SED–Erdbebenforschung zu Schweizer Kernanlagen

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ABSTRACT

The goal of this project is to improve regional and local seismic hazard assessment in Switzerland. The project is split into three sub-tasks. In particular, for subproject 1, we have focused on the factors controlling the path- and site-specific attenuation properties. We performed numerical simulations to evaluate the relative contributions of scattering versus material damping. We also prepared a database of empirical ground motion durations extracted from waveforms recorded by the Japanese KiK-net network, with the goal to identify a proxy best explaining the site-specific duration patterns. Moreover, we have started to investigate the high-frequency ground motion at depth by separating the path- (observed at depth) and site- (observed at surface) terms of the attenuation, based on borehole seismological data. The resulting empirical models are complemented by physics-based numerical models derived in parallel. Within subproject 2, we have developed a library to accurately generate random fields for large-scale fully deterministic simulations that can be easily incorporated in many existing wave propagation codes. We have further extended a numerical code to simulate high-frequency stochastic time-series by solving the radiative transfer theory equations in laterally varying media. This tool is used in a collaboration with subproject 1 to study the physical origin of local site-attenuation parameter kappa. Within subproject 3, we have shown that increased pressure and temperature due to canister emplacements may lead to reduction in effective stresses and increase in shear stress on faults and fractures located at a distance from the repository. We investigate the short term (0–5000 years) effect of the canister emplacements and associated coupled thermo-hydro-mechanic processes (thermal pressurization, desaturation and re-saturation of the buffer material) on the stability of faults and other weak structures in the surrounding of the repository (at a distance of 200 meters or more) at different locations and orientations. The reactivation of such structures depends strongly on the background tectonic stress, while the magnitude of the perturbation depends on their proximity and relative location to the repository.

Project goals

This science project is split into three subtasks with the main goal to improve regional and local seismic hazard assessment in Switzerland. The sub-projects are:

1. Ground-motion attenuation models and earthquake scaling for Switzerland;
2. Modeling wave propagation in complex, non-linear media and limits of ground motion;
3. Induced seismicity and application for a deep geological disposal.

The focus of subproject 1 lies on the development and improvement of earthquake ground-motion attenuation and source-scaling models for Switzerland. We target ground-motion estimates for sites at depth and at the surface, in the near field, for damaging events and for smaller earthquakes as well. The work is based on observations in Switzerland and Japan. Studying the near-surface amplification and attenuation constitutes a key point in our research.

The scope of subproject 2 is to improve deterministic predictions of ground motion, especially with respect to near field, to nonlinear behavior in sedimentary rocks and soft soils, and to new trends in modeling complex source processes. This includes the calibration of material parameters via field measurements and the development of numerical codes to simulate ground motion in three-dimensional complex media. Results of subproject 1 will be linked to deterministic simulations from subproject 2, and the results will be tested and compared to observed data.

In subproject 3, we move towards a more realistic characterization of seismogenic sources for induced earthquakes. The goal is to adapt existing geo-mechanical models to a situation of a deep geological disposal (e.g. nuclear waste repositories), develop and validate new modeling methods, and integrate them in a probabilistic framework for seismic hazard assessment.

Work carried out and results obtained

1. Ground-motion attenuation models and earthquake scaling for Switzerland

Subproject 1 is aimed at improving ground-motion prediction in Switzerland. This requires full understanding of the local site conditions as these can strongly affect both amplitude and duration of the recorded ground motions. Amplification models, although widely used in seismic hazard assessment studies, present significant epistemic uncertainty mostly related to the local site-attenuation parameter kappa [1]. The origin of this parameter is not yet fully understood and still debated. In this context, [2] used Swiss data to investigate the contributions of path- and site-terms to the high-frequency attenuation and found the interplay of intrinsic attenuation and wave scattering. We analyzed different contributions to the high-frequency attenuation observed in earthquake recordings and have shown that measurements of kappa are significantly biased by aspects that are generally disregarded in scientific studies (e.g., installation features). Our ongoing investigation on the nature of kappa relies also on advanced numerical modeling techniques (Imperatori et al., 2019) that allow us, for the first time, to study the problem in 3D. These techniques have been recently extended to laterally varying media (see subproject 2).

