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, modelling of the wave propagation in complex media, research on induced seismicity, and applications for deep geological disposal. For subproject 1, we developed a method to assess the ground motion at a depth that can be used for the seismic hazard assessment of deep geological disposals such as nuclear waste repositories. This physics-based method was mathematically formulated and validated by empirical earthquake data from Japan. Then, we started with applications of the method to instrumented borehole sites in Switzerland. This is to adjust it to Swiss conditions and open the path for the seismic hazard assessment of the Swiss nuclear waste repository. Next, a systematic re-assessment and quality control of the determination of the local high-frequency attenuation term κ_0 at Swiss free-field stations was performed. We showed the consistency between the estimated κ_0,V_{s30} couples and the parameters of the Swiss reference rock profile, which is one of the key "ingredients" of the Swiss stochastic model. Within subproject 2, we further validated a 3-D geophysical model of the Upper Rhone valley (Wallis) using observed ambient vibration measurements, and we applied the model to simulate expected ground motion amplification during earthquakes. It has been deduced that it is important to properly validate 3-D velocity models originating from geophysical and geological methods through numerical modelling and observations, in order to reliably assess the site amplification. Next, we tested a hybrid modelling method to prepare synthetic broadband waveforms that can be used for engineering applications. Within subproject 3, we focus on understanding the geo-mechanical response due to canisters emplacement in terms of fault stability and potential induced seismicity. After investigating the role of rock rheology, in the current reporting period, we have focused on including the gas generation as an additional potential effect generating over-pressurization in the repository.

Project goals
This research project is split 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;
- Induced seismicity and application for deep geological disposal.

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 at depth and at the surface, in the near field, for damaging events, and 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, nonlinear behaviour in sedimentary rocks and soft soils, and 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. The 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 realistic characterization of seismogenic sources for induced earthquakes. The goal is to adapt existing geo-mechanical models to a situation of deep geological disposal (e.g. nuclear waste repositories), develop and validate new modelling methods, and integrate them into 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 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, slope, lithology). Further, the local effects were studied in detail within this project phase.

First, the local ground-motion attenuation and amplification are linked to the near-surface velocity of seismic waves. In previous years, we developed a Bayesian inversion method that is capable to infer the near-surface shear-wave (S-wave) structure including uncertainties [3]. The approach was tested with the real data measured near seismic stations of the Swiss Strong Motion Network (SSMNet), it was applied to single-station ambient vibration data recorded on Mars, and it is currently applied to a large dataset in the Basel area to retrieve a 3-D geological-seismological model at an urban scale [4]. As a result, our method developed within this project framework will help to retrieve a velocity model of the Basel-Stadt area including rigorously evaluated uncertainties. The 3-D model can be used for the evaluation of ground-motion amplification maps in terms of the theoretical SH-wave amplification at specific locations.

This year, we put a lot of effort into advancements to characterize the ground motion at depth. This is especially important for seismic hazard assessment of deep geological disposals such as nuclear waste repositories. To tackle this task, we proposed a novel stochastic model to characterize the high-frequency ground motion at depth in the frequency domain by using a set of randomized SH-wave transfer functions. The rigorous theoretical background, comparison with empirical amplification functions at numerous Japanese sites, and examples of its application were published in an international impact journal by Hallo et al. (2022a). The method is introduced and thoroughly investigated by synthetic tests; then, we validate the method through the comparison with empirical surface-to-borehole amplification curves observed in 144 selected KiK-net vertical arrays in Japan (equipped with both surface and borehole seismometers). This verification is done in the broad frequency range of 0.1–50 Hz, and we were able to identify several sites with a good mutual fit of theoretical and empirical amplification curves. This proved that the stochastic model can relate the ground motion at depth and on the ground surface in a broad frequency range. In addition, we made the first attempts to extend the stochastic model to complex 3-D media (Oprsal et al. 2022). Next, we demonstrated the performance of the method in some practical applications: I. Bayesian inversion of the empirical surface-to-borehole amplification to retrieve the S-wave velocity model; II. full-waveform prediction of the ground motion at depth from surface earthquake recordings. The latter is especially important for seismic hazard assessment because full waveforms include all parameters needed by engineers for the design of earthquake-resistant structures. In particular, the ground-shaking caused by earthquakes is characterized by the peak ground acceleration (PGA), peak ground velocity (PGV), cumulative absolute velocities (CAV), Arias intensity (I_A), and acceleration response spectra. The full-waveform prediction of the ground motion at depth was performed at several KiK-net sites in Japan and published in Hallo et al. (2022b, 2022c). An example of the full-waveform prediction of the ground motion at depth from the surface recordings of the 2018 northern Osaka M_w 5.6 earthquake is shown in Figure 1. Indeed, the theoretical prediction is close to the real data measured in the borehole at 110 m depth. This applies to all: acceleration waveform, PGA, PGV, CAV, I_A, and response spectra.

