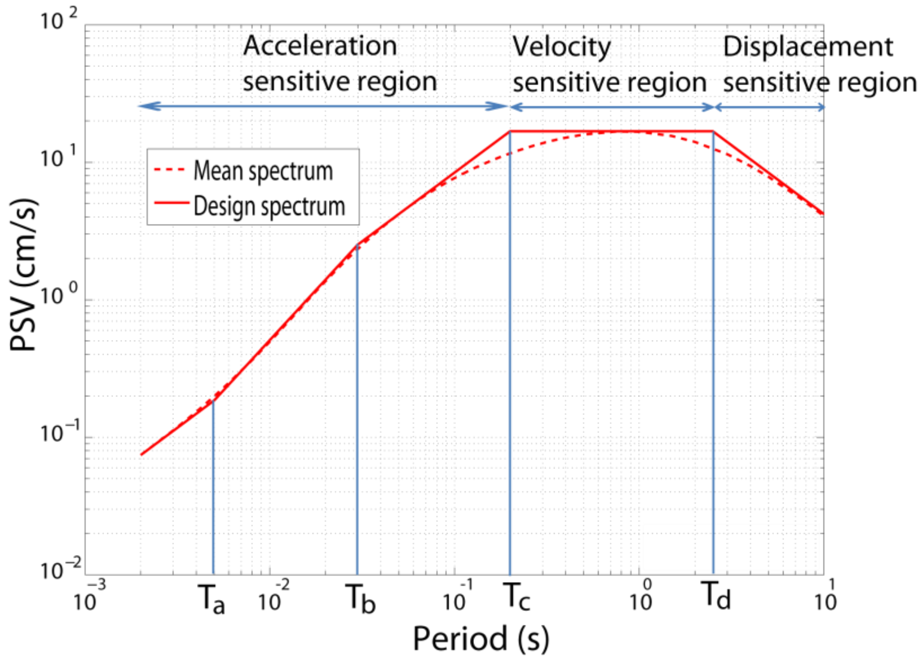

Fig. 8. Schematic representation of the spectral regions (acceleration, velocity and displacement) and definition of the corner frequencies to construct the piecewise linear design spectrum from the PSV.

We follow the procedure previously described to construct the design spectrum from the mean normalized spectrum calculated from the ensemble of the synthetic spectra (Fig. 2). As shown in the previous section, the statistic definitions of M–R–κ scenarios are the main controlling parameters for the calculation of mean and normalized response spectra shape. Particularly for the normalized means spectral shape that is used, in this paper, for constructing the design response spectra. As the factor κ is not well constrained, as explained above, we consider three distributions for κ shown in Fig. 2d. Therefore, three mean and normalized spectra are calculated, and consequently three design response spectra for very hard rock are proposed. The solid lines in Fig. 9 show the mean spectra (left side) and mean normalized spectra with respect to PGA (right side) for the three models. On the top of each curve is plotted the respective piecewise linear design spectrum (dashed line) for each mean spectrum constructed following the procedure described above and in Fig. 8. In Table 1 the corresponding corner periods that connect the piecewise linear segments are listed and the corresponding PSA plateau amplitudes of the spectra anchored to a PGA=1.0 g.

Table 1: Values of the parameters describing the proposed three piecewise linear design spectra for very hard rock. Spectra are anchored to a PGA=1.0 g.

Model	T_a (s)	T_b (s)	T_c (s)	T_d (s)	spectral plateau (g)
1	0.0050	0.030	0.20	2.50	2.27
2	0.0060	0.038	0.21	2.45	2.32
3	0.0065	0.041	0.21	2.45	2.34

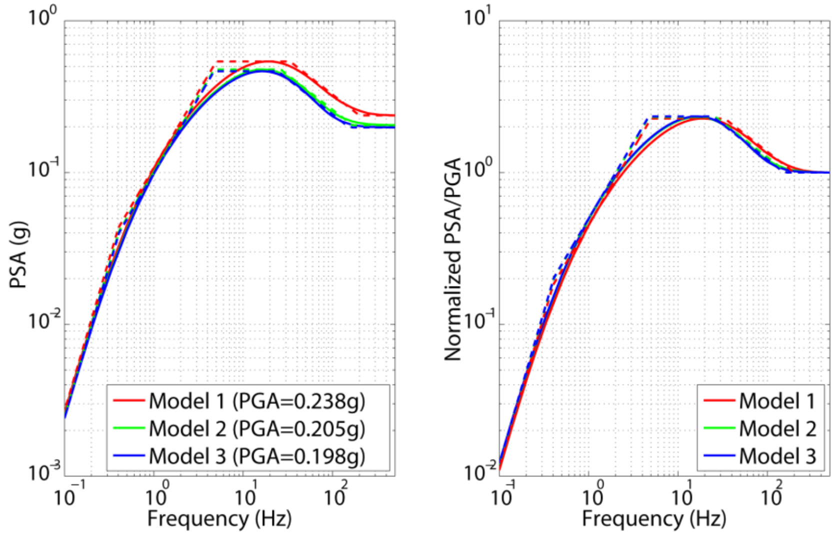

Fig. 9: Mean (solid line) and proposed (dashed line) design spectra. [left] Absolute acceleration response spectra. [right] Normalized spectra with respect to PGA for the three kappa models of Fig. 4d.

