Seismological research concerning Swiss nuclear installations

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Abstract
The main goal of this research project is advancements in the regional and local seismic hazard assessment in Switzerland with a particular focus on nuclear facilities. The project includes an assessment of the local amplification of ground motions on the ground surface and underground, modelling of the wave propagation in complex media, research on time-dependent earthquake forecasting, and applications for the deep geological disposal of nuclear waste. For subproject 1, we developed and applied a method to assess the ground motion at a depth. This physics-based method was validated by empirical earthquake data measured at six borehole sites in Switzerland. As an application, we performed full-waveform prediction of ground motion at depth from surface recordings of seven significant Swiss earthquakes, which showed a very good performance of the method. We also tackled the issue of predicting the ground motion at depth caused by future potentially damaging earthquakes. To do so, we modelled synthetic broadband waveforms for an event that can occur within the 9975 years return period and associated motion at depth. Within subproject 2, we developed a computational mesh that fully accounts for surface topography and crustal velocity structure in the Rhône basin. Based upon spectral-element simulations, we verified our numerical setup up to 1Hz. With the developed framework, we aim to continue implementing models of other Swiss basins for ground motion numerical modelling with spectral-elements. In subproject 3, we did a thorough review of operational earthquake forecasting (OEF) systems worldwide and gathered expert recommendations for their establishment. Based on these guidelines, we developed and tested several model variants that can be applied for this purpose in Switzerland.

Project goals
This research project is divided into three subtasks with the main goal to improve regional and local seismic hazard assessment in Switzerland. The subprojects are:
- Ground-motion attenuation models and earthquake scaling for Switzerland;
- Modelling wave propagation in complex, non-linear media and limits of ground motion;
- Time-dependent earthquake forecasting.

The focus of subproject 1 lies in the development and improvement of earthquake ground-motion attenuation and source-scaling models for Switzerland. We target ground-motion estimates for sites in the near field (at the soil surface and at depth) for damaging events; we also target smaller induced earthquakes. 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 concerning near-field, nonlinear behaviour in sedimentary rocks and soft soils, and new approaches for modelling 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. The results of Subproject 1 will be linked to deter-

ministic simulations from Subproject 2, and the results will be tested and compared to observed data.

In subproject 3, the aim is to develop a time-dependent earthquake forecasting model which during an ongoing seismic crisis can answer questions related to the probability of the occurrence of large earthquakes in the near future. This includes the development and testing of a model describing the time-dependent seismic hazard, the establishment of communication products that translate the model output into useful information for ENSI, and the assessment of the applicability of earthquake early warning in Switzerland.

Work carried out and results obtained

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

Subproject 1 is aimed at improving knowledge of ground-motion attenuation and amplification at Swiss sites. On the national scale, the ground-motion prediction equations and site amplification models were developed within the previous phase of the project [1]. On the regional scale, a relation between site amplification and site characteristics was studied by [2] via site proxies (e.g. bedrock depth, multi-scale topographic slope, lithology). Further, site-specific effects on the ground surface and underground were studied in detail within this project phase.

First, we made a significant step forward regarding the characterization of the ground motion at depth in the Swiss Molasse basin. This is especially important for the seismic hazard assessment of the planned deep geological disposal of nuclear waste. In particular, we focused on the SED Swiss stations of BOBI, HAMIK, STIEG, ROMAN, WOLEN, and SVISP, which are equipped with both surface and borehole seismometers (part of NAGRA, SDSNet, and SSMNet networks). We determined empirical surface-to-borehole amplification and compared them with the theoretical model introduced by [3]. Next, we performed full-waveform prediction of ground motion at depth from surface recordings (by method [4]) of seven significant regional earthquakes with $M_L > 4$. The comparison of predicted and observed acceleration waveforms showed a high level of similarity in a broad frequency range and well-predicted values of the peak ground acceleration (PGA), peak ground velocity (PGV), and response spectra of single-degree-of-freedom systems. Then, we modelled a scenario earthquake for 9975 years return period at a test site (assuming the Swiss seismic hazard model SUIhaz15 from [5] (Figure 1a), and we predicted associated broadband waveforms at depth (Figure 1b). By the latter, we demonstrated that our method to predict ground motions at depth can be used as a basis for the site-specific seismic hazard of deep geological disposals of nuclear waste in Switzerland. More specifically, response spectra at depth have smaller amplitudes and different shapes than on the ground surface; and the ground motion predicted at depth may cause damage to sensitive parts of the underground structure if neglected during the construction design. These results were published in an international impact journal by Hallo et al. (2023a).