Further, we have already started with the application of our novel stochastic model to characterize the ground motion at depth in Switzerland. In particular, we focus on BOBI, HAMIK, STIEG, ROMAN, WOLEN, and SVISP sites equipped with both surface and borehole seismometers (NAGRA network, SDSNet, and SSMNet). We determined surface-to-borehole amplification functions and performed the prediction of the full waveform at depth from surface recordings of the 2017 M_w 4.1 Urnerboden earthquake (Uri). The preliminary results of this research were presented in Hallo et al. (2022d) and are planned to be compiled into a scientific paper next year. The gained knowledge and developed tools allow us to draw a procedure to evaluate the local seismic hazard for deep nuclear waste repositories in Switzerland (i.e. extension for large earthquakes that can occur in the future). Note, the latter will require broadband waveform modelling from subproject 2.

Next, in continuity with the research carried out in the previous years, a systematic re-assessment and quality control of the local high-frequency attenuation term κ_0 (e.g. [5]) at free-field and urban free-field stations in Switzerland was performed. The output is a dataset of verified κ_0 values obtained for 248 temporary and permanent stations in Switzerland (Figure 2a). The procedure by [6], which is routinely applied at SED after every earthquake to determine the source and site terms, was verified in its part related to the estimation of the high-frequency attenuation parameter κ as follows: The parameter t* (rate of decay of the acceleration spectrum amplitudes at high-frequency, e.g. [5]) was computed for all recordings from the time-period January 2001 – September 2022 fulfilling the quality criteria listed in [6]. The eligible earthquakes have to have $M_L > 2$, epicentral distance R_{epi} larger than 5 km, and a signal-to-noise ratio larger than 3 over at least one log10 unit along the frequency axis at both horizontal components of at least 3 stations. The set of horizontal-component t* values referring to the same station were linearly regressed versus the R_{epi} of the corresponding earthquakes to retrieve the intercept for R_{epi} = 0 km, which is the κ_0 (site-related high-frequency attenuation). To estimate κ_0 consistently with the stochastic model of [1], the path attenuation was represented with a homogeneous Q model valid for a reference halfspace of 3.5 km/s ($Q_{0,3.5}$=1200). The correspondence between the simplifying assumption of [1] and the overall increment of t* with R_{epi} was verified, resulting in a good agreement.

The result of the above-described procedure is the robust estimation of κ_0 for 248 stations in Switzerland, supplemented by a confidence interval and relevant earthquake metadata (Figure 2a). The median of κ_0 is 0.019 s, 5^{th} and 95^{th} percentiles are 0 and 0.053 s, respectively. As generally performed in regional κ_0 studies, the κ_0 obtained at stations with measured velocity profiles were cross-referenced with the corresponding V_{S30} values (Figure 2b). We would like to highlight that the fitted exponential line at the V_{S30} = 1100 m/s (i.e. V_{S30} of the Swiss standard rock profile, [7]) predicts a κ_0 that is very close to that of the reference profile (i.e. 0.016 s). The consistency between the estimated κ_0,V_{S30} couples and the param-

