# 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. Subproject 1 focuses on the investigation and improvement of ground-motion attenuation models and earthquake source scaling for Switzerland. Based on data of the Swiss borehole sites, we recognize a clear dependency of the attenuation on the local shallow subsoil conditions. Rather homogeneous hard rock sites are characterized by almost no scattering attenuation whereas, on the contrary, for unconsolidated soft soils the motion tends to be significantly more scattered. This means that, despite considering the local attenuation parameter $\kappa_0$ as a modeling variable, it can be seen as a real physical variable and should be treated as such.

Within subproject 2, we have studied the effects of source and wave propagation phenomena on the observed ground motions. We have shown the consequences of inaccurate validation of 3D velocity models in scenario simulations for moderate to large earthquakes reaching the Earth surface. Mach waves, which may have a relevant role in observed large-amplitude ground motions, are heavily affected by multi-scale source and medium heterogeneities. A popular hybrid technique to calculate synthetics has been further improved.

Within subproject 3, we have studied the potential for inducing seismicity in deep geological disposal. After improving the current physical and statistical modelling tools for induced seismicity, we have started the application of such tools for the study of possible seismicity induced during the deep geological repository site construction and post closure operations.

## 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 subprojects are:

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

Subproject 1 focuses 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 as well as for smaller induced earthquakes. The work is based on observations in Switzerland and Japan. Studying the near-surface attenuation constitutes a key point in our research during this year.

The scope of subproject 2 is to improve deterministic predictions of ground motion, especially with respect to near field, to nonlinear 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. In the end, 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 geomechanical 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 has focused on improving ground-motion prediction in Switzerland. Building on ground-motion prediction equations (GMPEs) and site amplification models developed for Switzerland during this project [1], [2], [3], we have focused on providing further analyses and refinements. Recently, the attenuation at Swiss hard-rock sites has been studied [4]. Hard rock sites are important because they are mostly free of amplification effects and therefore form the basis of hazard maps, such as the Swiss National Seismic Hazard. They found that the epistemic uncertainty in assigning attenuation measurements at hard rock sites was significant – with different methods leading to very different results. Besides the absence of standardized measurement technique, this is generally due to the model simplifications that are made when measuring attenuation. Despite the known relevance of the local attenuation parameter ($\kappa_0$) in a wide range of seismological applications, standard methods for its calculation capture mostly the intrinsic part, therefore neglecting the possibility that $\kappa_0$ might also comprise a scattering component. However, sites at which scattering attenuation will dominate intrinsic attenuation suffer a robust and reliable estimate of $\kappa_0$. As a consequence, such scattering effects will cause an overestimation of the actual attenuation effects.

Using surface and downhole stations of the Swiss seismic networks, Pilz & Fäh (2016) computed the path-corrected attenuation parameter $\kappa_0$ at six locations in Switzerland. The intrinsic properties of the wavefield show a clear dependency on the local shallow subsoil conditions with differences in the structural heterogeneity of the shallow subsoil layers producing different scattering regimes (Figure 1). Such deviations from the ballistic behavior are indicative for local structural heterogeneities and the associated level of scatter. A small level of scattering, as observed for most of the very hard rock sites, allows the level of attenuation largely to be seen as representative for the regional and mainly intrinsic attenuation. As additional weathered rock or low-velocity soft layers are added to the hard rock base, the apparent $\kappa_0$ increases due to the combined intrinsic and scattering attenuation effects. The joint contribution of both effects, which significantly affects $\kappa_0$ estimates, is particularly strong if the dimension of the scattering layers is in the order of the wavelength and might lead to an actual over-estimation of $\kappa_0$ if scattering attenuation dominates over intrinsic attenuation. In the seismic hazard context, such values can be useful for providing one of the most significant site-effect parameters for ground-motion prediction equations in the high-frequency part of the ground motion.

