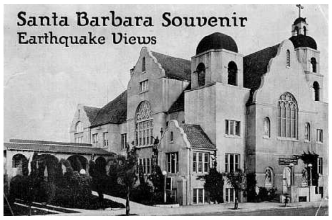

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A STOCHASTIC GROUND-MOTION MODEL FOR SWITZERLAND

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ABSTRACT

We present an overview of the stochastic ground-motion model for Switzerland, commissioned by *swissnuclear* for the PEGASOS Refinement Project. We derive a model for earthquake Fourier spectra and use this in a stochastic simulation technique to generate predictions of pseudo-spectral acceleration (PSA). Several potential models were tested using instrumental and macroseismic observations and a final model is proposed for the prediction of ground-motion in the Swiss Foreland region. Ground-motion prediction uncertainty is described in terms of inter- and intra- event uncertainties through residual analysis of response spectra, leading to a value of the single-site sigma. The stochastic ground-motion model comprises of a crustal Q, a geometrical decay function, a stress-parameter model, a shaking-duration model and site-specific parameters (e.g., κ, site-amplification) accounting for near-surface heterogeneity. Consistency of the model is emphasized through its compatibility with other seismic hazard products: the model is referenced to a generic rock-profile that was developed by utilizing velocity profiles of the sites of seismic stations and is calibrated at higher magnitudes to the macroseismic model used in the derivation of historical magnitudes for the local earthquake catalog. Finally, the model is based on moment magnitudes from the recently developed Earthquake Catalog of Switzerland 2009 (ECOS09). Keywords: stochastic model, ground-motion, attenuation, source scaling, site amplification, seismic hazard.

INTRODUCTION

The *swissnuclear* PEGASOS Refinenement Project (PRP) (Renault et al., 2010) is a SSHAC level 4 seismic hazard analysis of nuclear power facilities in Switzerland. One aspect of this project was the development of a representative ground motion model logic tree for the Swiss Foreland region (e.g., Bommer and Scherbaum, 2008). In this article, we present an overview of the stochastic ground-motion model developed to define a Swiss specific ground motion prediction equation (GMPE). GMPEs are a simple way of estimating the expected ground-shaking given a basic description of an earthquake (magnitude, depth, etc.) and relative location (distance, site conditions, etc.). They are typically derived from recordings of strong ground-motion, such that they statistically represent the mean and standard deviation in a parametric form. Unfortunately, the formulation of GMPEs in regions of moderate or low seismicity is significantly limited. For instance, in Switzerland, the maximum instrumentally recorded local event is M_W=4.9; although even this event is recorded only at rather far distances (R>100km).

A common way to develop GMPEs for such low seismicity regions is to stochastically simulate strong ground-motion (e.g., Boore, 2003). The stochastic method allows the simulation of ground-shaking even for very large earthquakes (e.g., **M**7). Using this method we can therefore derive a GMPE based on locally derived parameters. Our approach is centred on the consistency of several aspects of seismic hazard analysis. Firstly, the final ground-motion model is consistent with the recently developed earthquake catalogue of Switzerland (Fäh et al., 2011). This is important if we consider that the derivation of the model can sometimes be separate from the magnitude scale later applied (e.g., Bay et al., 2003), which can cause disparities in estimates of ground-motion. Secondly, the model is based on a Swiss specific generic-rock shear-wave velocity profile and associated 1D SH-amplification (Poggi et al., 2011). As a result the reference condition upon which to apply further site-specific amplification is well defined, which is not always the case with GMPEs. Finally, the model is calibrated in the high-magnitude range using the macroseismic intensity model that was used for the determination of the M_W values of historical earthquakes in the ECOS09 catalogue. This carefully integrated approach ensures that the model is complementary to other aspects of PSHA, such as source model characterization (e.g., Wiemer et al., 2009) and site specific amplification (e.g., Cramer, 2006).