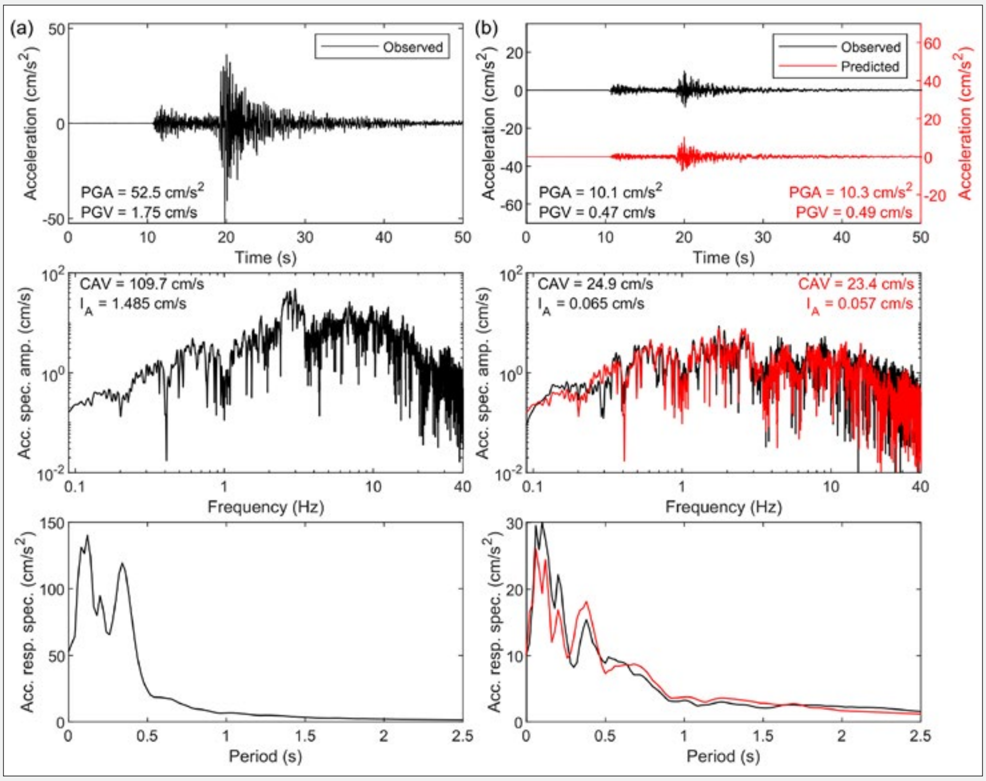

Figure 1:
Full-waveform prediction of the ground motion at depth from surface recordings of the 2018 northern Osaka M_w 5.6 earthquake (Japan). It shows empirical data (black lines) and the theoretical prediction by the stochastic model (red lines) at the HYGH08 site. Observed and predicted acceleration waveforms, amplitude spectra, and response spectra are shown (a) on the ground surface and (b) in the borehole at 110 m depth.

