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SELECTION OF GMPES FOR PROBABILISTIC SEISMIC HAZARD ASSESSMENT IN AREAS OF MODERATE SEISMICITY AND RESULTING EPISTEMIC UNCERTAINTIES

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Abstract

In 2015, the reference probabilistic seismic hazard maps for Switzerland were updated. In order to cover epistemic uncertainties in ground-motion prediction two major sets of models were implemented: (1) stochastic and (2) empirical-based models.

The stochastic models describe the synthetically generated ground-motion predictions specifically derived for Switzerland. Four models were implemented, in the Alpine and Foreland regions, segregating deep (hypocentral depth > 6 km) and shallow seismicity. All models are referenced to a well-defined rock shear-wave velocity profile and *kappa0* value. This reference was derived from shear-wave velocity measurements and the assessment of *kappa0* at a large number of seismic stations of the Swiss national seismic networks. The stochastic models are consistent with the magnitudes in the earthquake catalogue of Switzerland (ECOS-09), which was also used to derive the earthquake activity rates in the source model for the probabilistic hazard assessment. Geometrical spreading and attenuation were modeled from the observations in the Foreland and the Alpine regions, derived based on earthquake recordings of small events of the seismic networks in Switzerland and neighboring countries. The scaling to larger magnitudes was achieved using macroseismic data of historical events together with their calibrated moment magnitudes, resulting in an additional branch of the logic tree for the epistemic uncertainty on the stress drop. For verification, the stochastic model was successfully tested against European and Japanese strong-motion data.

The empirical set of ground-motion models contains four empirical global ground-motion prediction equations (hereinafter GMPEs) extensively tested within other projects (i.e. Pegasos, SHARE). These models, however, had to be adjusted to the *Vs-kappa0* conditions at the reference rock in Switzerland. The adjustment functions were obtained based on the ratio of the expected Fourier amplitude spectra at the host region and the target region. The host *Vs* profile for each empirical GMPE was estimated based on published information, personal communication with the GMPEs' authors and expert evaluation. The host *kappa0* values were obtained from a mixture of direct measurements and *Vs30*-based estimates. Additionally, the empirical GMPEs were corrected for small magnitude extrapolation using instrumental data. The adjustments and corrections were applied only to the empirical GMPEs and additional epistemic uncertainties due to these corrections were taken into account in the logic tree.

The aleatory uncertainty is represented by single-station variability based on two alternative models. Finally, the two sets of ground motion models were combined together in the logic tree structure, by weighting the stochastic set and the empirical models. Here we present results that show the influence of the two sets of models on the resulting seismic hazard, and discuss the possible reason in the resulting epistemic uncertainties.

Keywords: seismic hazard; ground motion prediction equation; epistemic uncertainty; moderate seismicity;

1. Introduction

In 2015, the national probabilistic seismic hazard maps for Switzerland were updated [1]. The main inputs to the hazard computations were a set of earthquake rate models and different ground-motion prediction equations. Hazard was described in terms of peak ground acceleration (PGA) and 5%-damped (pseudo-)spectral acceleration (SA) for the following vibration periods T: 0.05s, 0.10s, 0.15s, 0.20s, 0.25s, 0.30s, 0.35s, 0.40s, 1.0s, 2.0s, 3.0s, 4.0s. The output of the model consists of seismic hazard curves, seismic hazard maps and uniform hazard spectra for various return periods from 50 years to 10,000 years. The results are presented as mean and median probabilities of exceedance in addition to other of units of hazard estimates (e.g. quantiles). The hazard curves and maps refer to a reference-rock shear-wave velocity profile with V_{s30} = 1105 m/s. In this paper, we refer to the updated model as "*SuiHaz2015*".

Generally, a probabilistic seismic hazard model is dominantly controlled by uncertainties of input models, describing either ground-motion or earthquake rate forecast models. These uncertainties can be split into two types: aleatory uncertainty, which is due to the random nature of a process and epistemic uncertainty, which represents our lack of knowledge. Herein, we address the epistemic uncertainties of the ground motion model. In order to cover epistemic uncertainties in ground-motion prediction for SuiHaz2015 two major sets of models were implemented: a stochastic-based and an empirical-based set of models [2]. After a description of the main input for the seismic hazard computation, we discuss the properties and epistemic uncertainties of the stochastic and empirical models, in particular the adjustments of the latter to the reference-rock velocity profile and to small magnitudes.

2. Input for the 2015 probabilistic seismic hazard assessment for Switzerland

2.1 Earthquake rate model

An earthquake rate model summarizes all critical information on long-term earthquake occurrence to be used as input to probabilistic ground-shaking computations. The earthquake rate computation used in *SuiHaz2015* comprises four different earthquake source models [1]:

1) an area source model inherited from the 2004 Swiss seismic hazard model [3];
2) a newly developed area source model which preserves the spatial distribution of source zones of the 2004 model while updating the seismic activity based on the earthquake catalogue ECOS-09 [4];
3) a smoothed seismicity model relying on the ECOS-09 catalogue to estimate the earthquake activity rates, which where spatially distributed with an adaptive kernel-smoothing approach using a Gaussian kernel;
4) the area source model as developed within the 2013 European Seismic Hazard Model [5].