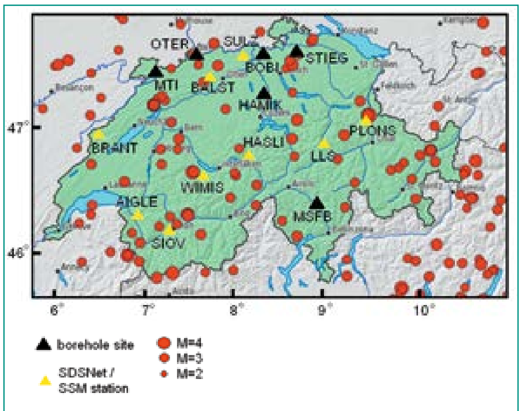
As it is well known that the uppermost soil layers might strongly modify the amplitude and duration of ground motion measured at the surface during an earthquake, it is of particular interest to quantify these effects. Vertical arrays of seismometers, with the downhole sensor serving as the reference, can, in principle, overcome this difficulty. In fact, downhole measurements can provide critical constraints for both the interpretation methods for surface observations as well as information on the real material behavior and overall site response over a wide range of loading conditions. Moreover, current empirical amplification models still suffer the incorporation of strong ground-motions propagating in surficial soil layers. In this case, large shear strains are often predicted within the soil columns and these may reduce soil stiffness and increase nonlinear effects. Such nonlinear behavior of the soil may have beneficial or detrimental effects on the dynamic response at the surface, depending on the energy dissipation process. Based on Japanese (KiKNet) and Swiss seismic networks, our approach is to observe in a statistical way relationships between soil parameters, site response and input ground motion parameters with particular focus on the observed nonlinear soil behavior and ground motion at depth.

We also finalized a study (Edwards and Fäh, 2016) investigating the prediction of strong ground-motion at rock sites in Japan, where a wide range of recording-site types are available for analysis. We employ two approaches: empirical ground motion prediction equations (GMPEs) and stochastic simulations. Comparisons of empirical GMPE's predictions with the hard-rock data showed that all investigated empirical models lead to overestimation of median ground-motions at hard-rock sites in Japan. The stochastic simulation is based on the adjustment of the Swiss stochastic model [1] in terms of geometrical attenuation and a reference rock model valid for Japan. The median simulation prediction at rock sites was found to be comparable due to including site-specific information in the simulations. The results of this study support the use of finite or pseudo-finite fault stochastic simulation methods in estimating strong ground motions in regions of weak and moderate seismicity. Furthermore, it indicates that weak-motion data has the potential to allow estimation of between- and within-site variability in ground motion, which is a critical issue in site-specific seismic hazard analysis, particularly for safety critical structures.

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

Research in subproject 2 has focussed on ground-motion modelling in complex 3D media, improvement of hybrid techniques to compute synthetic seismograms and nonlinear behaviour of soft soils near the surface.





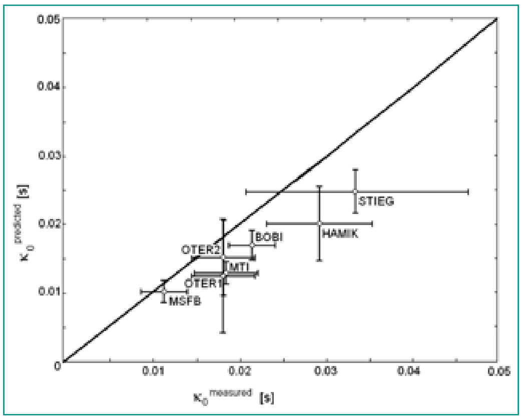




**Figure 1:**
*Left: Map of Switzerland and border regions showing events included in the dataset. The black triangles represent tunnel and borehole sites. Right: Predicted and measured $\kappa_0^{surface}$ values for each station. For all sites, the measured $\kappa_0^{surface}$ becomes larger than theoretically predicted based on the available site information (seismic quality factor, S-wave velocity and distance between surface and downhole sensor).*

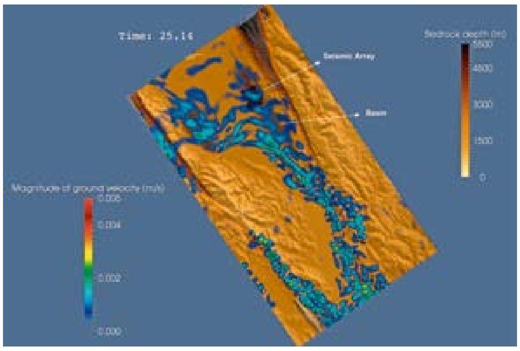



**Figure 2:** *Snapshot of the simulated peak ground motion velocity for the Ml4.9 Gilroy earthquake (Hobiger et al., 2016). The wave field arriving at the array is affected by scattering from a geological formation south of the basin and by diffraction along the basin edge.*