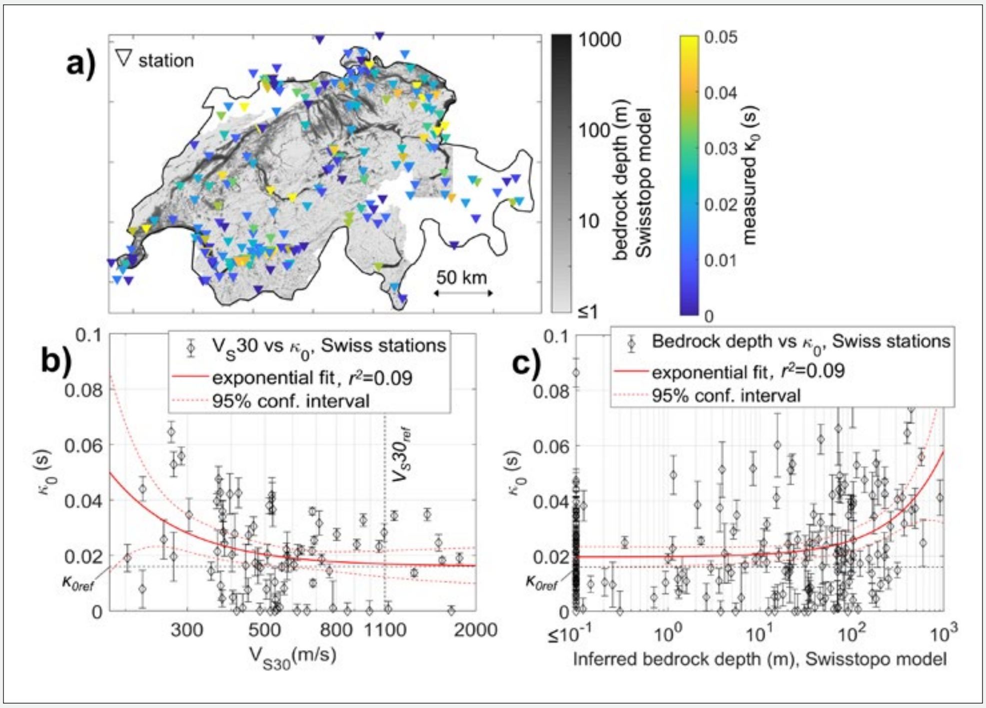

Figure 2:
(a) measured values of the κ_0 at 248 (urban) free-field stations of Swiss permanent and temporary networks (coloured triangles). In the background, the bedrock-depth model from [9].
(b) Correlation between κ_0 and measured V_{S30} (for stations with measured V_S profile). Note that the fitted exponential line predicts a κ_0 value very close to that of the Swiss reference rock model (i.e. κ_{0ref} = 0.016 s) at the V_{S30} of the Swiss reference rock model (V_{S30ref} = 1100 m/s).
(c) Correlation between κ_0 and the depth-to-bedrock from Swisstopo [9].

eters of the Swiss reference rock profile (i.e. one of the key "ingredients" of the stochastic model of [1]) provides a reciprocal validation for both. Furthermore, the empirical estimates of κ_0 were also correlated with layers of indirect site-condition information (see ENSI research report 2018 and the work carried out for the Earthquake Risk Model Switzerland project in [2] and [8]). The intended purpose is to explore the possibility to infer from such layers the κ_0 term at sites that are not instrumented, even in a mapping framework. Figure 2c displays an example of the correlation with the bedrock depth as estimated by the national geological model of [9]. The correspondence between the two parameters is well represented by an exponential model, as in V_{S30} (Figure 2b). The correlation level is quite low; however, it is comparable to that of established correlations with measured geophysical parameters (namely V_{S30}).

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

Within subproject 2, we performed 3-D model validation using numerical simulations in the context of reconstructing 3-D geophysical models for site amplification inference in the Upper Rhone valley, Valais, Switzerland (Panzera et al. 2022). The research included 3-D modelling of ambient noise vibrations using the code by [10] in order to validate a 3-D velocity model around the city of Visp. Specifically, the modelling of 3-D ambient vibrations was used to predict theoretical horizontal-to-vertical spectral ratios and then compare them to measurements. The results show an overall good agreement between synthetic and observed spectral ratios for most stations involved, especially in terms of the fundamental resonance frequency. The validated 3-D model was then used to produce synthetic seismic site amplification maps of the area using the standard spectral ratio method (SSR). To assess the validity of the synthetic SSR curves, they were compared to the empirically derived amplification functions from earthquake recordings. The comparison reveals a good agreement for all seismic stations within the valley, which degrades at borders, likely due to velocity model inaccuracies. For different frequencies for which the amplification values were modelled (Figure 3), it was noted that the depth of the sedimentary basin and its accurate implementation in the 3-D model plays a crucial role in the reliability of the inferred amplifications. It has been deduced that it is important to properly validate 3-D velocity models through numerical modelling and observations, in order to reliably assess the site amplification and to investigate the reliability of resulting velocity models derived combining geophysical and geological information.

Second, a finite-difference wave propagation code was used to simulate seismic waves in inelastic media, in order to verify a method that allows a joint estimate of S-wave velocity and damping ratios of the near-surface lithological layers from ground motion recordings. This method is based on the wavefield decomposition approach and can be applied to active seismic surveys. The method and results were published by Bergamo et al. (2023). In that study, the role of numerical modelling was to perform wave propagation simulations and produce synthetic ground motions for well-defined inelastic media, which are then used to verify the performance of the inversion approach. For real data applications shown in that work, the proposed method allows for the modelling of the inelastic local site response.