The four earthquake rate models, describing the earthquake-size distribution and activity rate, were given different magnitude-dependent weights. Strongest weights were given to models (2) and (3). The resulting ensemble earthquake rate forecast model was used to capture the epistemic uncertainties of the earthquake activity rates; five independent earthquake rate branches depicting the median, and 2.5th, 16th, 84th, 97.5th quintiles of the earthquake rate distribution were used for the hazard calculation. Seismic sources were represented as point sources following the standardized seismic source representation of OpenQuake [6]. More details are given in [1].

2.2 Ground-motion predictions and the associated uncertainty

Generally, the uncertainties associated to ground motion are referred to as epistemic and aleatory. The former describes our lack of knowledge and incomplete data on a complex process associated with ground shaking; the latter is associated with the true randomness of the process. Epistemic uncertainty controls the distribution (*i.e.*, the spread) of the hazard estimates, whereas the aleatory controls the shape of the hazard curves (the larger the aleatory uncertainly, the higher the hazard levels at long return periods). Both uncertainties must be considered in any modern probabilistic seismic hazard assessment (PSHA). Albeit our understanding of ground motions (*e.g.*, earthquake nucleation and wave propagation, travel path effects) has advanced in recent decades, we are not fully confident in choosing a single ground-motion model representative for application in PSHA. The ground-motion model used in SuiHaz2015 is the result of several iterative phases. First, we investigated existing empirical GMPEs. We used expert judgment to evaluate each empirical GMPE, supported by the use of Trellis plots for different scenarios. Although objective ranking indexes are available for testing the performance of empirical GMPEs with observations (e.g. [13]), we did not consider data-driven testing due to the limited number of strong-motion recordings in Switzerland. We finally selected two sets of GMPEs: a stochastic-based and an empirical-based set of models [2].

The stochastic set of models describe the synthetically generated ground-motion predictions specifically derived for Switzerland [7] and parameterized by [8]. Four specific models were implemented, in the Alpine and Foreland regions, segregating deep (hypocentral depth > 6 km) and shallow events. All models are referenced to a well-known reference-rock shear-wave velocity profile and *kappa0* value (*i.e*, the near-surface site-specific attenuation), which were based on shear-wave velocity measurements and the assessment of *kappa0* at a large number of seismic stations of the Swiss network [9]. The stochastic models are consistent with the homogeneous magnitude definition in the earthquake catalogue of Switzerland (ECOS-09 [4]), which was also used to derive the earthquake activity rates in the source model (2) to (4). Geometrical spreading and attenuation in the stochastic ground-motion prediction equations are modeled from the observations in the Swiss Foreland and the Alpine regions [10], derived from earthquake recordings of small events of the seismic networks in Switzerland and neighboring countries. The scaling to larger magnitudes was achieved using macroseismic data of historical events together with their calibrated moment magnitudes [7]. This scaling introduces epistemic uncertainties that are treated as additional branches of the logic tree using different values of stress drop for the source part of the stochastic model. For verification, the stochastic model was tested against data from Europe and the Middle East [11], and Japanese data from the KIKNet (http://www.kyoshin.bosai.go.jp/) by adapting the geometrical spreading and anelastic attenuation from the Swiss to the Japanese conditions [12]. This comparison showed that the pseudo-finite fault stochastic simulation model provided unbiased predictions even for large events (M_W = 7.3), giving confidence on its performance for predicting ground motion from even the largest earthquakes included in the PSHA.

The empirical set of models contains empirically derived GMPEs that were selected to describe ground motions for the 2013 European seismic hazard model in project SHARE [13]. Only models have been selected which were extensively tested and verified in other recent hazard projects. The following four empirical GMPEs were chosen: Akkar and Bommer (2010) [14], Chiou and Youngs (2008) [15], Cauzzi and Faccioli (2008) [16] and Zhao et al. (2006) [17], hereinafter referred to as AB2010, CY2008, CF2008 and ZH2006, respectively. As a next step, the empirical models had to be adjusted to the Vs30-*kappa0* of the reference-rock condition, following a revised procedure [2] proposed originally in [18]. This procedure is called host-to-target adjustment of empirical GMPEs, in which we must make a correction to account for the fact that the average reference site of the GMPE may be different to that of the target (the reference-rock). In recent seismic hazard assessment projects (i.e. SHARE Project), this task has proved difficult to accomplish, mainly for two reasons. Firstly, the reference rock spanning large regions of different tectonic settings pose difficulties when evaluated. For simplification, a single reference value is chosen based on a subjective classification of the soil classes, and usually represented by a Vs30 of about 800m/s. Secondly, the empirical GMPEs do not include an implicit site reference apart from Vs30 or site-class, both of which are unable to provide unique physical reference that can be interpreted in terms of anelastic amplification. Instead, we currently have to estimate a range of possibilities, accounting both the model selection and adjustments to describe the uncertainty that is then propagated into the hazard as epistemic uncertainty.