As a second topic of research, we focused on the robust estimation of the geo-mechanical properties of the near-surface, such as shear-wave velocity and material damping; these are the parameters determining the local amplification, hence their proper reconstruction is of interest to this project. In previous years, we developed a Bayesian inversion method that is capable of inferring the near-surface shear-wave (S-wave) structure including uncertainties [6], and applied it to a large dataset in the Basel area to retrieve a 3-D geological-seismological model at an urban scale [7]. As the next step, we developed a new method to predict the site-specific amplification based on the near-surface S-wave velocity model. This physics-based method is based on a novel energy-based concept of the multipath propagation of waves in viscoelastic media with random heterogeneities. Similar to the method by

[3], the site-specific response is defined by two coupled spectral curves, which relate the energy spectral density (ESD) and envelope delay (ED) on the soil surface to those at the reference rock outcrop. Then, the predicted amplification is corrected to the Swiss reference velocity profile following the approach by [8]. Our paper about this method and its application in Zürich city has just been published in an international impact journal (Hallo et al., 2023b). In fact, in the perspective of integrating site effects into future probabilistic seismic hazard assessment (PSHA) – a topic of current development in the seismological community – the study of Hallo et al. (2023b) provides a method to translate velocity models of the subsurface into realistic transfer functions, predicting also the soil response in terms of ground motion duration. The method may be applicable, for instance, to transfer the ground motion from a standard reference rock condition to a specific target site on the soil surface.
Further, to estimate local near-surface S-wave velocity models and local damping (κ_0) in Switzerland, we adapted the wavefield decomposition technique for the processing of surface waves propagating in inelastic soil media [9]. This improved method allows us to retrieve multimodal phase velocity and ellipticity as well as the frequency-dependent attenuation coefficient. The method was applied to real data from Switzerland; we determined the S-wave velocity and damping ratio for the soil column below a test SED station (SKLW), through which we were able to model the empirical inelastic earthquake response (including values of κ_0) observed at the test site. These results were published in an international impact journal by Bergamo et al. (2023). This study is part of a more general effort – within this project – to better understand, estimate and model high-frequency attenuation. As earlier mentioned by Hallo et al. (2023b), future PSHA studies including site effects may benefit from the work of Bergamo et al. (2023). In fact, Bergamo et al. (2023) provide a method (and a code) to estimate the shear-wave damping ratio profile of the subsurface (i.e. to predict high-frequency attenuation at a target site) with non-invasive geophysical tests; secondly, performing experiments similar to the one carried out for the station SKLW at other Swiss instrumented sites may provide insight on the concurring contribution of material damping and scattering to attenuation.

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

The purpose of subproject 2 is to advance numerical modelling using novel techniques for simulating strong ground motion at Swiss sites including advancements in hybrid modelling, addressing scattering and incorporating shallow crust complexity. Within the scope of this subproject, we implemented models of the Rhône Valley, an area with countrywide higher seismic hazard according to the SUIhaz15 model [5]. The region is characterized by complex geometry and velocity structure. These developments serve as a base for advancing the implementation of basins and valleys in Switzerland for high-fidelity spectral-element waveform and ground motion modelling. To robustly constrain local seismic hazard assessment in areas of critical infrastructure, we deem it necessary to develop modular numerical meshes for geometries such as valleys surrounded by rough topography and include 3-D basin velocity structure. This is done in a workflow that is based upon the spectral-element method and allows us to calculate full waveforms and properly account for complex wave propagation effects. The developed workflow will also be used for 3-D modelling of wave propagation in the Swiss Molasse basin and Basel area. With this high-fidelity ground motion modelling procedure, we can reliably perform simulations of larger magnitude scenario earthquakes at long-return periods, necessary for local hazard assessment in areas of important infrastructure.
First, a numerical mesh accounting for soft sediment layers by [10] above fully 3-D deeper crustal velocity structure by [11] was constructed. A second mesh was implemented