Recently, Bard et al. (2019) showed that the Vs_{30}-kappa adjustments on classical GMPEs in the response-spectral domain should be avoided, as the epistemic uncertainties are very high and not well defined. A reliable assessment of properties of local near-surface layers is essential for reducing epistemic uncertainties of the amplification models. Hence, we focused also on improvements of the cutting-edge inversion techniques on these properties (i.e. inversions on Vs-profiles). Specifically, in Hallo et al. (2019) we propose a novel trans-dimensional probabilistic inversion technique on near-surface Vs-profiles from dispersion and ellipticity curves.

The development of reliable empirical site-amplification models, especially from the point of view of ground motion duration, constitutes another important research direction. In particular, we aim to provide a tool to discriminate between sites with 1D or 2D/3D site response and to develop site-specific duration models. For these purposes, we prepared a database of total durations, computed using different algorithms (based on Arias intensity, [3]; or on the slope of the Arias intensity graph [4]). The database was compiled from Japanese KiK-net waveforms [5], recorded in the period 1997–2016. The dataset comprises ~115000 measures of duration on the horizontal component, originating from 5200 events with magnitude ≥ 3 and recorded at 689 surface stations. For compat-

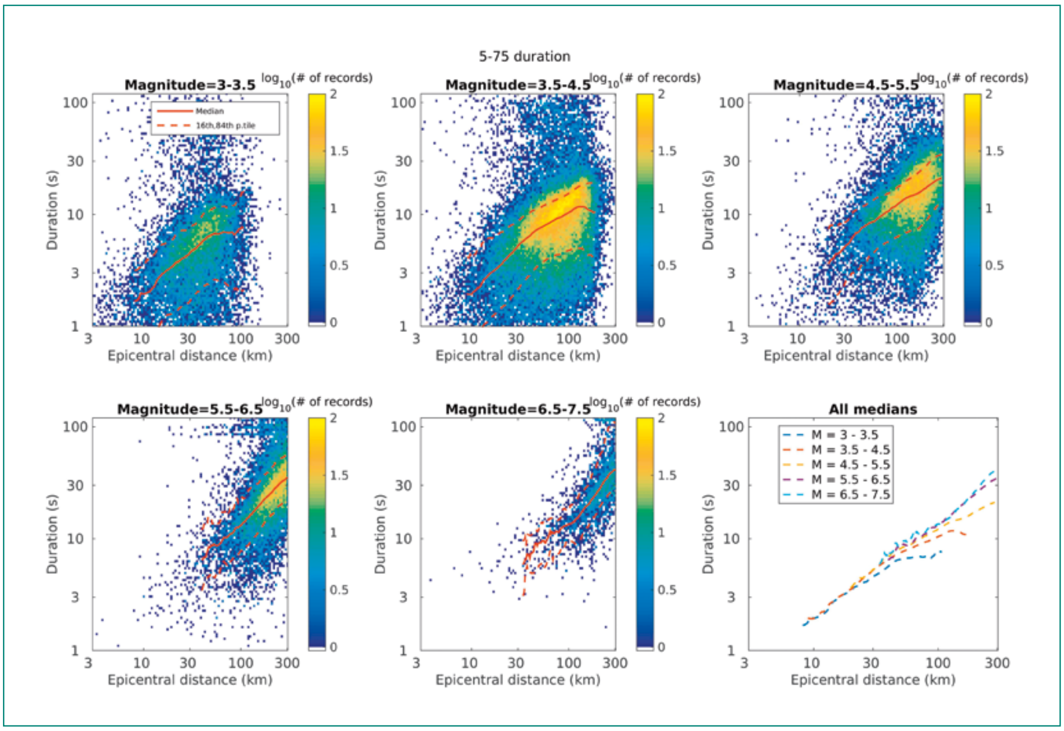


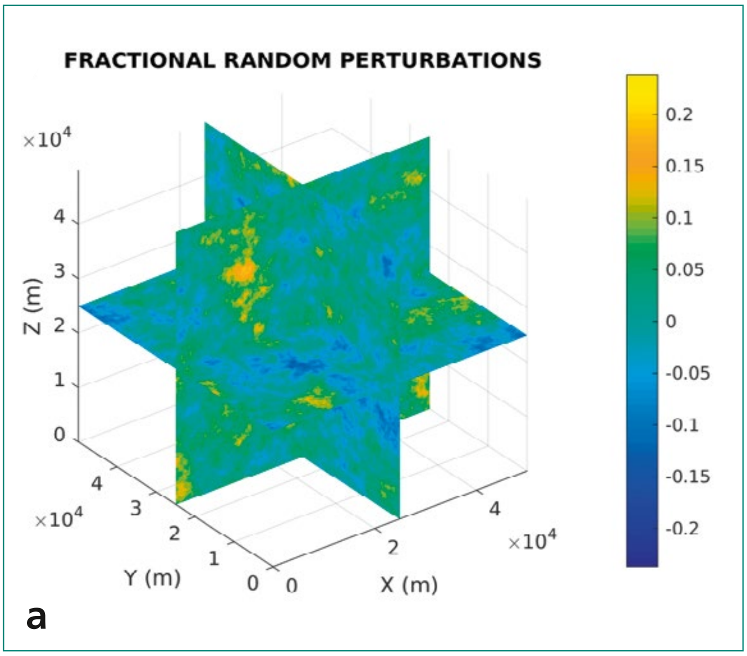
Figure 1: *Overview of the database of durations obtained from KiK-net recordings from the time interval 1997–2016. Each of the first 5 panels shows the 2D histogram of horizontal durations for events within a respective magnitude bin. The color scale refers to the number of records in the bin; red lines represent the data median and 16th and 84th percentiles. The medians from all magnitude bins are compared in the lower right panel. Note that, within a definite distance range (15–50 km), the rate of duration median as a function of epicentral distance is the same, for all magnitudes. Deviations from this patterns occur at long distances (> 50 km) for low magnitudes (M≤5), possibly because of the decay of the signal-to-noise ratio.*

ibility with the Swiss condition, we analyzed only crustal events. Figure 1 presents an overview of the collected data. The database of durations is accompanied by events' metadata (magnitude, hypocentral depth, epicentral distance) as well as a proxy-based description of the recording stations. These proxies include a description of site condition based on Vs profile, geological information, as well as topographical parameters (e.g. terrain slope and curvature). We are currently analyzing the deviations from the