DATA

A total of 720 earthquakes since 1998 with M_L > 2 were available. 18308 individual horizontal records (N-S or E-W) of these 720 events were used to define the stochastic model parameters. Fig. 1 shows the distribution of events and seismic stations in addition to the distribution of magnitudes and recording-distances. The largest events in our dataset occurred near St. Dié, France, to the north-west of Switzerland, with M_L=5.8 (M_W=4.8) and to the south-east of Switzerland, in Bormio, Italy, with M_L=4.9 (M_W=4.9).

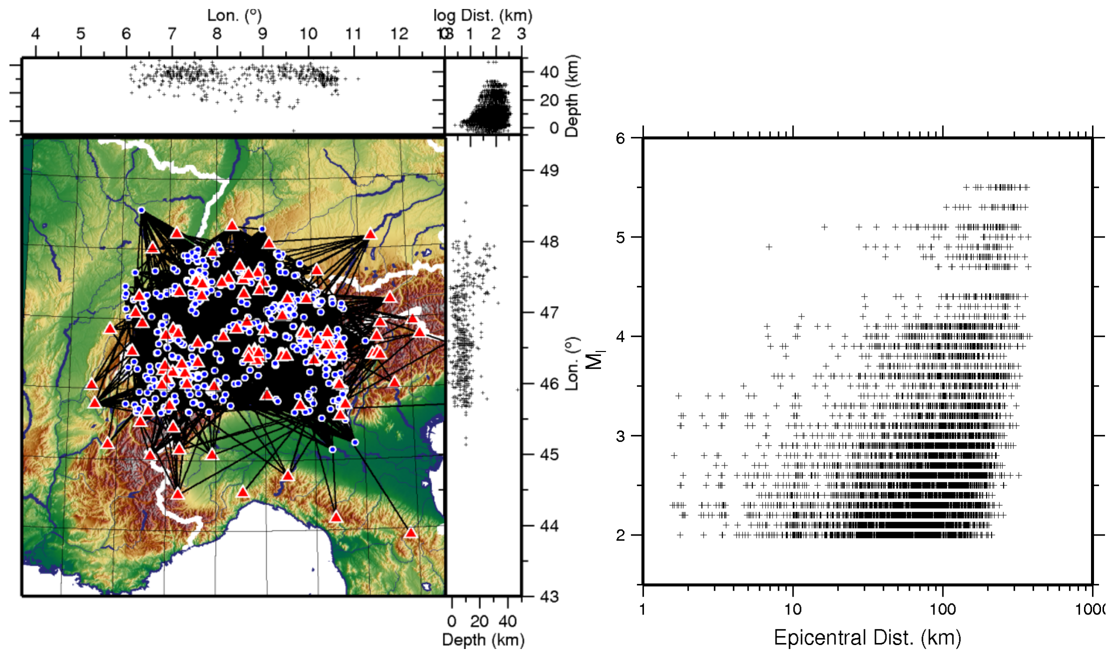


Fig. 1: left: map of Switzerland and border regions showing events (circles) and stations (triangles) included in the dataset. Right: distribution of data in terms of magnitude – distance coverage.

MODEL PARAMETERS

Several modelling aspects need to be considered for the stochastic simulation of ground-motion. Essentially, the input of the simulation is a model for the Fourier spectral amplitude of ground-motion, the duration of shaking and a shaping function for the acceleration time-series. The method we employ is based on a point-source earthquake, but we implement pseudo-finite-fault predictions through the use of the R_{eff} distance metric (Boore, 2009).

Rock Reference

We use the rock-reference model and corresponding shear-wave amplification model of Poggi et al. (2011). They computed a reference profile corresponding to null-average amplification at a series of well-characterised seismic stations in Switzerland. The generic rock profile was determined using a number of active and passive site investigations obtained for the PRP (Fäh et al., 2009) in addition to a microzonation project in the Basel area (Fäh and Huggenberger, 2006; Havenith et al., 2007). Poggi et al. (2011) defined the reference condition through the correlation of ¼ wavelength velocity profiles with the observed amplification of seismic signals relative to the network-average. The reconstruction of the site producing null-amplification was then possible. The results of this work were also used as the reference for the derivation of other parameters used in this study, such as attenuation and stress-parameter.