The adjustment functions were obtained based on the ratio of the expected Fourier amplitude spectra at the host region and the target region. The host Vs30 profile for each empirical GMPE was obtained based on published information, personal communication with the GMPEs' authors and expert evaluation. The host *kappa0* values were obtained from a mixture of direct measurements and Vs30-based estimates [2]. The target corresponds to the reference–rock velocity profile of [9] and *kappa0* of [10]. The resulting adjustments for the different empirical GMPEs are shown in Figure 1. Additionally, the empirical GMPEs were corrected for small magnitude extrapolation using the instrumental data as shown in Figure 2. Such adjustment is required because empirical GMPEs do not extrapolate well outside the range of magnitudes and distances of the calibration dataset and the minimum magnitude considered for SuiHaz2015 was M_W = 4, below the minimum magnitude used for most GMPEs. In particular, the low magnitude adjustment was necessary to account for potential bias in the low magnitudes of the original datasets used to derive the empirical GMPEs.

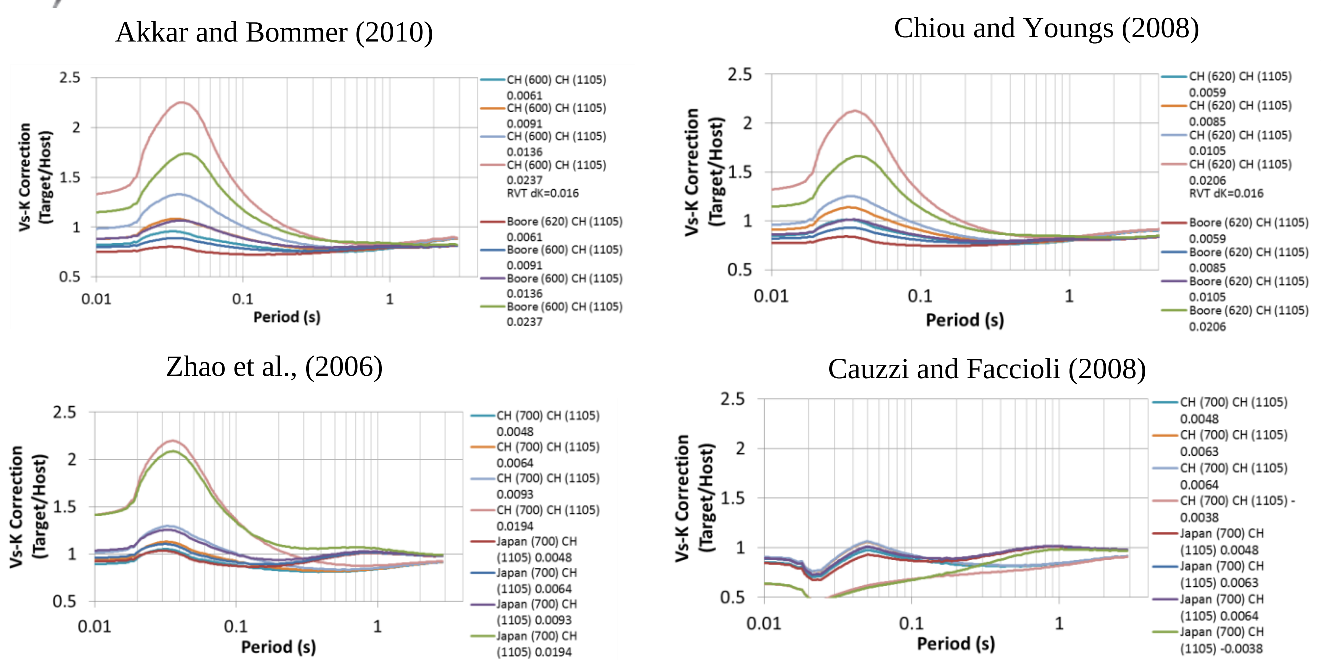

Fig. 1 - *Vs-Kappa0* adjustments corresponding to different host *Vs* profiles and *kappa0* for the AB2010, CY2008, ZH2006 and CF2008 empirical predictive models.

The aleatory uncertainty of the chosen GMPEs is represented by single-station variability, and its dependence on magnitude and distance was adjusted for each empirical GMPE following [19]. The host-to-target adjustments and corrections were applied only to the empirical GMPEs and additional epistemic uncertainties due to these corrections were taken into account in the logic tree (e.g. in Figure 3, the branching level attached to each empirical GMPE).