average duration behavior site by site, so to identify the proxy (or proxies) best explaining the site term in the modeling of strong motion duration. We expect to find some kind of correlation between time elongation of ground motion and topography in particular configurations (sedimentary valleys or basins). It should be noted that these topographical environments host as well 2D or 3D wave phenomena; hence we anticipate to be able to identify sites where 2D-3D resonance occurs from the analysis of the elongation of ground motion.

We also focused on separating the path- (observed at depth) and site- (observed at surface) terms of the attenuation based on borehole data. For this task we applied a correction procedure for surface-to-borehole Fourier spectra [6], and obtained empirical surface-to-borehole amplifications as the site-effects of the near-surface layers. These empirical models are complemented by a parallel physics-based modeling approach for the surface-to-borehole amplifications and envelope delays [7]. In this approach we first derive a set of 1D velocity profiles considering of various possible effects of the near-surface geology on ground motions. The depth-to-surface transfer functions computed in these random 1D velocity models are then used to construct a stochastic model of ground motions at depth.

2. Modeling of wave propagation in complex, non-linear media and limits of ground motion

Research in subproject 2 has focused on several aspect of ground motion modeling, particularly at high-frequency. As it has been shown (e.g., [8], [9]), random velocity heterogeneities in the crust can heavily influence the ground motions in terms of amplitude and spatial variability. Such effects can be comparable to those induced by complex rupture processes along the fault plane ([8]). It is therefore of utmost importance that physics-based broadband deterministic simulations, which are



becoming increasingly more popular, correctly incorporate small-scale perturbations of the elastic parameters.

Unfortunately generating random fields with arbitrary statistical characteristics on very large grids (in the order of billions of points) is not straightforward. Moreover, computational limitations may force researchers to produce random fields whose actual characteristics deviate from the desired ones (e.g. [10]). To overcome such limitations, we have developed a library that can be used to conveniently generate random fields with the correct characteristics directly inside the wave propagation tool of choice, thus also avoiding costly input/output operations. Our library is designed to strike a good balance between performance and memory requirements and targets both structured (e.g. finite-differences) and unstructured (e.g. spectral