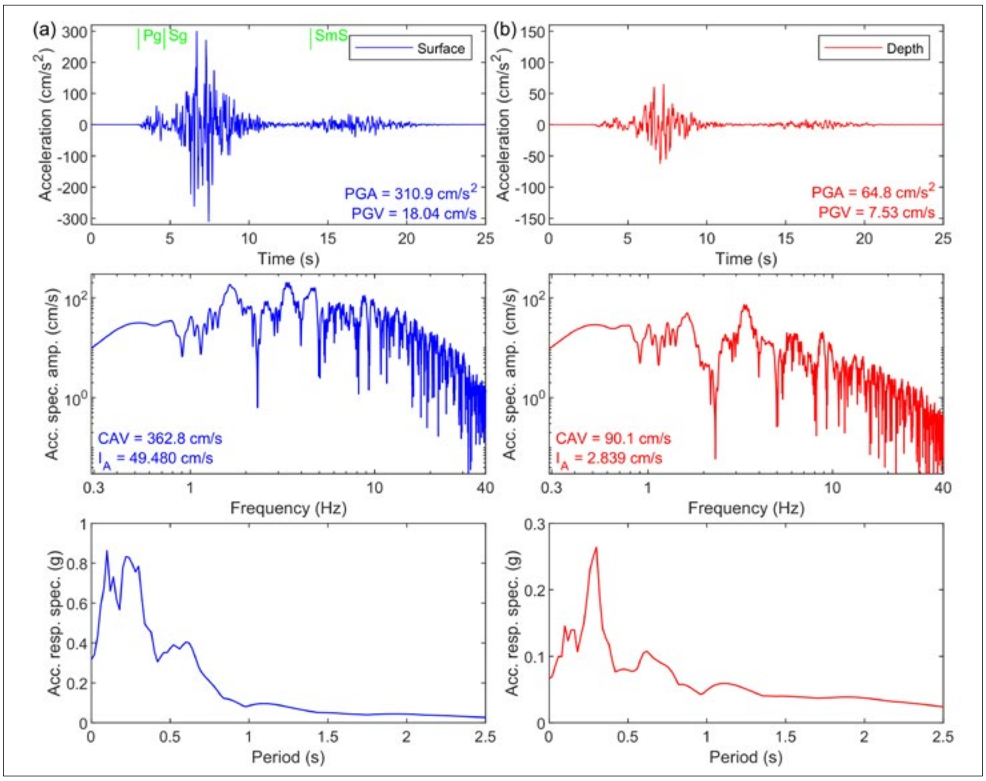

Figure 1: Full-waveform prediction of ground motion at depth for the M_w5.8 earthquake scenario (i.e., the dominant event from disaggregation of the Swiss seismic hazard model SUIhaz15 for 9975 years return period). Acceleration waveforms, Fourier spectra, and elastic response spectra of the dominant horizontal component are shown for (a) synthetic broadband waveform modelled on the ground surface at the BOBI site of Nagra network (Joyner-Boore distance 5 km from the assumed fault plane), and (b) borehole waveform predicted at 153 m depth from surface synthetics.