5. Comparison with Eurocode 8 (EC8) spectra

EC8 [26] defines two types of spectra (Type 1 and Type 2) and each type considers 5 different site classes (A, B, C, D and E) characterized in terms of V_{S30} ranges. Class A is for V_{S30} > 800 m/s relevant for comparison with our proposed design spectra for very hard rock. Detail description on the 5 classes is found in CEN [26]. The recommendation to choose between the two types of spectra, Type 1 and Type 2, depends on which earthquake magnitude (surface-wave magnitude, Ms) contributes most to the seismic hazard in the context of PSHA. If M_S<5.5 then Type 2 spectrum is recommended. For the purpose of comparison with our proposed design spectra we opt for the two types of spectra and class A. Fig. 10 shows such comparison for the spectra normalized with PGA. Our proposed spectra are more similar with the EC8 Type 2 in terms of the width from the spectral plateau and its corner frequencies, particularly for Model 2 and 3. The lower amplitude of the spectral plateau and the shift toward the higher frequency with respect to the EC8 models are also consistent, since our models represent spectra for very hard rock (V_{S30}=2000 – 3500 m/s).

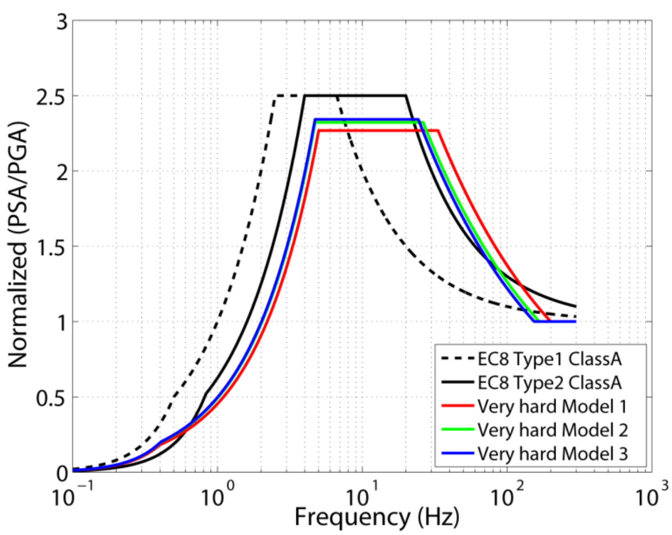

Fig. 10: Comparison of the three proposed design spectra with the Type 1 and 2 EC8 spectra for hard rock (class A). Spectra are normalized with PGA.

6. Comparison with observed data

Observed data for hard rock are very spare and even more spare for very hard rock of interest (V_{S30}=2000 – 3500 m/s, or even larger). Perhaps the best available database worldwide in which hard rock site can be found is the one from PEER NGA-East [27]. There are records in some stations in which the site is assigned to V_{S30} = 2000 m/s as maximum value. In most of the cases these values are based on expert judgment and not from direct measurements, so the uncertainty of whether these sites correspond to very hard rock is large. Fig. 11 shows the NGA-East database selected for V_{S30} ~ 2000 m/s. In the distance of interest (<100km), the data is dominated by low magnitude M<5. So there is lack of data for M>5. This lack of data is reflected in Fig. 12 where we compare the proposed design spectra with the NGA-East spectra for V_{S30}~2000 m/s. Remarkable is that the proposed spectra cover all the range of high frequency observed in the NGA-East dataset. The sparse observed data for M>5 (identified at the low frequency region in Fig. 12) is filled by our models. Notice also that the proposed spectra cover areas larger than around 90 Hz not observed in the NGA-East. The lack of data for V_{S30} larger than 2000 m/s may correspond to this area; if that is the case, our proposed model would be covering this gap.

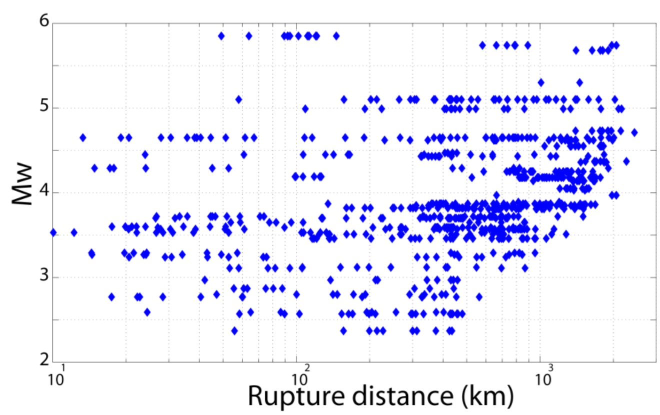

Fig. 11: Magnitude and distance of the NGA-East database for sites characterized with V_{S30}~2000 m/s.

