SED – Erdbebenforschung zu Schweizer Kernanlagen

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Duration of the Project: July 2018 to June 2022

Abstract

The goal of this project is to improve regional and local seismic hazard assessment in Switzerland. For subproject 1, we continued with applications of the Bayesian inversion procedure for site-specific near-surface structure to several Swiss sites. Further, we advanced with preparation of the stochastic model to characterize high-frequency ground motion at depth relevant for site-specific seismic hazard assessment of deep geological disposals. We formulated this stochastic model in a rigorous manner and compared predicted depth-to-surface amplification with empirical borehole data from Japan. Within subproject 2, we further developed and validated a 3D geophysical model using observed ambient vibration measurements, and applied the model to simulate expected ground motion amplification during earthquakes. Moreover, we tested an inversion scheme to calibrate site-specific scattering parameters that can be used to simulate the stochastic part of three-component waveforms. A procedure to assess the liquefaction potential of soft sediments has been finalized and published. Finally, a procedure for calibrating material parameters for the simulation of non-linear soil behaviour has been implemented and is now used to simulate non-linear site response for sites in the Lucerne area. Within subproject 3, we further refined the study of the evolution of pressure and temperature around a geological nuclear waste repository and evaluated the potential for inducing earthquakes. New results now include the modelling of plastic behavior within the repository accounting for a layered system in 3D. We employed a geomechanical-statistical model to simulate the evolution of potential seismic events and compared plastic and elastic rheologies. Future implementation will allow modelling gas generation at the emplacement scale.

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:

- Ground-motion attenuation models and earthquake scaling for Switzerland;
- Modelling wave propagation in complex, non-linear media and limits of ground motion;
- 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 induced 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 non-linear behaviour in sedimentary rocks and soft soils, and to new trends in 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. Results of subproject 1 will be linked to deterministic simulations from subproject 2, and the

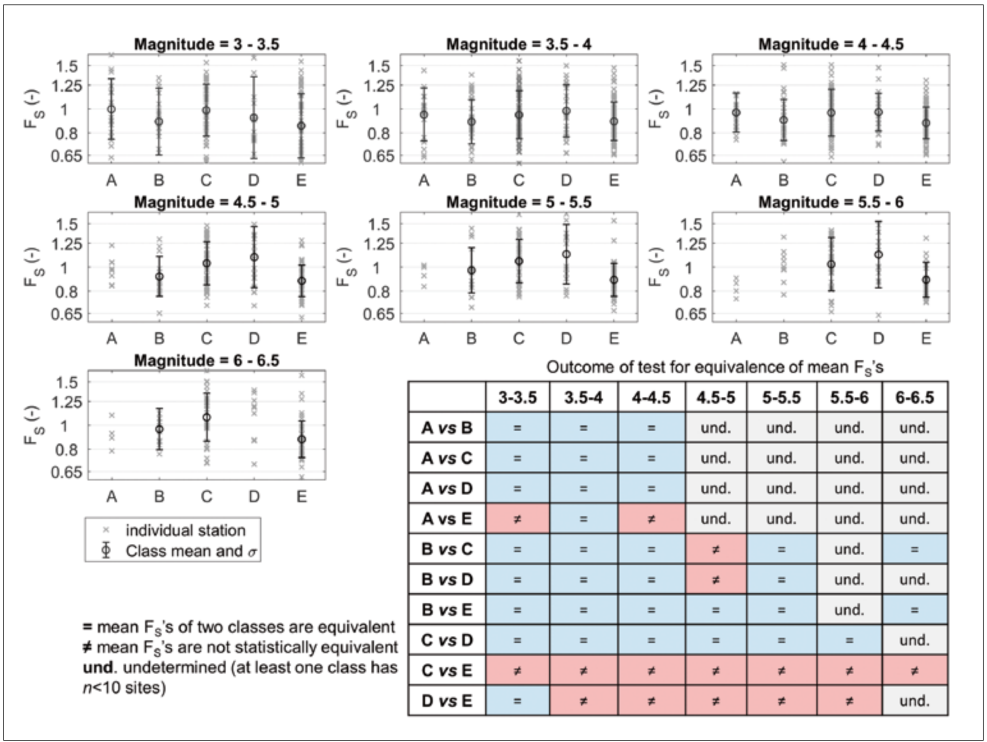

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Figure S1 – Upper half: panels displaying the distribution of site terms of duration (Fs, following Afshari and Stewart, 2016) estimated for KiK-net stations sorted by SIA soil classes (A-E). Each panel corresponds to a particular magnitude interval. Lower right corner: table showing the outcome of the statistical test assessing the equivalence of mean Fs's between couples of classes (Welch, 1947). Every row of the table corresponds to the comparison between two specific classes, every column refers to a particular magnitude interval.

results will be tested and compared to observed data.