Further, engineering applications to the earthquake-resistant design of buildings usually require response spectra or design-compatible broadband waveforms. To this end, we tested and used the Statewide California Earthquake Center (SCEC) broadband platform [11] that allows the modelling of broadband waveforms using a hybrid approach. We used this platform in order to compare synthetic waveforms and spectra to those obtained from stations in Switzerland at sites BOBI, HAMIK and STIEG (NAGRA network). The hybrid modelling by the Graves-Pitarka method [12] was utilised and we ran simulations for the M_w 4.1 earthquake

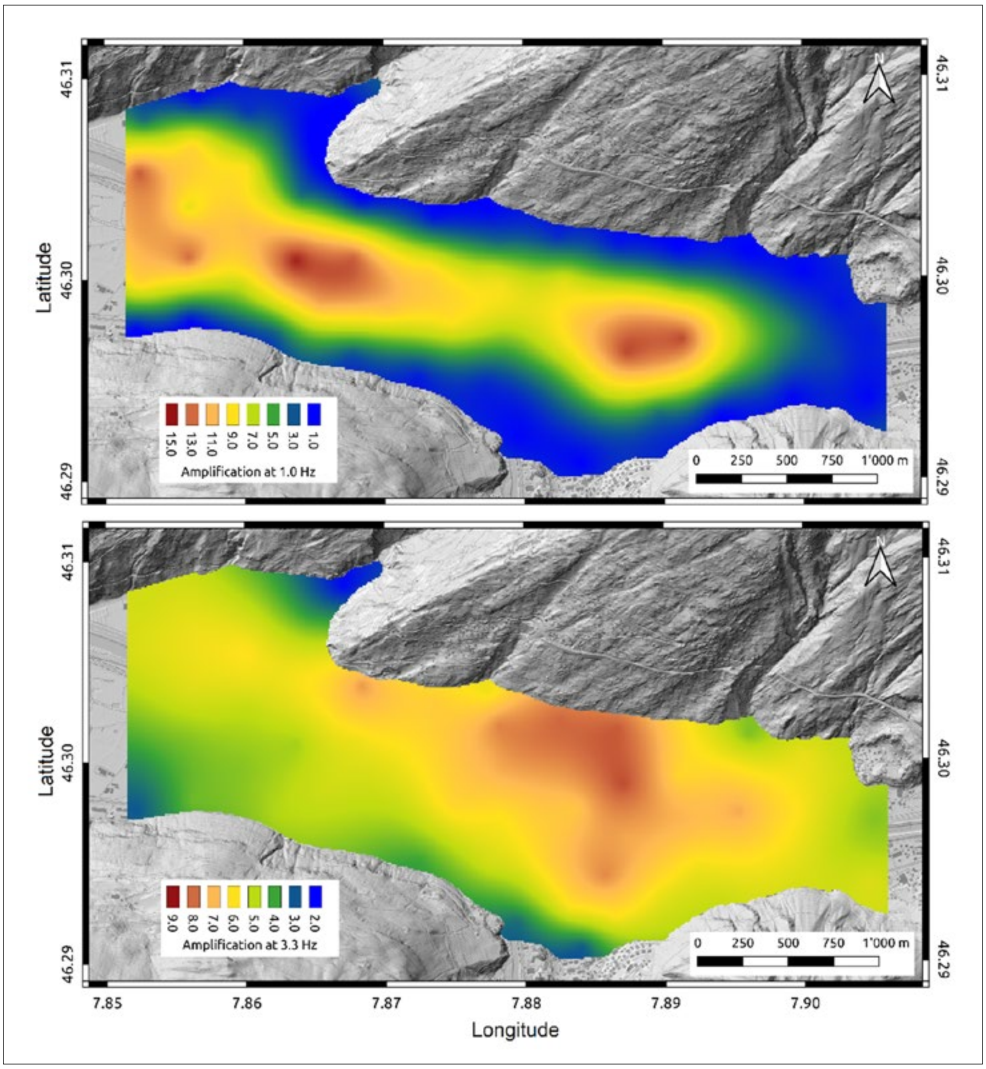

Figure 3: Amplification maps of the Upper Rhone valley (Switzerland) modelled for frequencies 1.0 and 3.3 Hz (top and bottom panels, respectively). The amplification values are referred to the local reference rock in the Visp area. This figure is taken from Panzera et al. (2022).

that occurred at Urnerboden (Uri) on 6th March 2017 [13] with an approximate velocity model to assess the reliability of predicting acceleration waveforms and amplitude spectra. However, due to the lack of a detailed Swiss velocity model within the SCEC broadband platform software, the first comparison was only preliminary. To this end, we will adapt this software in order to properly account for the velocity structure of Switzerland by implementing an existing velocity model of the Swiss Molasse Basin. In perspective, we will simulate past and scenario earthquakes, of larger magnitudes, to predict the surface ground-motion waveforms and spectral parameters at Swiss sites of interest. The preliminary results of this work were presented by Koroni et al. (2022a, 2022b).