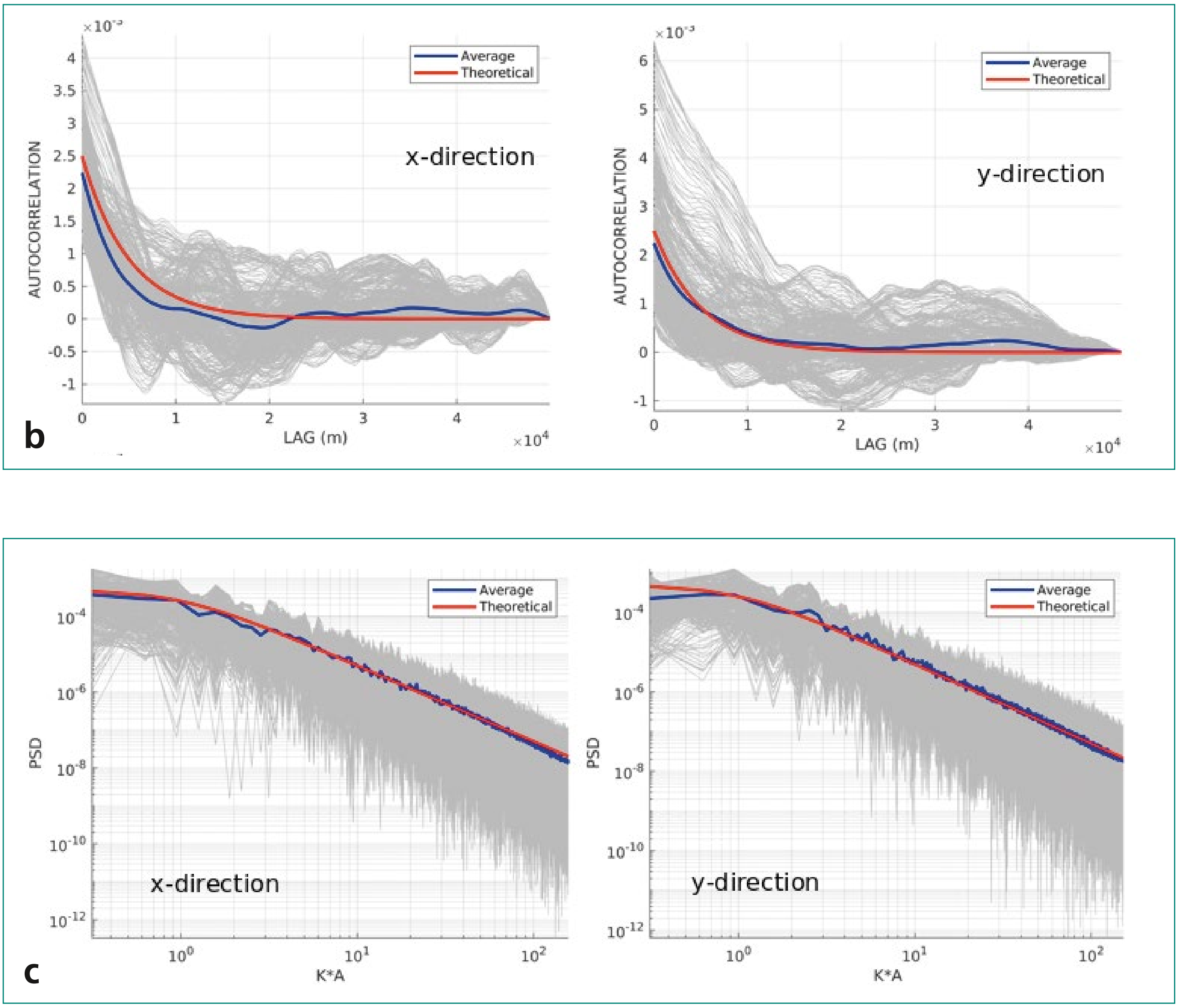


Figure 2: *A) Sample realization of isotropic 3D fractional random perturbations based on the FFT approach for structured grids. The random field is characterised by a Von Karman autocorrelation function having 5000 m correlation length, Hurst exponent equal to 0.5 and 5% standard deviation. Inset B) show the autocorrelation of the random field on the horizontal plane Z=25 km along the X- and Y-direction, while inset C) show its Fourier transform (corresponding to the power spectral density PSD of the random field), where the spatial frequency is multiplied by the correlation length. The resulting average autocorrelation and PSD (in blue) fit nicely the corresponding theoretical curves (in red).*