In subproject 3, we move towards a 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 modelling 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 attenuation and amplification at Swiss sites. The ground-motion prediction equations (GMPEs) and site amplification models for Switzerland were developed within the previous phase of this project. There is a relation between site-amplification and site characteristics which can be described by site proxies (e.g. local lithology, shear-wave velocity profile, bedrock depth, lateral variability of the structure). Hence, these site proxies and the influence of the local near-surface shear-wave velocity profile were studied in detail within this project framework.

Firstly, we developed a Bayesian inversion method that is capable to infer the near-surface shear-wave structure including uncertainties. The performance of this method was demonstrated in terms of inversion of modelled synthetic data and example of inversion of data measured in the vicinity of the SENGL site (Engelberg, Obwalden) in Hallo et al. (2021a, 2021b). We performed also numerous inversion tests with the real data measured in the vicinity of seismic stations of the Swiss Strong Motion Network (Hobiger et al., 2021), namely we tested the method for sites SVISP (Visp), SAARA (Aarau), SBAV (Basel), SMZW (Muttenz), SDES (Delémont), and SEPFL (Lausanne). Moreover, the method was applied to ambient vibration array data recorded with ocean bottom seismometers in Lake Luzerne [1] and to single-station recordings on Mars at the InSight landing site [2].

This near-surface structure inversion method can be used for evaluating any arbitrary property associated with velocity profiles

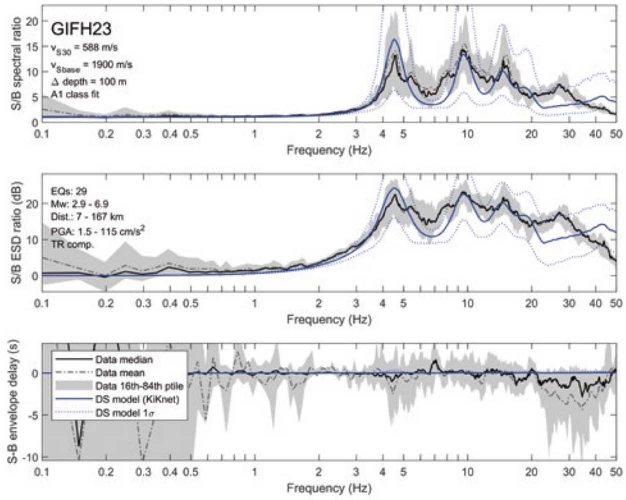

Figure 1 – Comparison of the depth-to-surface ground-motion amplification as predicted by our stochastic model (blue lines) and as retrieved from earthquake recordings (black/gray lines) for the GIFH23 site in Japan. Panels from top to bottom show: S/B spectral ratio, Energy Spectral Density ratio and the Envelope Delay (delay from phase spectrum).

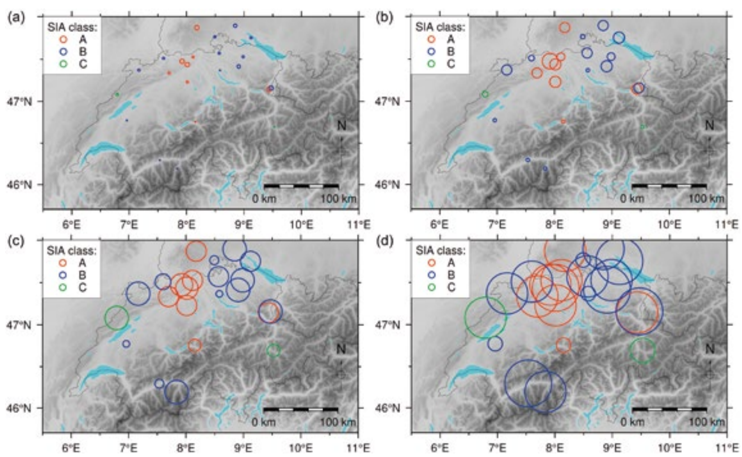

Figure S2 – Retrieved site-specific scattering parameters for sites of seismic stations in Switzerland. Panels (a,b,c,d) show scattering in 2-4 Hz, 4-8 Hz, 8-16 Hz, and 16-32 Hz frequency bands, respectively. The size of circles is proportional to the S-wave scattering quality factor.