Finally, the two sets of ground motion models were combined together in the logic tree structure, by weighting the stochastic set with 0.6 and the empirical models with 0.4 respectively. More detail related to the ground-motion model for the hazard calculation is provided in [2]. The logic trees of the ground-motion models for the two representative tectonic regions (Alpine and Foreland) and two layers of seismicity depicted as shallow and deep (hypocentral depth > 6 km), are presented in Figure 3.

The epistemic uncertainties in both stochastic and empirical approaches are considerable (Figure 4). While epistemic uncertainties remain small for small magnitudes and larger distances, they increase in the near-field and for large magnitudes. The stochastic model has limitations related to scaling to larger magnitudes: even if there was a careful comparison with Japanese data including large events, this extrapolation is the reason for uncertainties represented by the set of different stress drops (in the range of 10 Bar to 120 Bar) in the source part of the stochastic model. On the other hand, the main limitation of empirical GMPEs is related to the quality of meta-data, in particular the reliability of V_{s30}, reference velocity profiles and *kappa0*, in addition to the uncertainties introduced by the procedure for the Vs-*Kappa0* adjustments. This uncertainty in the definition of the empirical GMPE's host Vs-reference profile and *kappa0* had to be taken into account by assuming a set of possible models (named KappaVs30Lower, KappaVs30Mid, KappaVs30Upper). Another problem of empirical GMPEs is that they typically predict 5%-damped spectral ordinates instead of Fourier amplitude spectra. Since response spectra at high frequency are determined by the low-frequency part of the spectrum in a non-linear manner, such Vs-*Kappa0* adjustment always remains uncertain.

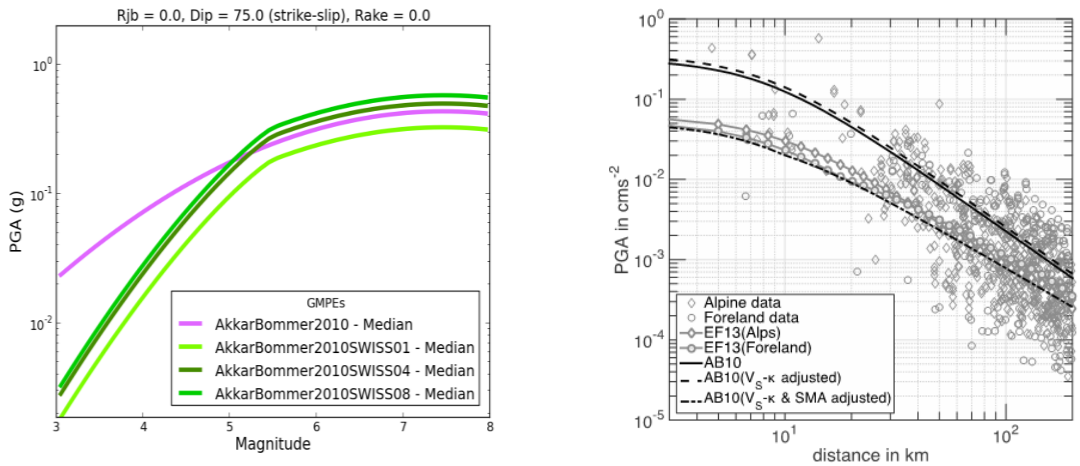

Fig. 2 - Left: Combined effects of *kappa0* adjustments and small magnitude adjustment (SMA) on the AB2010 original model (magenta) as a function of magnitude. The green curves represent the models obtained from the original AB2010 after applying the *Vs-kappa0* and SMA adjustments. Right (adapted from [2]): effect of *Vs-kappa0* and SMA for AB2010 as a function of distance. Recorded Swiss foreland and alpine data for events with magnitude ranging between 3.3 and 3.7 are shown as symbols. The original (non-adjusted) GMPE for $M_W = 3.5$ over-predicts the median observations. The fully adjusted GMPE is shown to reasonably match the data distribution and the Swiss model of Edwards and Fäh (EF13, 2013) [7]. It is clearly apparent that the SMA is much stronger than the *Vs-kappa0* adjustment for small magnitude events.

Fig. 3 - Ground motion models used in the seismic hazard calculation. Top: logic tree structure for the Swiss Foreland region. Bottom: logic tree structure for the Swiss Alpine region. The branches for the different Vs-kappa0 (named KappaVs30Lower, etc.) adjustments repeat for all empirical models and are not shown in all cases.