3. Induced seismicity and application for a deep geological repository

Research activity within subproject 3 focuses on understanding the geo-mechanical response due to canisters emplacement in terms of fault stability and potential induced seismicity. We developed simplified models of a geological repository that simulates the full thermo-hydro-mechanical response of the rock mass around the repository. The simulated stress evolution is then used with a stochastic seismicity simulator to study potential fault reactivation. After investigating the role of rock rheology, in the current reporting period, we have focused on including gas generation as an additional potential effect generating over-pressurization in the repository.

We used the simulator TOUGH-FLAC that allows modelling a variety of processes, including heating, thermal pressurization, complete equation of state for multi-component, multi-phase fluid flow, as well as complex rheology to simulate stress and strain evolution [14]. In the reporting period, the paper (Rinaldi et al. 2022) presenting the latest version of the software has been published in the journal Computational Geosciences. The paper describes the implementation method and the code performances, as well as a base case simulation of nuclear waste disposal according to the Swiss concept as reported in the past. The stress evolution modelled with TOUGH-FLAC is then fed to a stochastic-geomechanical simulator, referred to in the literature as seed-model and extensively used to study induced seismicity [15], [16], [17]. Such an approach was implemented in previous phases of this project and adapted to the case of nuclear waste disposals. 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 potential effect of gas generation on the induced failure events outside the repository. We simulated the gas generation as a gas injection source for each element of the emplacement caverns. The gas generation starts at 3000 years after the emplacement, and linearly reaches a maximum of 3.0 x 10^{-9} kg/s/m at 6500 years. Then it decreases linearly up to 10,000 years. These values are consistent with the ones provided by NAGRA for spent fuel and high-level waste [18]. The time evolution of heat and gas generation for each meter of the emplacement tunnels is shown in Figure 4a. As shown in Figure 4b, the imposed heat source will produce immediate thermal pressurization, with pore pressure rising up to ~9 MPa in the considered case. Then as the heat decreased, the pore pressure tends to stabilize toward the hydrostatic value (~7 MPa), only to rise again when the gas generation starts, reaching up to 8 MPa. Such evolution is consistent with more complex simulations reported in [18]. Figure 4c shows the evolution of the cumulative number of failure events: for the case with gas generation (blue line the average and shaded area the stochastic variation), most of the events are generated within the first 1000 years, with only a very minor number of events induced around 3500 years within the active gas generation phase. The trend is overall very similar to a case with heat-only (red line and shaded area), with most of the observed deviation within the standard deviation of the stochastic realizations.

While the gas generation results in a second peak in terms of pore pressure, in the current model the maximum value reached is quite below the maximum reached during the initial repository pressurization. Furthermore, in terms of stress and strain evolution around the repository, this effect results in very minor changes. Indeed, as reported in the past, the long-term evolution is strongly affected by temperature changes rather than pressurization (see [14], [16]), with the deformation caused by the heat reaching a depth of several hundreds of meters below the repository. These effects motivate the little difference in evolution compared to a case with heat-only.

Additionally, the results from field measurements at the Mont Terri Rock Laboratory about the recent excavation of the Gallery-18 have been published in the current reporting period (Hopp et al. 2022). We reported the deformation observed via various sensors, in particular fibre-optics measurements. Results show how the deformation is mostly confined within the Mont Terri Main Fault zone.

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. The development and validation of the geophysical model for Visp involved Swisstopo and the Canton of Wallis. Code development and high-performance computing benefited