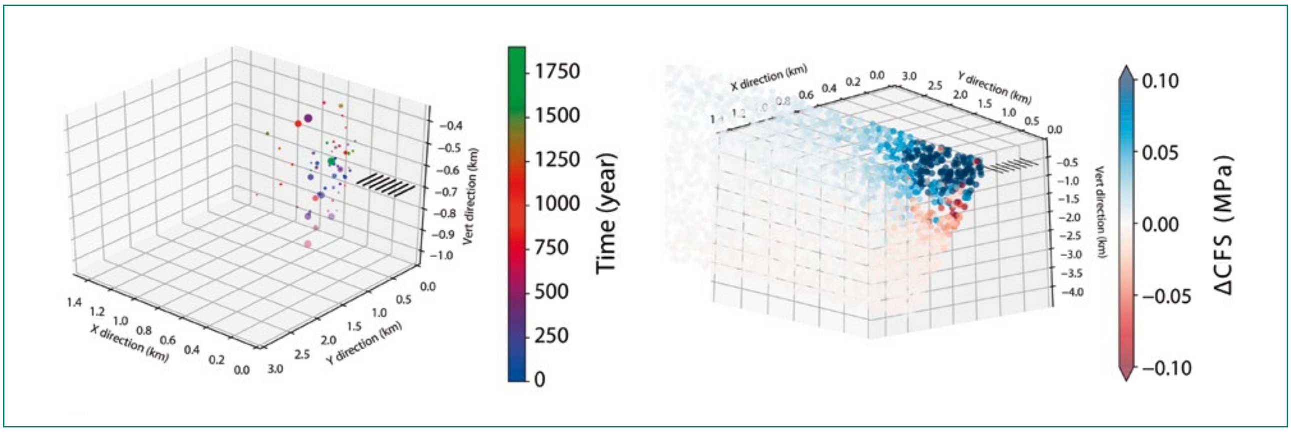


Figure 3: *Realization of a single synthetic catalogue generation from a large scale 3D model. Small black line are the locations of 12 half emplacement tunnels (representing one quarter of the repository). A) Seeds triggered during the repository evolution (from 0 to 5000 years after emplacement). Colours represent time of rupture. B) Example of variations in Coulomb Failure Stress for a given stress state (here at 1000 years after emplacement) for a volume of seeds representing a fault structure located at 450 m from the outer edge of the repository.*

elements, discontinuous Galerkin) meshes. In particular, we have implemented a recently developed random field generation technique ([11]) and extended its use to general Von-Karman autocorrelation functions. This technique has the particular characteristic of presenting a very low memory footprint but it is computationally very intensive, requiring GPUs-equipped computing infrastructures. For this reason, we have implemented also an FFT-based generator that works well with ordinary CPUs and that is well suited for structured meshes. Figure 2 shows a sample random field generated on a regular mesh, demonstrating how the desired statistical characteristics are retained.

In the framework of a collaboration with subproject 1 targeted to determine the physical origin of the local site-attenuation parameter kappa, we have extended a numerical code developed to generate high-frequency stochastic time-series based on the radiative transfer theory (RTT, [12]). The code computes sets of random, uncorrelated time-series at a large number of receivers shaped by energy envelopes representing the joint effect of scattering and intrinsic attenuation. In its initial version, we considered isotropic sources embedded in a half-space and modelled only S body waves as these represent the largest component of coda waves. In an effort to improve our modeling, we have resorted to a Monte Carlo simulation technique to solve the RTT equations in laterally varying structures (e.g. basins) and in presence of irregular free-surface. Our approach is based on a particle-counting method and it can be used to simulate direct and scattered elastic body waves. Comparisons with semi-analytical solutions for simple media have indicated so far the validity of our approach. Finally, we have started a project concerning the validation of a high-resolution 3D velocity model for the Visp area (Switzerland). The validation is based on comparisons between fully deterministic high-frequency numerical simulations and seismic events and noise recorded by the local Swiss seismic network.

3. Induced seismicity and application for a deep geological repository (DGR)

The overall objective of this subtask is to extend the work performed in Phase 1 of the project on the geo-mechanical response due to canisters emplacement in term of fault stability, including additional complexities and a stochastic approach to the fault stability analysis.

In particular, we move along the following directions:

- We extend the results from [13] with the stochastic seed model [14, 15] and include three-dimensional effects on the fault stability, investigating the a-posteriori effects of stress changes.
- We develop an enhanced forward model to include the possible influence of near-field effects (gas generation and pressurization, bentonite buffer effects) on the occurrence of induced (micro-) seismic events, extending the results obtained in the Phase 1 (2014–2018) by our approach based on the iterative coupled geo-mechanical solver *TOUGH2-FLAC3D [13].*

Regarding the near-field processes, a site-specific assessment of their relevance can be found in [16]. The small-scale model there presented investigates the evolution of the stress path in the host rock, finding that integrity of intact rock is not affected by the additional complexity introduced by considering the gas generation and the bentonite buffer or the extended damage zone. These results confirm the intact rock mass response simulations already presented in [17]. However, the interaction of near-field effects with the thermal pressurization and their combined effects on nearby plane of weakness (i.e. faults or other geological discontinuities) as calculated in [13] remains to be determined. A numerical tool based on *TOUGH3-FLAC3D,* replacing the previously used *TOUGH2,* allows to obtain a solution for a model with more than 106 degrees of freedom [18].