with the same 3-D deeper crust model and realistic surface topography of the Rhône valley and surrounding mountains. Both meshes were constructed with a maximum frequency resolution of 1 Hz and were implemented within spectral-element software Salvus, developed by [12, 13]. This numerical method is preferred because it naturally accounts for surface topography via its free-surface boundary condition, without external mesh refinements, and it also allows us to easily determine layered velocity structure from shallow to deeper crust. Both these properties of the Earth model are essential for accurately simulating full waveforms and ground motion. Both surface topography and 3-D shallow velocity of soft sediments have been shown to affect ground motions greatly, e.g. [14]. Surface topography is shown to reduce PGA in hilly areas. At the same time, in adjacent valleys complex wave propagation can occur, determined by basin effects. It was also shown during past work within ENSI phase 2 by [15] that the combined effect of these Earth parameters can intricately influence strong ground motion and their separability can be difficult due to quite varying effects on seismic waveforms. Additionally, it was speculated that scattering due to either surface topography or velocity heterogeneity can be approximated by back and forward scattering, thus necessitating hybrid scattering models. With the spectral-element method and HPC resources at the Swiss National Supercomputing Centre, granted to Koroni et al. (2023) for the project [16], physics-based full-waveform deterministic modelling up to 1–10Hz (depending on the domain size and velocity model resolution) can be routinely performed for complex topographies together with subsurface 3-D basin velocity structure without excessive computational overhead and with fewer approximations of complex wave propagation.

Further, the implementation was used to assess the influence of two separate parameters on time series representing displacement, velocity and acceleration waveforms recorded by the Swiss broadband stations and the temporary network in the area of Sion operating between 04/2004-04/2006

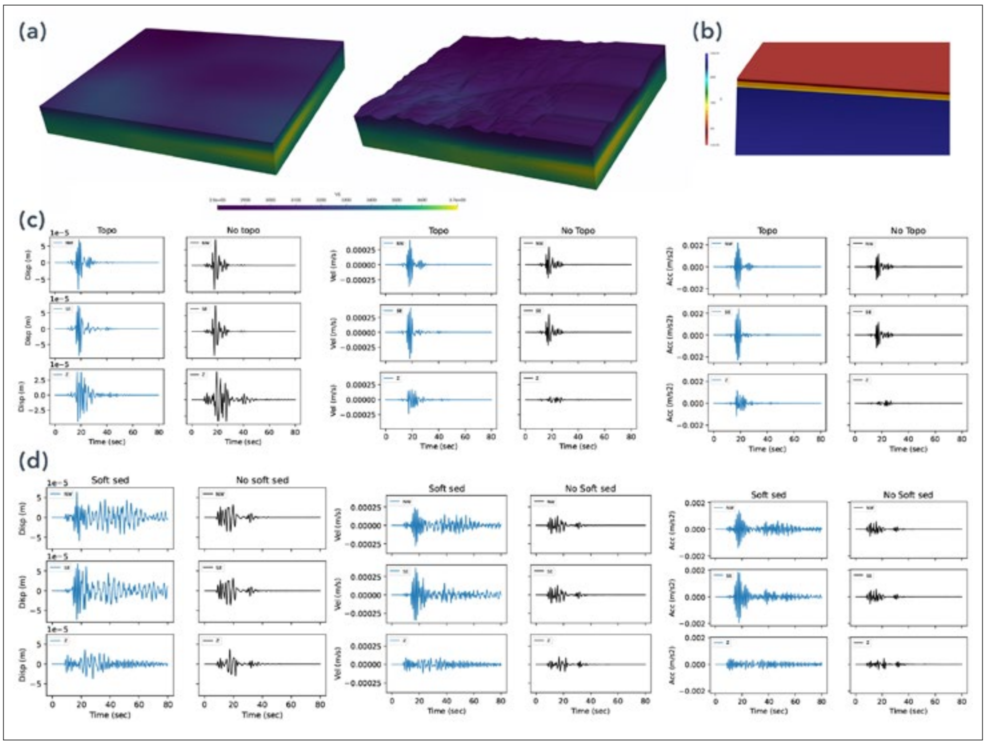

Figure 2:
(a) Numerical mesh of the Rhône valley without topography (left) and with topography (right) adeptly including surface topography with resolution up to 1Hz. (b) Close-up of numerical mesh without topography, but including soft sediments by [10]. The mesh resolution is again 1Hz. (c) From left to right: Synthetic waveforms of displacement, velocity and acceleration with (black line) and without (blue) surface topography for the location of the broadband station CH.SENIN at 2019.6 m. (d) Similar to (c) for simulations with (black) and without (blue) soft sediments from [10] and deeper 3-D crustal velocity from [11].