Attenuation

We take the attenuation model from Edwards et al. (2011), whose study analysed the same records of 720 earthquakes used here. They parameterised the decay of Fourier spectral amplitude with distance using crustal Q models and site specific κ values in addition to geometrical decay that varied as a function of hypocentral distance. They found that Q_0=1200 for an average shear-wave velocity of 3.5km/s, with site dependent κ values determining the near-surface attenuation at each of the recording sites. The average κ value, corresponding to the reference shear-wave profile was 0.017s. The geometrical decay model was separated into Swiss Foreland and Alpine specific regions and accounted for distance dependent decay, such that amplification due to SmS reflection phases was modelled.

Magnitude and Stress Parameter

We computed stress parameter values, given a half-space velocity of 3.5km/s, following Boore (2003), such that the values are consistent with the SMSIM software used for the stochastic simulation:

$$\Delta\sigma_{3.5} = M_0\left(\frac{f_c}{0.4906\beta}\right)^3. \quad (1)$$

(Brune 1970, 1971; Eshelby, 1957), where β is the shear-wave velocity at the source, in this case 3.5km/s. It is assumed that the seismic moment is given by:

$$\log(M_0) = 1.5M_W + 9.1. \quad (2)$$

(Hanks and Kanamori, 1979). M_W values are taken from the Earthquake Catalog of Switzerland (ECOS09). The source corner frequency (f_c) was found through inversion of the Fourier spectra using a grid-search along with a Powell's minimization for the seismic moment (fixing attenuation as defined by Edwards et al. (2011)). Stress parameters were similar to those found by Bay et al. (2003), with values tending to be between 0.01 and 1Mpa with some indication of increasing stress parameter with M_W for the Swiss Foreland events (*Fig. 2*). However, these values are dominated by earthquakes with rather small magnitude (M_W<3) which may bias the stress parameter used for the larger-magnitude events. We later test various stress parameter models at higher magnitudes using the Swiss macroseismic model.

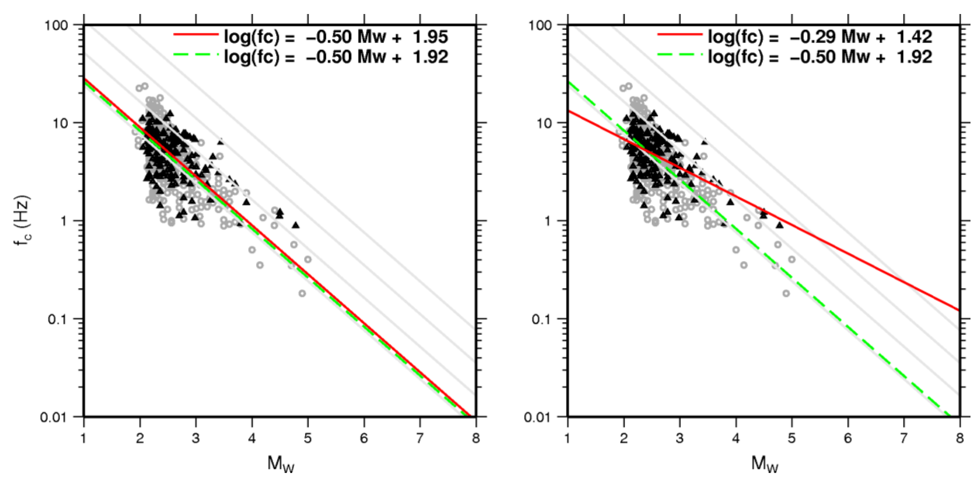


Fig. 2:corner frequency (f_c) plotted against Mw. Triangles are Foreland events, circles are Alpine events. Left: fitting a constant stress-parameter model. Right: fitting a variable stress-parameter model. Red line: for foreland events; green line: for Alpine events. Grey lines indicate lines of constant stress-parameter: 0.1, 1.0, 10 and 100MPa from bottom to top.

Duration of Shaking

The duration model adopted was based on the measurement of the integral of squared-acceleration in the time-series after the S-arrival. The model used is shown in Fig. 3 compared to that used by Bay et al. (2003) for 1Hz and the ENA model of Atkinson and Boore (2006). We observe that a bi-segment model is suitable, with durations extending to over 15s at 100km, and then increasing more slowly to 200km. The source duration was assumed to be given by $1/f_c$.