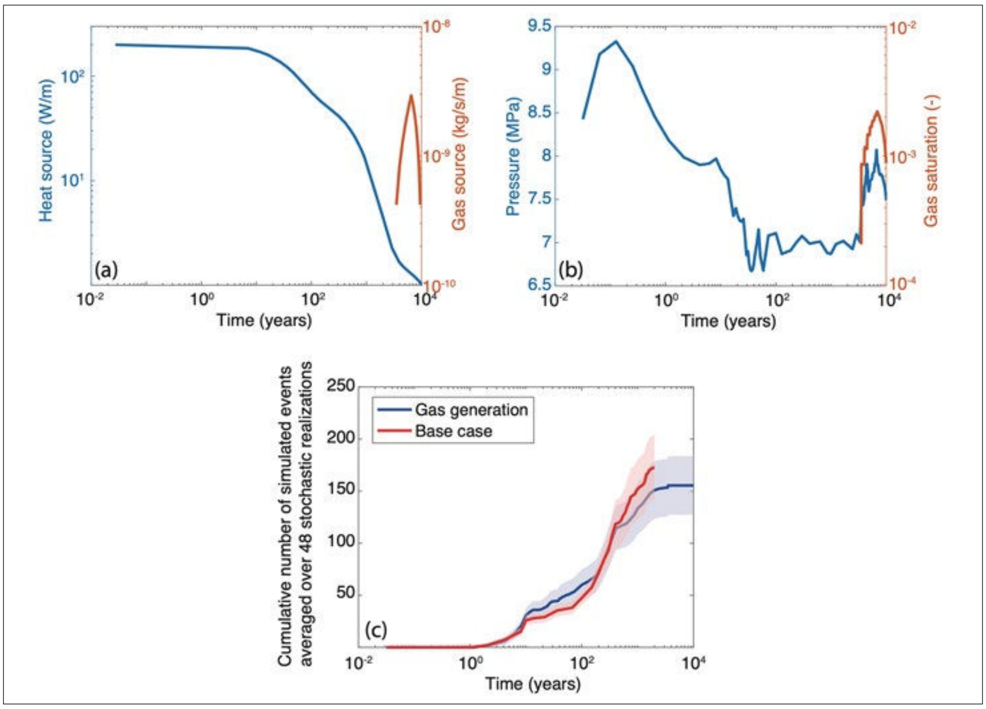

Figure 4:
(a) Generation rates for heat (blue) and gas (red) for each waste element.
(b) Resulting pressure (blue in MPa) and gas saturation (red) for a single element of the emplacement tunnel.
(c) Comparison of the simulated number of failure events for two cases, with and without gas generation (blue model with gas and heat, the red base case with only heat).

from the infrastructure at the Swiss National Supercomputing Centre. We also collaborated with various teams performing experiments at the Mont Terri Underground Lab (FS-B, GT, CS-D).

International Cooperation

Modelling of the surface-to-borehole amplification in the complex 3-D media is carried out with the Institute of Geophysics of the CAS (Prague, Czech Republic). 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, 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). Research on induced seismicity during the operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory LBNL (Berkeley, USA). We also took part in international initiatives to benchmark and validate hydro-mechanical models (BENVASIM, DECOVALEX).

Assessment 2022 and Perspectives for 2023

Lessons learned and results gained in the third phase 2018–2022 of the project are very satisfactory. This may be emphasized by a large number of publications acknowledging ENSI as the main supporter of research activities this year. There are also some innovations resulting from the project. For instance, the novel stochastic model to characterize the ground motion at depth and its potential usage in the seismic hazard assessment of deep geological disposals. Regarding perspectives for 2023, future work in subproject 1 will involve applications of the stochastic model to characterize ground motion at depth to Swiss sites. In particular, we will focus on NAGRA monitoring sites instrumented with both surface and borehole seismometers, and we will predict full waveforms at depth for a historical earthquake and an earthquake scenario that can occur in the future. Next, we will extend the surface-borehole stochastic model to the surface-outcrop case, which can be used for the theoretical prediction of the amplification observed on the ground surface driven by a velocity model. Further, we plan to implement the double-corner-frequency source spectra in the Swiss national stochastic ground-motion model as a preparation of the next generation ground motion model. As far as the study on local high-frequency attenuation (κ_0) is concerned, the perspective for 2023 is testing the possibility of its prediction in a multivariate framework, using as predictor variables measured geophysical parameters (V_S profile) and indirect site condition indicators (e.g. multi-scale topographical indexes, inferred bedrock depth). In subproject 2, we will perform complex deterministic 3-D waveform modelling using spectral elements and high order finite-differences together with high-performance computing in order to assess the role of the thickness of sedimentary basins, interfaces between bedrock and sediments and account for complex full wave effects on waveforms of frequencies up to 10 Hz. Next, we plan to develop a hybrid modelling method based on Generative Models for stochastic simulations of high-frequency waveforms and high-performance deterministic modelling for lower frequencies. It will be developed in collaboration with the Swiss Data Science Centre. This technique will allow us to perform scenario simulations with conditional Generative Models to site parameters and for large magnitude earthquakes. In future work, the subproject 3 will focus on time-dependent probabilistic seismic hazard assessment for emergency and communication planning with regard to nuclear facilities.