[17]. Given the paucity of strong-motion instrumental records, the event that occurred in Vallorcine (FR) on 8/9/2005 ($M_w = 4.4$) was used. Examples of synthetic waveforms for a location of one Swiss broadband station at a high altitude and a station from the temporary network within the valley, along with the numerical mesh used for simulations, are shown in Figure 2.

The figure shows the validation of implemented meshes with surface topography and soft sediments, with the relevant waveforms for each channel of the selected stations. We have successfully validated the deterministic simulations up to 1 Hz, which produced waveforms with expected features of basin and topography effects. The results from the workflow implementation have been submitted in a conference paper for the 18th World Conference of Earthquake Engineering by Koroni et al. (2023). We aim to implement both properties into one mesh with higher resolution for the Swiss Molasse basin using existing velocity models starting from [18] and tested also in Hallo et al. (2023a).

3. Time-dependent earthquake forecasting

Subproject 3 aims to develop a time-dependent seismic hazard model for Switzerland, including the specification of forecast visualization products based on the needs of the user of the forecast, and to revisit earthquake early warning (EEW) capabilities in Switzerland.

As a basis upon which the development of the time-dependent seismic hazard model for Switzerland can be built, we conducted a thorough review of the current state of operational earthquake forecasting (OEF) systems in Italy, New Zealand, and the United States. Partitioned into the three pillars **Model development, Model testing,** and **Forecast Communication,** the three OEF systems were characterized and compared. Subsequently, we conducted an expert elicitation using the Delphi method – an iterative process in which experts can indicate their level of agreement with given statements in an anonymous survey and then discuss dissent among the group during a joint workshop. Based on the workshop discussion, the statements are adapted and rated by the experts in the next round of the process. Again, distinguishing the three pillars, the Delphi study yielded a comprehensive overview of what experts in the field view as best practices in developing, testing, and communicating earthquake forecasts. Key findings were that epidemic-type aftershock sequence models (ETAS, [19]) are the recommended default model type to be used for earthquake forecasting. More specific model development guidelines were difficult to elicit, possibly because of the dissent among experts on whether models should be developed based on user needs. Similarly, for the testing of earthquake forecasting models, specific tests were not endorsed, but the focus was rather on testing philosophies. Models should be tested prospectively or pseudo-prospectively, benchmark comparisons and participation in third-party testing experiments (e.g., by the Collaboratory for the Study of Earthquake Predictability, CSEP, [20]) are recommended, and transparency and reproducibility of the results are highly encouraged. A main result in the communications pillar is that communication products should be developed in close collaboration with the end-users of the forecast. A review paper describing these findings has been submitted (Mizrahi et al., 2023).

Building upon these recommendations, we developed and tested seven variants of the ETAS model for Switzerland. Four of them were calibrated on the Swiss earthquake catalog (the live catalog based on ECOS-09, [21]), one uses parameters calibrated on Californian data [22], and two use parameters used by the USGS AftershockForecaster software which were calibrated on global data [23]. All model variants were afterwards tested in two different ways. First, pseudo-prospective one-week forecasting experiments were carried out, where all models were used to issue a forecast for a given week (without using the data recorded during or after that week), and their forecasts were compared to the actually recorded $M \geq 2.5$ earthquakes in Switzerland in that week. This was done for 8.5 years' worth of non-overlapping one-week testing periods to establish which models significantly outperform the other models, quantified through cumulative information gain (CIG) of a model compared to the time-independent null model. Figure 3 shows example forecasts issued by the different models for a specific week, and the overall results of these pseudo-prospective tests. Second, all model variants also underwent retrospective long-term consistency tests to check whether the number of expected $M \geq 4.5$ earthquakes within each model is, over longer periods of 30 years, consistent with past observed 30-year periods in Switzerland. This type of consistency test was also applied to check for the consistency of the spatial distribution of events as well as the distribution of magnitudes.