and their uncertainty. We evaluate the local site amplification in terms of the theoretical SH-wave amplification. The theoretical amplification is referenced to the Swiss profile [3] and can be compared to measured amplification using empirical spectral modelling [4], which has an importance when site-specific seismic hazard is estimated using the national seismic hazard maps that are referenced to the same Swiss profile [5]. In Hallo et al. (2021c), we compared the predicted amplification at the SEPFL site (Lausanne) with the empirical amplification computed from earthquake recordings by the method of [4]. The comparison shows a high similarity of the amplification spectral curves, as this is an example of the site with predictable 1D resonance effects.

Ground-motion prediction at depth on a local scale is needed for the seismic hazard assessment of deep geological disposals. Recently, we proposed a theoretical stochastic model to characterize the high-frequency ground motion at depth using statistical evaluation of 1D depth-to-surface SH-wave transfer function considering random effects of surface geology (Hallo et al., 2021d). To demonstrate the applicability of this stochastic model, we retrieved surface-to-borehole amplitude spectral ratios from borehole installations of the Japanese KiK-net network and compared them with our predicted amplification curves (Hallo et al., 2021e). The comparison shows a high similarity of some amplification spectral curves, which validates the applicability of the theoretical model for the prediction of the ground

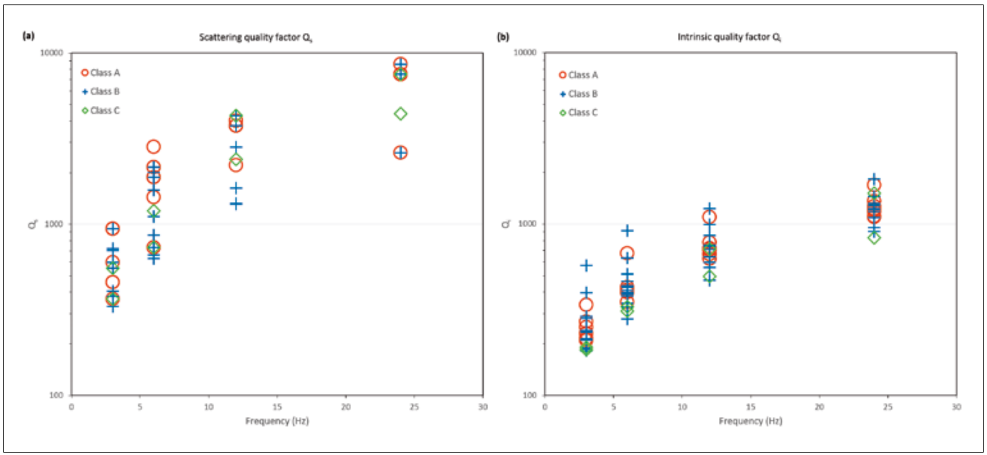

Figure 2 – Comparison of the inverted site-specific S-wave scattering and attenuation parameters for sites of seismic stations in Switzerland. The scattering parameters do not show a dependence on the soil classes A, B or C as defined in the Swiss building code [6].

motion at depth. An example of one site is shown in Figure 1. This validation opens a path to applications, namely 1) the prediction of the high-frequency ground motion at depth from surface recordings, and 2) adjustments of the velocity profile between surface and borehole receivers. Furthermore, we started already with an extension of the depth-to-surface stochastic model for complex 3D media by establishing international cooperation with the Institute of Geophysics of the Czech Academy of Science (CAS) on this new task.

To complete, we continue with activities carried out in the previous years. In particular, we presented the outcome of our study on the site-term of ground-motion duration at the 37th General Assembly of the European Seismological Commission (Bergamo et al., 2021). The work carried out in the previous years on the estimation of the S-wave quality factor of the subsurface by means of active surface wave surveys has been condensed in a manuscript that will be submitted to Geophysical Journal International very soon.

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

Research activity within sub-project 2 has focused on aspects of ground motion in complex media and on the assessment of non-linear site response and liquefaction potential of soft soils.