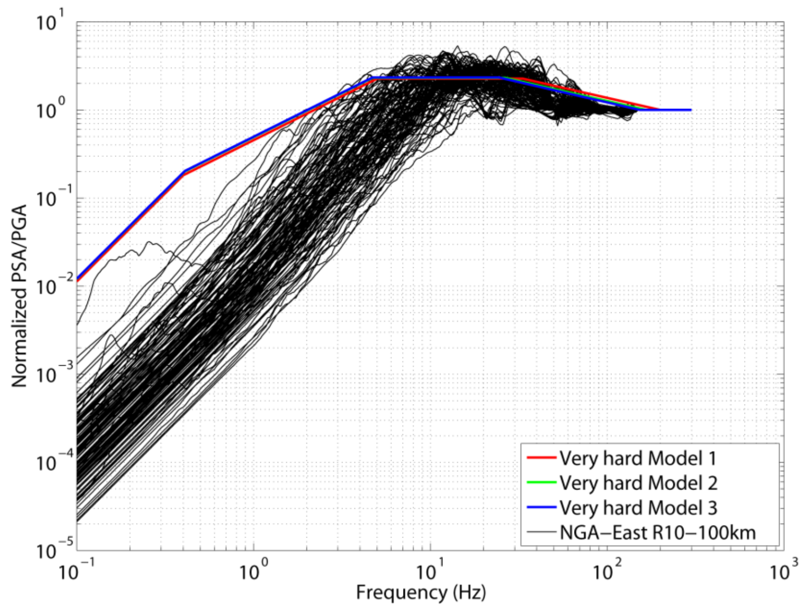

Fig. 12: Comparison of the three proposed design spectra for very hard rock with the NGA-East database spectra for V_{S30}~2000 m/s and distance <100 km.

7. Conclusions

We propose a procedure and from there derived a generic design spectrum for very hard rock (V_{S30} larger than 2000 m/s). The development of this spectrum had to rely on synthetic seismograms because there are not observed data for such type of site. For that purpose, the stochastic model of Boore [5] was used, assuming a point source to generate a total of 924 synthetic spectra, covering scenarios of magnitude M_W=4.5 – 7.5, distance R=5 – 100 km, kappa (κ)=0.002 – 0.02 s and V_{S30} 2000 – 3500 m/s. The main controlling parameters that define the shape of the design spectra are the magnitude, distance and κ. The magnitude and distance have been constrained with the probabilistic density functions obtained from the PRP project in Switzerland. This is justified considering that the PRP model is derived for low and moderate seismic activity. The application of the proposed design spectrum can be generalized to be used in low to moderate seismic regions in Europe. This is because geographically Switzerland is located in an area between low and moderate seismicity countries (from the north – Germany, to the south – Italy). In this context, Switzerland may be acceptable as good reference in Europe for a generic model.

Due to the importance of the κ factor that mainly controls the shape of the high frequency region and due to the lack of a robust constraint of this parameter in defining values for very hard rock, we have developed three design spectra models with different combinations of probability distributions of κ. The proposed three design spectra for very hard rock are in general consistent with the Type 2 class A spectrum from the Eurocode 8, but they covered wider high frequency region at the plateau. The proposed spectra also cover consistently the whole range of high frequency observed in the NGA-East data base for V_{S30}~2000 m/s, but also fill the lack of data for magnitude larger than 5 and V_{S30} larger than 2000 m/s. In conclusion we propose to use the "Model 1" proposed in this study as the final model defining the design response spectrum for very hard rock, because it covers larger high frequency region. It is important to mention that the proposed design spectrum is not intended to substitute neither to verify nor evaluate any other existing design spectra, such as those from Eurocode, rather it is to cover the rock regions not considered by the others spectra. Therefore any comparison done here is for reference purpose.

8. References

[1] Trifunac MD (1995): Pseudo Relative Velocity Spectra of Earthquake Ground Motion at High Frequencies, *Earthquake Engineering and structural dynamic*, **24** (8), 1113-1130.

[2] EPRI (2013): High Frequency Program - Phase 1 Seismic Test Summary, Palo Alto, CA: 2012. 3002000706.

[3] EPRI (2014): High Frequency Program - High Frequency Testing Summary, Palo Alto, CA: 2014. 3002002997.

[4] EPRI (2015): High Frequency Program - Application Guidance for Functional Confirmation and Fragility Evaluation, Palo Alto, CA: 2015. 3002004396.