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., 3, 1560–1579, DOI: 10.1093/gji/ggad010.

■ **Hallo, M., Bergamo, P., and Fäh, D. (2022a).** Stochastic model to characterize high-frequency ground motion at depth validated by KiK-net vertical array data. Bull. Seismol. Soc. Am., 112, 1997–2017, DOI: 10.1785/0120220038.

■ **Hallo, M., Bergamo, P., and Fäh, D. (2022b).** Predizione della forma d›onda dello scuotimento in profondità, a partire da registrazioni di terremoti in superficie: applicazione a siti ed eventi giapponesi. 40° Convegno del. Gruppo Nazionale di Geofisica della Terra Solida, June 27–29 2022, Trieste, Italy. [extended abstract]

■ **Hallo, M., Bergamo, P., and Fäh, D. (2022c).** Full-waveform prediction of high-frequency ground motion at depth from surface recordings in Japan. In: Arion, C., Scupin, A., Ţigănescu, A. (eds), Proceedings of the Third European Conference on Earthquake Engineering and Seismology - 3ECEES, September 5–9 2022, Bucharest, Romania, Conspress, Bucharest, pp. 4914–4921.

■ **Hallo, M., Koroni, M., Imtiaz, A., and Fäh, D. (2022d)**. Prediction of broadband waveforms at depth from earthquake recordings on the surface in Switzerland. 20th Swiss Geoscience Meeting, November 18–20 2022, Lausanne, Switzerland. [presentation]

■ **Hopp, C., Guglielmi, Y., Rinaldi, A.P., Soom, F., Wenning, Q., Cook, P., Robertson, M., Kakurina, M., and Zappone, A. (2022).** The effect of fault architecture on slip behavior in shale revealed by distributed fiber optic strain sensing. J. Geophys. Res. – Solid Earth, 12, e2021JB022432, DOI: 10.1029/2021JB022432.

■ **Koroni, M., Hallo, M., Imtiaz, A., and Fäh, D. (2022a)**. Broadband waveform simulations of earthquake scenarios in the Swiss Molasse basin using the BBP tool from SCEC. SCEC Annual Meeting, September 11–14 2022, Palm Springs, USA. [poster]

■ **Koroni, M., Hallo, M., Imtiaz, A., and Fäh, D. (2022b).** Broadband waveform simulations of earthquake scenarios in the Swiss Molasse basin. 20th Swiss Geoscience Meeting, November 18–20 2022, Lausanne, Switzerland. [presentation]

■ **Oprsal, I., Hallo, M., Fäh, D., Burjanek, J. (2022).** Modelling of the surface to depth spectral amplification in 3D media. Seismological Society of America Annual Meeting, April 19–23 2022, Bellevue, USA. [poster]

■ **Panzera, F., Alber, J., Imperatori, W., Bergamo, P., and Fäh D. (2022).** Reconstructing a 3D model from geophysical data for local amplification modelling: The study case of the upper Rhone valley, Switzerland. Soil

Dyn. Earthq. Eng., 155, 107163, DOI: 10.1016/j.soildyn.2022.107163.

■ **Rinaldi, A.P., Rutqvist, J., Luu, K., Blanco-Martín, L., Hu, M., and Sentís, M. (2021)**. Parallel modeling of coupled processes: the recent development of TOUGH-FLAC. AGU Fall Meeting, December 13–17 2021, New Orleans, USA. [poster]

■ **Rinaldi, A.P., Rutqvist, J., Luu, K., Blanco-Martín, L., Hu, M., Sentís, M., Eberle, L., and Kästli, P. (2022).** TOUGH3-FLAC3D: a modeling approach for parallel computing of fluid flow and geomechanics. Comput. Geosci., 26, 1563–1580, DOI: 10.1007/s10596-022-10176-0.

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