We continued the work on the calibration and validation of a 3D velocity model for the Visp area, southern Switzerland. Building on an initial geophysical model, we have developed a procedure to validate and refine its main features, first based on the comparison between measured and simulated ambient vibration horizontal-to-vertical (H/V) spectral ratios. Based on an iterative procedure, data misfit could be used to further refine the initial geophysical model. The model has then been used to simulate earthquake ground amplification from many earthquake sources and to compare derived standard spectral ratios with observations from the seismic stations installed in the Visp area. The final model satisfactorily reproduces most observations. A paper was recently submitted (Panzera et al., 2021) and is under review.

We further developed a hybrid technique to simulate ground motion in a broad frequency range using deterministic ground-motion simulations for the low-frequency part of the synthetics and stochastic simulations for the high-frequency part. The stochastic part can be tuned for a specific location, thanks to an inversion procedure targeting the observed coda waves (i.e. waves arriving after the direct P- and S-waves). The inversion derives the site-specific scattering parameters (Figure 2) and permits to minimize the misfit between the modelled and the observed ground motion temporal behaviour. The work of van Ede et al. [7] has provided some guidelines for further improvements of the code. We addressed extended sources in the stochastic part, which is needed for large-magnitude events. The code was not yet verified.

In the framework of soil non-linearity, we have implemented and applied a procedure developed during the second phase of the ENSI project to estimate the soil liquefaction probability and to define the parameters for the simulation of the non-linear soil response. The procedure generally used in geotechnical engineering to evaluate soil liquefaction potential typically relies on a single specific peak ground motion level. We have developed an extension by taking into account the whole range of possible peak ground motion levels for a given magnitude. The approach is based on cone penetration tests (CPT) performed at sites of recently installed strong-motion stations in the strong motion renewal project for Switzerland. Applications of the procedure to estimate soil liquefaction probabilities for stations in Switzerland are published in Hobiger et al. (2021). Dilatancy parameters are needed to model the non-linear behaviour of seismic waves in soft soils. Ground motion estimates assuming purely elastic rheologies will be sensibly biased at large motion levels. The site-specific calibration of dilatancy parameters was based so far on laboratory measurements and inversion of time-series recorded by vertical arrays (e.g. [8], [9]). However, in the first case, the in-situ conditions are likely lost, while vertical arrays are expensive to install and operate. We have introduced a calibration procedure based on CPT measurements, originally proposed in the first phase of the ENSI project, representing a fast and cost-efficient alternative to maintaining the in-situ conditions. A PhD student working in the framework of the European URBASIS project will apply these methods. In particular, she will test the calibration of the non-linear soil model for sites in the Lucerne area and will perform numerical simulations of non-linear soil response. A particular focus is related to the uncertainties in the soil response resulting from the uncertainties of the estimated material parameters.

3. Induced seismicity and application for a deep geological repository

Research activity within sub-project 3 focuses on understanding the geo-mechanical response in terms of fault stability due to canisters emplacement. Hydro-geomechanical models of a geological repository are coupled with a stochastic simulator to study potential fault reactivation. We have focused on creating a more realistic model for the rock rheological response.

As in the past, we employ the simulator TOUGH3-FLAC3Dv6 to model a large number of coupled processes occurring in a geological nuclear waste repository ([10], [11]). In addition, we have revised the module to simulate the reactivation of fault/fractures via the use of a stochastic-geomechanical simulator. Such an approach, referred in the literature as «seed model» with a seed giving a potential hypocenter, has been used extensively to study induced seismicity (e.g. [12]) and was re-implemented in previous phases of this project [13]. Worth noting that a reactivated seed represents a failure event, but the current model does not discriminate between seismic or aseismic failure.

In the reporting period, we have focused on understanding the effect of the rock rheology on the Coulomb stress change, defined starting from the full stress tensor as $\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta p)$, where $\Delta\tau$ of the change in shear stress, $\Delta\sigma_n$ is the change in normal stress and Δp is the change in pore pressure. Shear and normal stresses are calculated for faults striking parallel to the tunnels and with a given dip angle toward the repository. We have performed a sensitivity analysis on the dip angle, and in general, it is confirmed that there is a potential for instability in the region