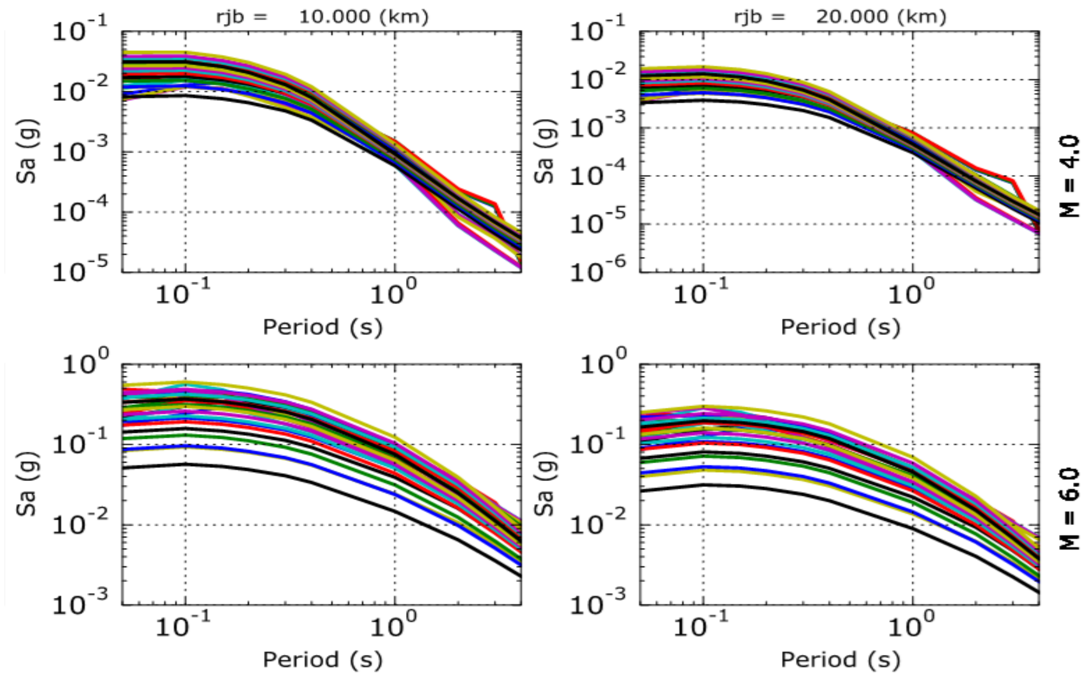

Fig. 4 - Comparison of all logic-tree branches of selected stochastic and empirical GMPEs for four magnitude-distance scenarios. The kink at 3s is due to an extension of AB2010 from 2s to 3-4s period.

All the above-mentioned issues informed the chosen weighting scheme. Since no instrumental data-driven testing was possible, the weighting scheme of the empirical GMPEs relied entirely upon expert judgment. It was decided to define the weights as degree of belief, penalizing the potential bias introduced by adjustments. Albeit subjective, the weights are higher for the stochastic models because they are likely to introduce less bias in comparison with the adjusted empirical models. As to the stochastic models, higher weights were assigned to those matching better historical well-constrained macroseismic intensity data [8]. Stochastic predictions of shallow events are based on six different values of the stress-drop parameter, and their weights decrease as the stress-drop parameter increases. Similarly, for deep events in the Alpine and Foreland regions, the weights decrease as the stress-drop parameter increases [2].

3. Stochastic versus Empirical GMPEs

Sensitivity analyses were conducted to understand the contributions of the stochastic and empirical GMPEs to the total hazard. In Figure 5, a sensitivity analysis is carried out for SA[0.2s], reference rock [Vs30 = 1105 m/s] and a return period of 475 years. A qualitative and quantitative measure of the difference between the stochastic and empirical GMPEs is given by computing the hazard using only one set of GMPEs. As can be observed, the difference between the two maps (stochastic and empirical) is from 20 to 70%, with lower differences in the Valais, in the Alpine region, and higher differences in the Foreland region. The Basel region shows about the largest difference of about 65~70%. This difference arises from the epistemic uncertainty resulting from different strategies. The difference in the hazard values between the stochastic and the empirical models can be seen in the uniform hazard spectra, as shown on Figure 6. Again, differences are larger for a site in the Foreland than observed for a site in Alps, but both are within the 16-percent and 84-percent quantiles. The stochastic models result in systematically lower values of the spectral acceleration than the empirical models.

While empirical models are based on a larger strong-motion datasets, covering larger magnitudes, complex fault ruptures, and diverse style-of-faulting, the related Vs reference profiles and *kappa0* values remain uncertain. The stochastic models have a reference-velocity profile and kappa0, but they are based on recordings of earthquakes in the lower magnitude range, and were scaled to larger magnitudes using macroseismic data. The differences between the stochastic and empirical models increase as the return period increases.