Regarding the stochastic model, a three-dimensional extension of work presented in [13] has been performed to permit the calculation of the stress and pressure changes taking place due to the canisters emplacement. Preliminary results of such a large scale model are presented in Figure 3. With the aid of the *seeds model* different stress regimes for different faults locations and orientations are being investigated: a statistically significant number of seeds is distributed in a thin volume representing fault location and orientation. The seeds are reactivated if the oriented Mohr-Coulomb failure criterion is reached. The main assumption behind the *seeds model* is the inverse relationship between differential stress and b-values (this is a statistical property arising from tectonic earthquakes and from laboratory experiments): as a consequence, when a seed is triggered, a random magnitude is drawn from a power law-distribution based on the assigned b-value (or stress). For a given seeds distribution, one synthetic catalogue is produced. Statistical analysis will then be performed for robustness on a large number of synthetically generated catalogues. Figure 3a shows a single catalogue, while Figure 3b depicts the stress changes on the seeds. Whether this stress changes will result in reactivation of the seed depends strongly on the background tectonic stress, while the magnitude of the resulting event depends both on the expected statistical behaviour from seismic sequences and the seeds' properties.

National Cooperation

The validation of the 3D velocity model for Visp is in collaboration with Swisstopo and the canton of Wallis. We also have collaborations with experiments performed at the Mont Terri Underground Lab (FS, FS-B).

International Cooperation

Part of the research activities within subproject 1 and 2 is in collaboration with IIT Gandhinagar, India. Research on numerical ground motion modeling has strengthened our cooperation with the King Abdullah University of Science and Technology in Jeddah. Research on induced seismicity during operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. We also take part to international initiatives to benchmark and validate numerical models (BENVASIM, DECOVALEX).

Assessment 2019 and Perspectives for 2020

Future work in the Subproject 1 will involve analysing deviations from the average ground motions duration behaviour in our database, so to identify the proxy best explaining the site term in the modeling of strong motion duration. We will also continue in the development of the physics-based stochastic model to characterize high-frequency ground motion at depth and we will compare our theoretical predictions with measured borehole-to-surface amplifications. We will enhance the Swiss stochastic model by assuming a stochastic kinematic finite-extent source model with azimuthally dependent source spectra. This should lead to improvements in the prediction of near field ground-motions at Swiss sites caused by large earthquakes which might occur during long return periods.

In the framework of subproject 2, we have developed a flexible library to conveniently generate large-scale random fields that can be used in challenging high-frequency deterministic simulations. This library guarantees that the output random field has the desired statistical characteristics. The library will be described in a dedicated paper and made available to the seismological community. We have further improved a numerical code to simulate stochastic high-frequency time-series in laterally varying media. The code has passed a first validation stage and will be further validated and calibrated by comparison with finite-difference simulations. It will be used to investigate the nature of site-attenuation parameter kappa in 3D and to quantify the relative contribution of scattering and intrinsic attenuation to the total attenuation at several sites in Switzerland. A paper focusing on an application of the hybrid broadband method has been finalized and published. The method will be further extended to handle receivers at depth. The ongoing validation of the 3D velocity model for Visp will help to define a robust validation procedure based on single-station and array recordings that can be extended to other sites in Switzerland.

Concerning subproject 3, the stochastic model will be improved considering heterogeneous properties on the fault and/or different stress regime. The extension to the 3D modeling and the statistical analysis will give insights into the behaviour of strike-slip structure which could not be analysed with the 2D model. The stochastic model will be based on general consideration of a repository built in an argillaceous rock formation. However, useful insights both for the quantification of the additional load due to the canisters and due to the presence of geological structures in relation to the contemporary stress state may come from international underground laboratories experiences (i.e. experience from the French underground laboratory in Bure) and/or from national Swiss investigations (the current drilling campaigns performed by NAGRA and previous investigations). The enhanced forward model will give insights into the far field effect of the gas generation and pressurization, both in terms of fault stability and ground heave/deformations: magnitude of the deformation and of the shear slip is unlikely to change with respect to a simpler model, however the occurrence time and the relation distance/rupture time found in [13] may be affected.

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