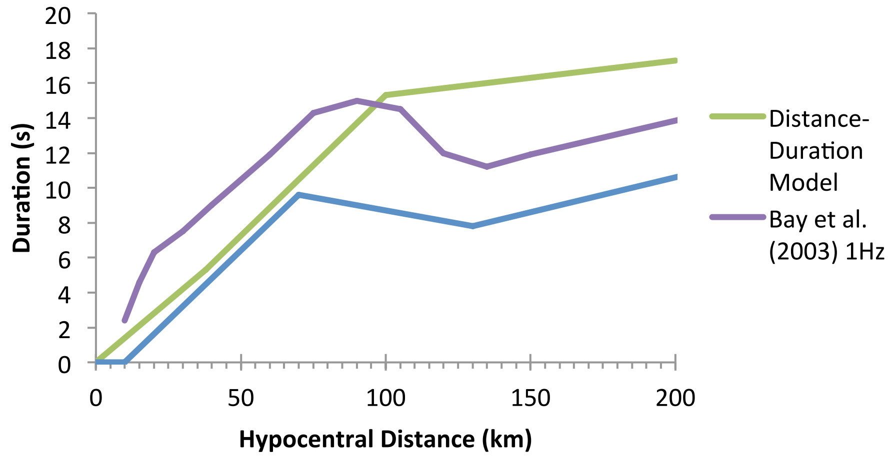


Fig. 3: Distance-duration model used in this study.

CALIBRATION TO HIGH MAGNITUDES

In order to calibrate the model at the upper end of the magnitude scale we used the intensity attenuation model described in ECOS09 (Fäh et al., 2011). This model characterizes the decay of felt intensity (EMS98) with distance, for a given magnitude earthquake. The minimum and maximum magnitudes used in the derivation of the intensity attenuation relation were around 3 and 6 respectively, with most intensity data recorded between magnitudes 4.5 and 5.5. The functional form of the model is:

$$M = c_1 I_{obs} + c_2 Ln\left(R/h \right) + c_3 \left(R - h \right) + c_0 , \qquad (3)$$

with

$$c_0 = \alpha\left(aLn\left(30/h\right) + b(30-h)\right) + \beta;\ c_1 = \alpha;\ c_2 = -a\alpha;\ c_3 = -b\alpha \qquad (4)$$

and

a=-0.67755
b=-0.00174
α=0.734
β=1.28
h=10km.

with R is the hypocentral distance, h the source depth, M is the moment magnitude and I_{obs} the observed intensity. In addition to the macroseismic model relating magnitude and intensity, Faenza and Michelini (2010) showed that:

$$I_{obs}=1.01+2.56 \log(PSA(0.3s)), \qquad (5)$$

$$I_{obs}=3.02+2.10 \log(PSA(1.0s)), \qquad (6)$$

$$\text{and } I_{obs}=4.22+2.05 \log(PSA(2.0s)) \qquad (7)$$

Using stochastic simulations for PSA, along with the PSA to intensity conversion relation of Faenza and Michelini (2010) we are able to simulate intensity attenuation. The simulation of ground-motion was performed following the method described in Boore (2003) using the program SMSIM. This method takes an input model for the Fourier acceleration spectrum based on parameters described above and in Edwards et al. (2011) such as M_W, Q, Δσ, κ, geometrical spreading, site amplification and the duration of shaking. The finite fault is considered in a geometrical sense by using the R_{eff} distance metric, which has been shown to work for events up to **M**7 (Boore, 2009).