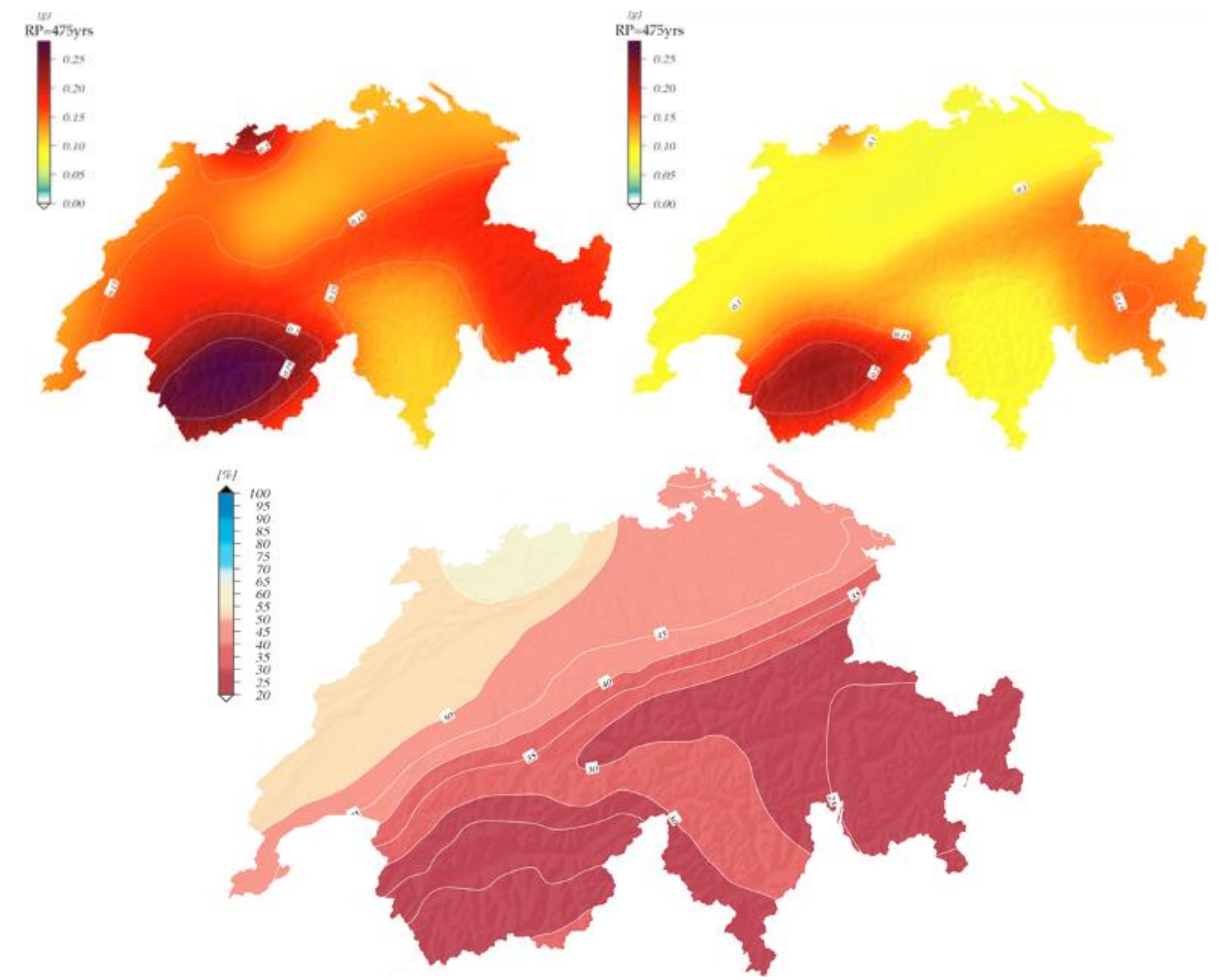

Fig. 5 - Percentage difference between the two ground-motion hazard map in terms of SA[0.2s] for a return period of 475yrs (lower part), as obtained for the empirical (top left, given in absolute SA values) and the stochastic (top right, given in absolute SA values) GMPEs and the corresponding full source model.

4. Individual GMPE contribution to the total hazard

Seismic hazard disaggregation is a technique that allows identifying an earthquake scenario that contributes significantly to a specified exceedence probability of ground motion levels. The disaggregation technique identifies relevant earthquake scenarios by earthquake magnitude and source-to-site distance pairs, taking into account ground-motion prediction equations and their aleatory variability. We do not want to disaggregate the entire logic tree due to a large computational demand. To select the most adequate GMPEs for the disaggregation, we use the radar plots depicting the sensitivity of individual GMPEs as a function of depth (in our case Deep or Shallow) and tectonic regime (Alpine or Foreland). The radar plots indicate the GMPEs (listed at the edges of the radar plot) and the ratio GMPE/mean, which is illustrated as a red polygon. Note, that the black circle always indicates unity. Thus, the values outside the black circle indicate a larger ground motion than mean value. A value inside the black circle suggests a lower ground motion than the mean value. For a site of interest, similar radar plots can be computed for all ground-motion intensity measures and various return periods. Figure 7 presents the radar plots for Sion for SA[0.2s] and a return period of 475 years. These plots reveal the Alpine Shallow logic tree as the main contributor to the amplitudes of total hazard, followed by the Alpine Deep logic tree. As expected, the

Foreland Shallow and Deep models have small impact on the amplitude of the seismic hazard estimates in Sion. The stochastic model EF13a75bar shows a 50% larger value than the weighted mean, whereas the lowest value is the 10 bar stochastic model (EF13a10bar). CF08adj04 (mid adjustment bound) and AB10adj01 (lower adjustment bound) equal the mean hazard.