Finally, the preferred model variant was selected using a multi-criteria decision analysis (MCDA) approach. Six relevant criteria were identified: the results of the short-term (one-week) as well as the long-term (30 years) tests, the consistency of the model with the existing time-independent hazard model (SUIhaz2015, [5]), the run time of the model and its implementation cost, and whether the model was calibrated using local data. All models were given a score under each of these criteria, and the criteria were weighted according to their importance. Different weighting methods were tested, which all led to similar results. The recommended ETAS model for Switzerland is one calibrated on the Swiss catalog, which uses SUIhaz2015 information to model the spatial distribution of seismicity. A paper describing the model development and testing has been submitted and is currently under review [24]. The findings of both the review paper and the Swiss forecasting model paper will be summarized in a report to ENSI by the end of 2023.

An analysis of the potential change in the applicability for EEW in Switzerland due to improved network and data processing capabilities at the SED is currently being conducted, and its results will be reported in 2024, as specified in the project plan.

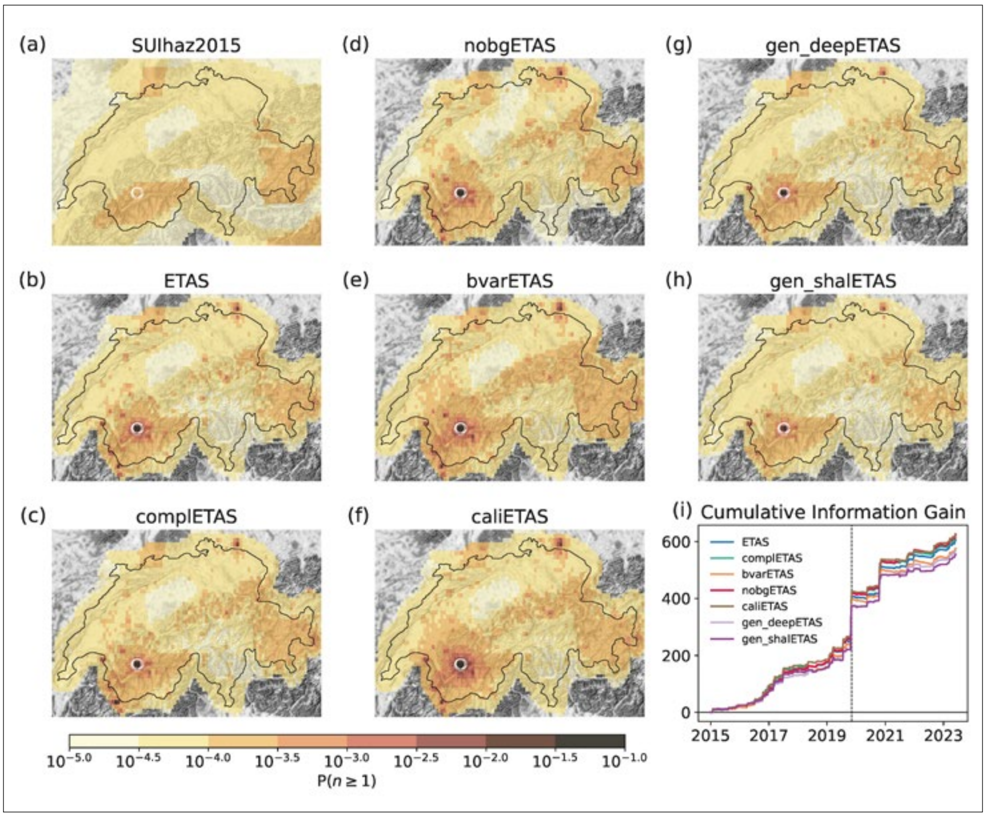

Figure 3: (a–h) Examples of 7-day seismicity forecasts produced by the considered models for the week starting on 07 Nov 2019. The colour of each pixel of 0.05°lat × 0.05°lon ≈ 5 km × 5 km corresponds to the probability of one or more M ≥ 2.5 earthquakes to occur in the pixel during 7 days. White circles represent 4 M ≥ 2.5 earthquakes which actually occurred during the period for which the forecast was issued. (i) Cumulative information gain (CIG) over time of the ETAS-based models versus the time-independent SUIhaz2015 model represented by the black horizontal line. The vertical line marks the date of the forecasts shown in (a–h). Source: Mizrahi et al., 2024.