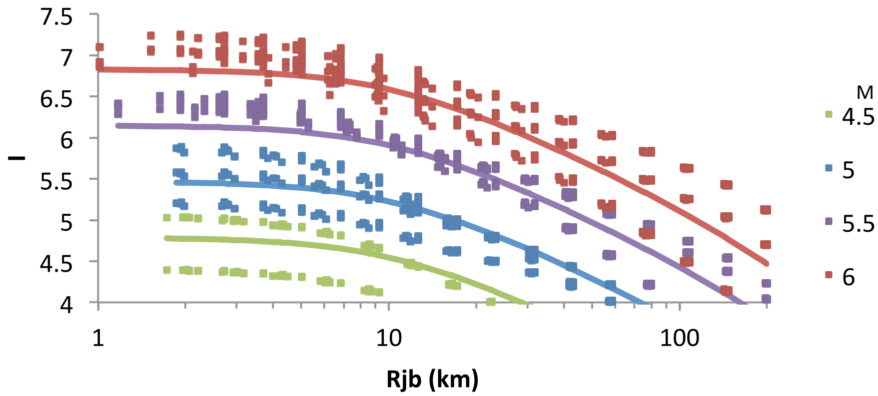


Fig. 4: Top: Fit of the simulated intensity values (points) (using Z_h=12km, $\Delta\sigma$=62.5 bars) to the ECOS09 macroseismic model (lines) corrected to rock for M=4.5 to 6.0.

The pseudo-finite fault simulations allowed us to compare predicted ground motion with the macroseismic model valid for Switzerland (*Fig. 4*). Using a fixed (Z_h=12km) hypocenter model (consistent with seismicity), the resulting calibrated stress-parameter was 6.3MPa.This resulted in the ECOS09 macroseismic model and the stochastic model being consistent at M>5.

In order to satisfy the observation of low average stress-parameter at low magnitudes and higher average stress-parameter at M>5 we use a simple model of increasing stress-parameter up to a cut-off magnitude. After the cut-off magnitude the stress-parameter is assumed constant. Fixing the average value of 0.2MPa at **M**2.5 we increase the stress-parameter linearly in the log scale with increasing magnitude up to the value of 6.3MPa at **M**4.5 to satisfy the calibration with the macroseismic model.

RESIDUAL MISFIT

We computed the response spectra of events with M>3 and R<100km in order to test the stochastic model predictions. *Fig. 5* shows the residual misfit for 1, 5 and 20Hz PSA. The residual misfit shows that the model performs well, without obvious trends in distance or magnitude.