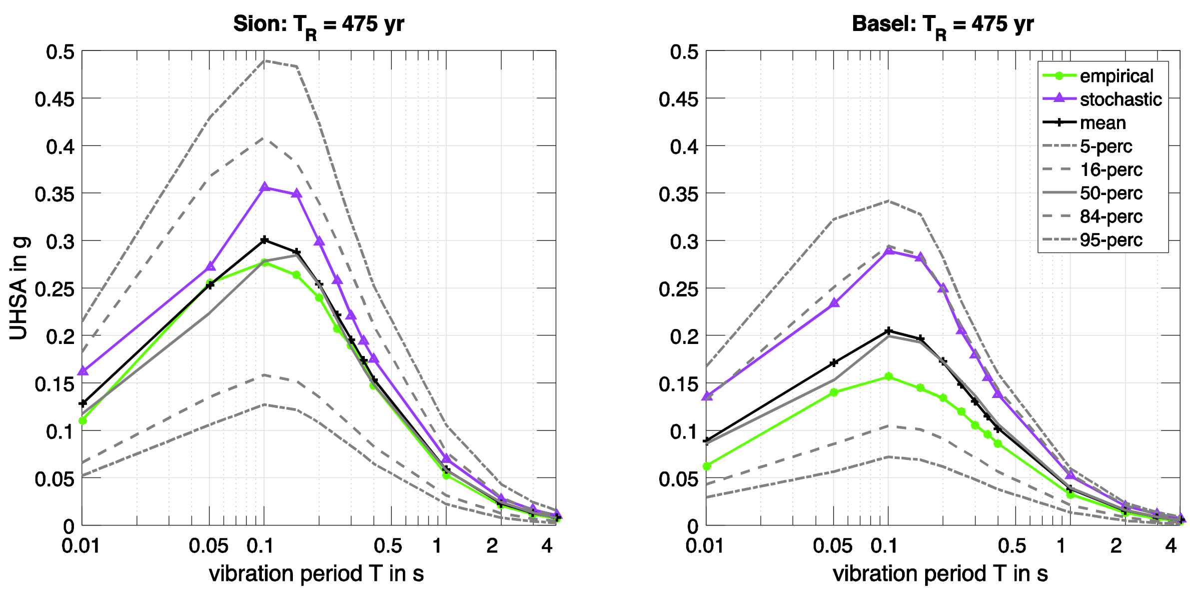

Fig. 6 - Uniform hazard spectra of the *SuiHaz2015* (mean in black) for Sion in the Alpine region and Basel in the Foreland region. The mean hazard curves resulting from the set of stochastic models is given in green, and from the set of the empirical models in red (modified from [2]).

5. Conclusions and outlook

Seismic hazard is controlled by uncertainties in ground-motion prediction, in particular for large return periods. It is therefore important to reduce epistemic uncertainties by improving our ground-motion modes and input data. As shown in Figure 8, uncertainties were reduced from the 2004 seismic hazard [3, 20] to the 2015 [1] by almost half. The 2004 mean hazard is within 16-percent and 84-percent quantiles, which shows that the mean hazard curve remains stable. Even if much reduced with respect to 2004, the uncertainty around the median SuiHaz2015 model remains large, as apparent in Figure 8. The 84-percentile hazard level exceeds the current code spectrum for all vibration periods $T < 0.3$.

As shown in this paper, epistemic uncertainty is still large, but can be reduced in the future. Future projects will focus on the reduction of epistemic uncertainties in seismic hazard analyses through improving the understanding of source processes and wave propagation in the earth's crust. This can be achieved through development of reliable physics-based models to describe attenuation of energy in the crust and near-surface (using Q and kappa0, respectively) and the integration of 3D attenuation models into deterministic and probabilistic based hazard assessments.