National Cooperation

We actively cooperated with researchers involved in the Swiss Strong Motion Network renewal project and the Earthquake Risk Model for Switzerland and Basel-Stadt projects carried out at SED of ETH Zurich. For numerical modelling shown in subproject 2, we cooperated with senior scientists from the Swiss Seismological Service (SED) by developing a workflow for local scales. For subproject 3, we have collaborated with several scientists and IT experts within the SED, related to forecast communication, the setting up of the necessary IT infrastructure to regularly run the forecasting model, and to revisit the EEW capabilities for Switzerland.

International Cooperation

The research on the ground motion at depth was carried out in collaboration with researchers from the French Alternative Energies and Atomic Energy Commission (Saint-Paul-les-Durance, France). The broadband waveform modelling was discussed with experts from the Statewide California Earthquake Center SCEC (Los Angeles, USA), and the National Institute of Geophysics and Volcanology INGV (Catania, Italy). For the research on numerical modelling of complex geometries and surface topography, specifically for the implementation of the numerical mesh for the spectral-element modelling in subproject 2, we discussed with experts from Mondaic AG, i.e. with the co-founder and developer in Philadelphia (USA). This was done in order to verify the implementation of the mesh into spectral-element code Salvus. The soft sediment geophysical model by [10] was discussed with the author (San Diego Supercomputer Center). The expert elicitation in subproject 3 benefited from the collaboration with scientists at the United States Geological Survey (USGS), GNS Science in New Zealand, the INGV and University of Naples in Italy, as well as other institutions worldwide. The tasks in subproject 3 were also partially funded by the European project RISE.

Assessment and Perspectives for 2024

With a new researcher in subproject 1, we will focus on the development of a revised stochastic ground-motion model, integrating the findings of the past project phases. We will continue to work on ground motion at depth with site-specific applications. In subproject 2, we will perform further simulations using the spectral-element method for the Swiss Molasse Basin and Basel area. The simulations will be performed up to a resolvable frequency of 10 Hz, given that for some of the areas there are very detailed 3-D velocity models. Additionally, we aim to produce visualizations of surface and body wave propagation within these complex meshes and perform ground motion analysis by assessing the goodness-of-fit between simulation and real data – when available. This will allow us to validate the used velocity models and to improve our simulations workflow. Past and scenario earthquake simulations for Switzerland will routinely be performed with our high-fidelity physics-based approach. In future work, subproject 3 will focus on the visualization of forecast model outputs that will be useful for ENSI. For this, workshops are being planned together with the SED and ENSI. Another focus will lie on developing improved forecasting techniques, for example by using smaller magnitude earthquakes and exploring the scale invariance of seismicity, through incorporating near-real-time earthquake source descriptions, or by applying machine learning models. This work may however extend beyond the time horizon of 2024. Finally, EEW capabilities in Switzerland are being reassessed and this work will be finalized within 2024.

Publications

- **Bergamo, P., Maranò S., and Fäh, D. (2023).** Joint estimation of S-wave and damping ratio of the near-surface from active Rayleigh wave surveys processed with a wavefield decomposition approach. Geophys. J. Int., 233, 1560–1579. DOI: 10.1093/gji/ggad105.
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- **Koroni, M., Ermert, L., Bergamo P., Fäh, D.** (2023). Physics-based 3-D ground motion simulations using spectral elements: An example of the Rhône valley. WCCE2024, Milan (IT), under review.
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