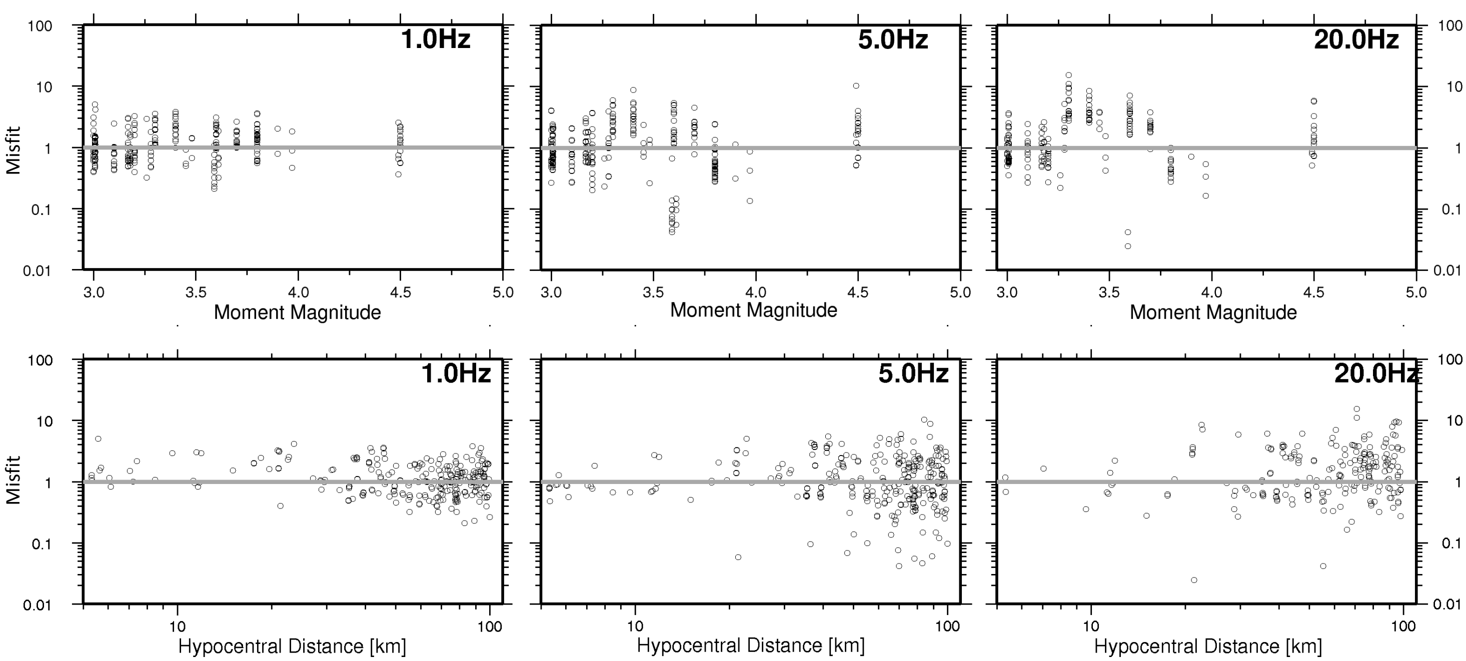


Fig. 5:residual misfit of the stochastic ground-motion model with response spectra from the Swiss Foreland region. The misfit is defined as the observed PSA divided by the modeled PSA.

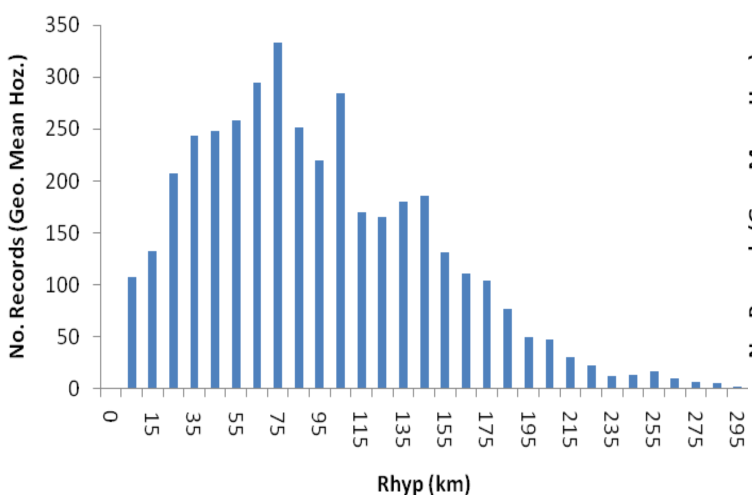
MODEL SIGMA

Following the nomenclature in Alatik et al. (2010), and assuming normal statistics, the total uncertainty of the model is given by:

$$\sigma^2 = \frac{1}{N}\sum_{n=1}^{N}(Y_n - \ln(f_n(\vec{X}_{es}, \vec{\Theta})))^2 \quad (8)$$

where Y_n is the natural log of the observed ground-motion and $f_n(\vec{X}_{es}, \vec{\Theta})$ is that predicted by the model for observation n. $\vec{X}_{es}$ is the vector of independent parameters (magnitude, distance , etc.) and $\vec{\Theta}$ is the vector of model parameters. This can be split into inter- and intra-event terms, τ and ϕ respectively. We separate the total uncertainty, σ into the parameters:

1. τ (or inter-event variability);
2. ϕ_{S2S} (inter-site variability);
3. ϕ_0, ϕ_{Amp}, ϕ_{P2P} (intra-site variability);
4. σ_{SS} (Atkinson, 2006)