[5] Boore DM (2003): Simulations of ground motion using the stochastic method. *Pure and Applied Geophysics*, **160** (3) 635–675.

[6] Edwards B, Fäh D (2013): A Stochastic Ground-Motion Model for Switzerland. Bull. Seismol. Soc. Am., **103** (1), 78-98. DOI 10.1785/0120110231.

[7] Yenier E, Atkinson GM (2015): Regionally adjustable generic ground-motion prediction equation based on equivalent point-source simulations: Application to central and eastern North America, *Bull. Seismol. Soc. Am.*, **105** (4), 1989-2009.

[8] Renault P, Abrahamson NA (2013): Lessons learned from the seismic hazard assessment of NPPs in Switzerland, SMiRT 22, Special Session on New Developments for Ground Motion Prediction for Stable Continental Regions and NGA-East, San Francisco, California, USA.

[9] Renault P (2014): Approach and Challenges for the Seismic Hazard Assessment of Nuclear Power Plants - The Swiss Experience, *Bollettino di Geofisica Teorica ed Applicata - Special issue for GNGTS*, **55**, 149-164.

[10] Campbell K (2003): Prediction of strong-ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America, *Bull. Seismol. Soc. Am.*, **93** (3), 1012–1033.

[11] Atkinson G, Boore D (2006): Earthquake ground-motion prediction equations for earthquakes in eastern North America, *Bull. Seismol. Soc. Am.*, **96** (6), 2181–2205.

[12] Van Houtte C, Drouet C, Cotton F (2011): Analysis of the origins of κ (Kappa) to compute hard rock to rock adjustment factors for GMPEs, *Bull. Seism. Soc. Am.*, **101** (6), 2926-2941.

[13] Newmark NM, Hall WJ (1969): Seismic design criteria for nuclear reactor facilities. In: Proceedings of 4th World Conference on Earthquake Engineering, B4, Santiago, Chile, 37–50.

[14] Newmark NM, Hall WJ (1982): Earthquake Spectra and Design, Earthquake Engineering Research Institute, Berkeley, Calif.

[15] Boore DM (1983): Stochastic Simulation of High-frequency Ground Motions Based on Seismological Models of the Radiated Spectra, *Bull. Seismol. Soc. Am.*, **73** (6a), 1865–1894.

[16] Aki K (1967): Scaling Law of Seismic Spectrum, *J. Geophys. Res.*, **72** (4), 1217–1231.

[17] Brune J N (1970): Tectonic Stress and the Spectra of Seismic Shear Waves from Earthquakes, *J. Geophys. Res.*, **75** (26), 4997–5009.

[18] Hanks TC, Mcguire RK (1981): The Character of High-frequency Strong Ground Motion, *Bull. Seismol. Soc. Am.*, **71**, 2071–2095.

[19] Graves RW, Pitarka A (2010): Broadband ground-motion simulation using a hybrid approach, *Bull. Seism. Soc. Am.* **100** (5a), 2095-2123.

[20] Anderson JG, Hough SE (1984): A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies, *Bull. Seism. Soc. Am.*, **74** (5), 1969-1993.

[21] Silva W, Darragh R, Gregor N, Martin G, Abrahamson NA, Kircher C (1998): Reassessment of site coefficients and near-fault factors for building code provisions, *Technical Report Program Element II: 98-HQGR-1010*, Pacific Engineering and Analysis, El Cerrito, USA.

[22] Chandler AM, Lamb NTK, Tsang HH (2006): Near-surface attenuation modelling based on rock shear-wave velocity profile, *Soil Dyn. Earthq. Eng.* **26** (11), 1004–1014.

[23] Ktenidou OJ, Abrahamson NA, Drouet S, Cotton F. (2015): Understanding the physics of kappa (κ): Insights from a downhole array, *Geoph. J. Int*., **203** (1), 678-691 DOI: 10.1093/gji/ggv315.

[24] Ktenidou OJ, Cotton F, Abrahamson NA, Anderson JG (2014): Taxonomy of κ (kappa): a review of definitions and estimation methods targeted to applications. *Seismol. Res. Letts*., **85**(1), 135-146.

[25] Veletsos AS (1969): Maximum deformation of certain non-linear systems. *Proceedings, 4th World Conference of Earthquake Engineering*, Santiago, Chile, 1:155-170.

[26] CEN (2004): Eurocode 8, design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. EN 1998-1:2004. *Comité Européen de Normalisation*, Brussels.

[27] Goulet C, Kishida T, Ancheta T, Cramer C, Darragh R, Silva W, Hashash Y, Harmon J, Stewart J, Wooddell K, Youngs R (2014): *PEER NGA-East Database. PEER Report 2014/17*, Pacific Earthquake Engineering Research Center, Headquarters at the University of California, Berkeley.