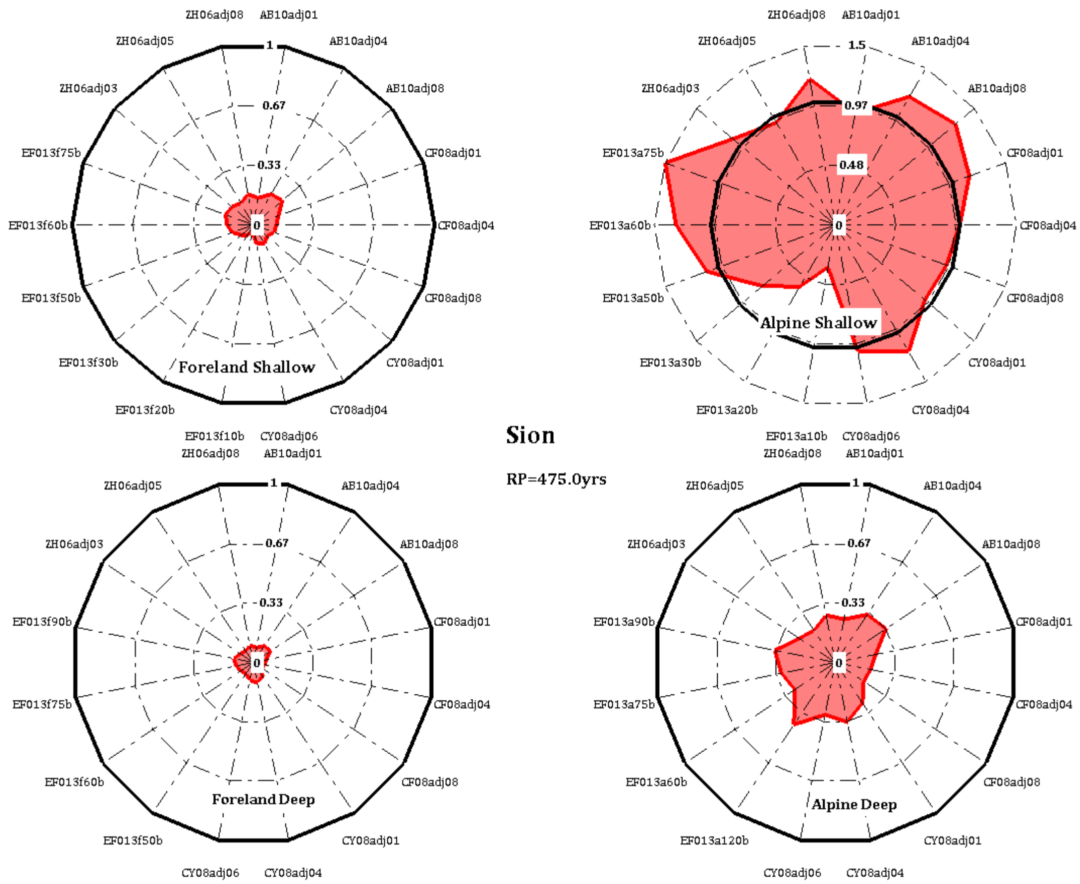

Fig. 7 - Radar plots for site Sion depicting the contribution to the weighted mean of Alpine and Foreland ground motion models and shallow and deep seismogenic sources. The plots are for SA[0.2s] and a mean return period of 475yrs. The red polygon describes the GMPE/mean ratio.

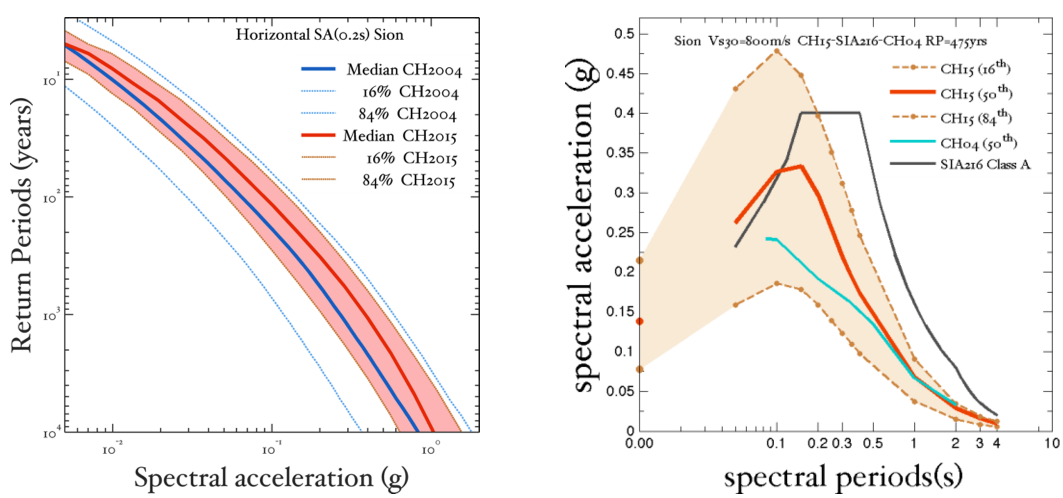

Fig. 8 - Left: Seismic hazard curves for Sion (SA[0.2s]) for SuiHaz2015 (red). The hazard curves for the 2004 Swiss Hazard Model (blue) are illustrated for comparison (blue). The values were adjusted to rock conditions with Vs30 of 800m/s. Right: The same, but showing the uniform hazard spectra at site Sion for 475 years return period. The design spectrum of the Swiss building code SIA261 for the rock class is also given.

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