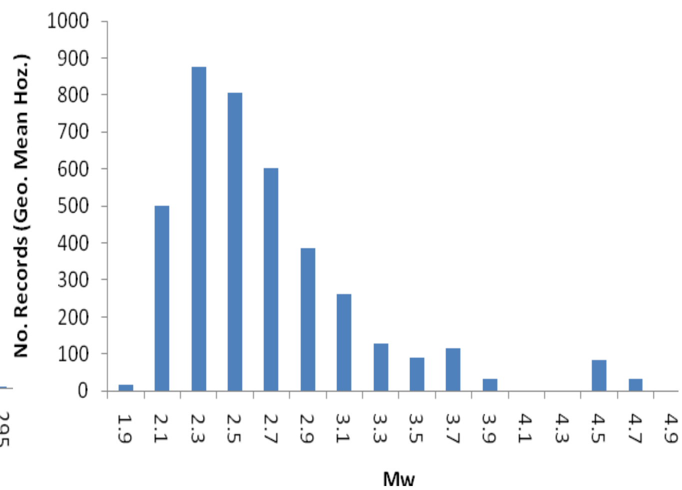


Fig. 6: Data distribution for residual analyses at 5Hz PSA.

Residual analysis of Swiss Foreland events with $2.0 \leq M_W \leq 4.8$ was undertaken using the response spectra data. Residuals are obtained from recordings (geometrical mean of both horizontal components) of Swiss foreland or Swiss foreland-border region events with $2.0 \leq MW \leq 4.8$ at distances between 5 and 300km, although the majority of recordings are made within 200km (Fig. 6). σ was computed from all events and stations in this selection. Following this, only events with more than 10 recordings and stations with more than 10 records were used to separate σ. This left 119 events recorded at 46 stations. The resulting uncertainty values are given in Table 1. It should be taken into consideration that at the lowermost frequencies sigma may be reduced due to the fact that only events with particularly strong PSA at those frequencies would pass the SNR checks.

Table 1: residual analysis of data from all events with $2.0 \leq M_W \leq 4.8$ including station correction terms and κ. Values are in natural-log scale.

T (s)	Freq. (Hz)	σ	τ	ϕ_{S2S}	$\sqrt{(\phi_{Amp}^2 + \phi_0^2 + \phi_{P2P}^2)}$	σ_{SS}
0.03	33.33	0.805	0.435	0.260	0.461	0.634
0.04	25	0.760	0.405	0.271	0.474	0.624
0.05	20	0.755	0.419	0.256	0.496	0.650
0.1	10	0.751	0.417	0.260	0.491	0.644
0.2	5	0.695	0.372	0.226	0.468	0.598
0.25	4	0.665	0.351	0.209	0.471	0.587
0.31	3.23	0.644	0.350	0.191	0.445	0.566
0.4	2.5	0.621	0.344	0.177	0.445	0.562
0.5	2	0.600	0.340	0.173	0.432	0.550
1	1	0.574	0.355	0.175	0.403	0.537
2	0.5	0.554	0.353	0.159	0.302	0.465
PGV		0.692	0.334	0.283	0.524	0.621
PGA		0.768	0.380	0.251	0.449	0.589

CONCLUSIONS

We presented an overview of the Swiss stochastic ground-motion model and corresponding uncertainties. The model is compatible with the Earthquake Catalog of Switzerland 2009 (ECOS09) and is referenced to a known shear-wave velocity profile. The model was calibrated at the upper end of the magnitude scale to the macroseismic attenuation model, itself consistent with the ECOS09. This carefully integrated approach ensures that the model is complementary to other aspects of PSHA, such as source model characterization (e.g., Wiemer et al., 2009) and site specific amplification (e.g., Cramer, 2006). Residual analysis confirmed that the model was suitable for predicting Swiss ground-motions between magnitudes 3 and 4.5 within 100km, while the calibration with macroseismic intensities should ensure the validity at the upper end of the magnitude scale.

Due to the stochastic nature of the model and the use of geometrical considerations of finite-fault effects the model is suitable for the prediction of ground-motion at all periods and magnitudes up to at least **M**7 (Boore, 2009). The valid distance range is 0 to 300km. Directivity effects are not included, but this is a feature in common with the majority of existing GMPEs. More deterministic scenarios could be implemented by utilizing software such as EXSIM (Motazedian and Atkinson, 2005), which discretize the fault into numerous point-sources and include rupture propagation effects. It is useful to decouple sources of uncertainty in PSHA in order to avoid double-counting. Model uncertainty was presented in terms of the single-site sigma (Atkinson, 2006), which provides a measure of prediction uncertainty for a particular site.

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