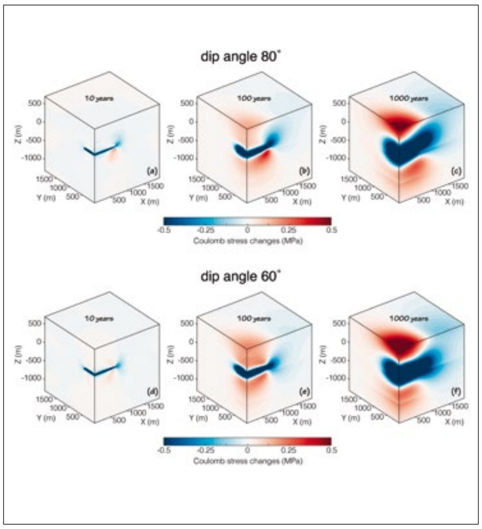

Figure S3 – Distribution of Coulomb stress changes at 10, 100 and 1000 years for the case of dip angle of 80° (a,b,c) and dip angle 60° (d,e,f) assuming a layered elastic medium (including a layer reflecting the clay repository).

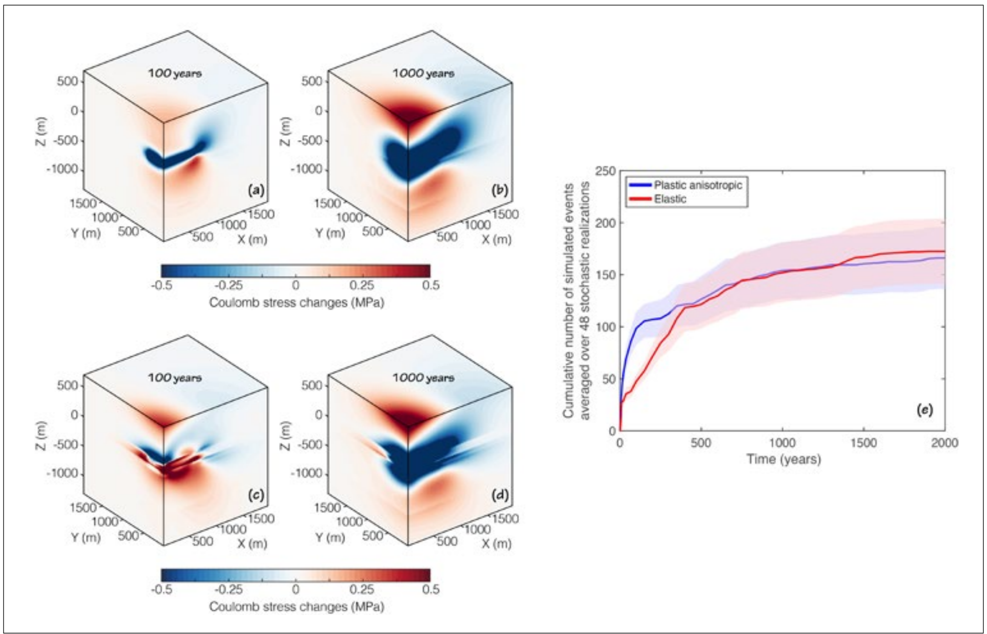

Figure 3 – Distribution of Coulomb stress changes at 100 and 1000 years for the case of elastic rheology (a,b) and including plastic behaviour of clay (c,d). Coulomb stress is calculated for faults dipping 80° and striking N180°, assuming the north is oriented in the y-direction.
(e) Comparison of the cumulative number of simulated failure events, averaged over 48 stochastic realizations, for the two rheologies by using a stochastic-geomechanical model. The shaded area represents the standard deviation.

below the repository, with Coulomb stress changes increasing for a larger dip.
The Coulomb stress changes, however, are limited to a given structure orientation, and for this reason, a stochastic approach is recommended. The simulated stress changes (full tensor) in the entire medium are then fed to the stochastic simulator to generate seismicity catalogues for fault/fractures with changing orientation normally distributed around an average value (that depends on the stress level). For a base case elastic rheology, the simulation resulted in an average of about 170 failure events in 2000 years after emplacement, with the temporal evolution following the temperature changes. Most seeds are reactivated below the repository up to 1 km distance. Assuming a normal distribution between 30 ° and 90 ° for the dip angle, with 60 ° average, most of the reactivated seeds are with a dip between 50 ° and 55 °.
Furthermore, we have compared two different rheologies: 1) elastic and layered rheology that accounts for a clay-like host rock, 2) plastic anisotropic rheology within the host rock, with the plane of anisotropy representing the potential bedding of the hosting clay formation. The comparison results are shown in Figure 3. Panels 3a and 3b show the Coulomb Stress changes 100 and 1000 years after emplacement, respectively, for the layered medium. Results show some negative Coulomb stress changes in the surroundings, meaning that failure is hindered. Compared to the elastic homogeneous medium, there are only minor variations at the boundary between layers. Figures 3c and 3d show the results for plastic anisotropic rheology, as before for 100 and 1000 years after emplacement. The main difference is at 100 years, for which positive Coulomb stress changes are developing in the surroundings. While this stress could potentially bring faults to instability, the frictional behaviour of the clay prevents the formation of seismic events, rather the instability evolves in aseismic slip (e.g. [14]).
Figure 3e shows the evolution of the cumulative number of failure events: for the plastic anisotropic model the rate of events is larger in the initial post-closure phase (first 100 years), but decreases later to match the trend of the elastic rheology. This indicates how the rheology could have an effect in the initial phase of the post-closure, dominated by the thermal pressurization, while at a later stage when the temperature changes become more prominent the rheology seems to play a minor role.
The current model can be easily modified to account for gas generation, as investigated in the past through benchmarking activities. We expect such a process to be relevant for fault stability, as the two-phase fluid flow

could affect the evolution of the repositories in terms of pressure and temperature, and consequently in plastic behaviour.
Additionally to the modelling effort, we have been collaborating in analyzing results from field measurements at the Mont Terri Rock Laboratory. Recent excavation of a new gallery has been monitored by various sensors, including deformation monitoring of the Mont Terri Main Fault zone. Distributed sensing via fiber optic shows how the rock deformed mostly where fractures/faults are present, with most of the deformation confined in the Main Fault zone (Hopp et al., 2021). This dataset provides a good confirmation of the model proposed in Phase 1 of the current project, which predicted how small deformation would have occurred on a large patch of a fault zone. No major seismicity was observed, but the seismic network was not sensitive enough to detect small earthquakes as expected from the model prediction.

National Cooperation

We actively cooperated with researchers involved in the Swiss Strong Motion Network renewal project. Code development benefited of the infrastructures at the Swiss Supercomputing Center. The development and validation of the geophysical model for Visp involved Swisstopo and the Canton of Wallis. We also collaborated with various teams performing experiments at the Mont Terri Underground Lab (FS-B, GT, CS-D).

International Cooperation

Our research on probabilistic inversion was carried out with the Australian National University and the Charles University of Prague. Modelling of the depth-to-surface amplification in the complex 3D media is carried out with the Institute of Geophysics of the CAS (Prague). Collaboration with King Abdullah University of Science and Technology (KAUST) was continued. Modelling of non-linear soil response is performed in collaboration with the French Institute of Science and Technology for Transport, Development and Networks, (IFSTTAR, Paris). Research on induced seismicity during the operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. We also took part to international initiatives to benchmark and validate numerical models (BENVASIM, DECOVALEX).

Assessment 2021 and Perspectives for 2022

Future work in subproject 1 will involve applications of the recently validated stochastic model to characterize high-frequency ground motion at depth on Japanese and Swiss data. For instance, we would like to publish the performed validation in a peer-reviewed journal, apply the stochastic model to predict the high-frequency ground motion at depth from surface recordings for real earthquake data, and design a novel inversion procedure to adjust the velocity profile between surface and borehole receivers. The latter application will include also the retrievement of the intrinsic quality factor between surface and borehole receiver that is proportional to the kappa0. Further, we plan to extend the depth-to-surface amplification stochastic model to complex 3D media; and implement the double-corner-frequency source spectra in the Swiss stochastic ground-motion model. In subproject 2, we announced a position looking for a candidate with experience in hybrid modelling of strong ground motion. The particular plan will depend on the experience of the successful candidate, but the direction is given by the ENSI research project plan. In the framework of subproject 3, the work performed in 2021 was important to provide a possible range of expected geomechanical variation in a repository after nuclear waste emplacement. Future work will focus on including gas generation effects in the 3D model.

Publications

Bergamo, P., Hallo, M., Panzera, F., and Fäh, D. (2021). Investigating the site-term of strong motion duration from a systematic analysis of the KiKnet waveform database. 37th General Assembly of the European Seismological Commission 2021, Session 31, abstract no. 175, virtual.

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