It is now widely accepted that deterministic ground-motion simulations may represent a fundamental tool in seismic hazard studies, since they could help decrease the epistemic uncertainty. Three-dimensional velocity models constitute a key element in strong ground-motion modelling and must be therefore accurately validated. In the current practice, these velocity models are typically validated by waveform modelling of many weak earthquakes with foci limited to depths greater than 5 km [5]. However, rupture during moderate and large earthquakes can propagate to shallower depths and eventually reach the surface. For such shallow sources, velocity models may not be validated with sufficient accuracy. We have investigated this aspect by conducting a series of tests based on the Mw 6.0 Napa earthquake, which was characterized by a very shallow slip asperity, and the high-resolution USGS 3D Bay Area velocity model within 30 km from the fault (Imperatori & Gallovic, 2016). We found that all the existing slip models for the Napa earthquake (based on 1D velocity structures) systematically excite large surface waves in many parts of the model. These waves are much larger than observed, develop inside basins or along basin edges and are likely due to exaggerated velocity contrasts and/or inaccurate basin geometries. Imaging the rupture process using the 3D velocity model could reduce such strong yet artificial ground shaking; however, in this case we also observed unrealistic features in the rupture model likely due to inaccuracies of the 3D velocity model. Therefore accurate velocity models are also fundamental for reliable source imaging. Our investigation has shown that modelling moderate to strong earthquakes reaching the Earth surface may represent a valuable tool for velocity model validation in the near-source region, provided the finite-extent source models are carefully investigated. The importance of 3D propagation effects (e.g. basin resonance, channelling of seismic waves) has been evidenced also in another study (Hobiger et al., 2016), where we showed that rock formations can eventually act as wave scatterers, deviating the propagation path of long period surface waves (Figure 2). These scattered waves, along with basin-edge diffracted waves, could be detected by local seismic arrays.

To improve our understanding of ground motion complexity in the near-source region, we have analysed the propagation of Mach waves generated by super-shear fault rupture in 3D highly heterogeneous media. Mach waves are extremely important for studying the limits of ground motion, as they may result in high amplitude, high frequency pulses [6]. Although largely reproduced in numerical simulations and laboratory experiments, shear and Rayleigh Mach waves are not widely observed [7]. In our study (Vyas et al., 2016) we have considered realistic source models and investigated how heterogeneities of medium and rupture parameters affect the coherence of such waves. We demonstrated that the coherence of Mach waves is significantly diminished by heterogeneities in the rupture process up to 10–15 km from the source and by small-scale heterogeneities in the Earth crust beyond that.

In the framework of earthquake engineering, hybrid techniques to compute broadband synthetic seismograms are of particular interest because they can reproduce fundamental features of the ground motion over a wide range of frequencies without sacrificing computational efficiency. In virtue of their relevance, these techniques are subject to frequent improvements. We have focussed on a widely used technique [8], included in the SCEC broadband platform. We exploited a ray-theory approach [9] to allow the code to efficiently compute high-frequency synthetics for large extended faults, and included a recently developed kinematic source model [10] to reproduce the frequency-dependent loss of directivity normally observed during seismic events.

The non-linear behaviour of soft soils has been another objective of our research. Observation of strong ground motion recordings suggests that water-rich, sandy soil could experience high-frequency amplitude bursts and possibly liquefaction as a result of pore-water pressure build-up during strong earthquakes. In this context, we have developed a new procedure to assess the non-linear soil response and liquefaction based on collected CPT data and ground motion prediction equations (GMPEs). This procedure takes into account the uncertainty in the empirical liquefaction curves used in engineering practice and the peak ground acceleration (PGA) variability for different magnitude ranges at a given distance. This method can complement existing procedures (e.g. [11]) based on numerical modelling and tri-axial testing on soil samples.

## 3. Induced seismicity and application for a deep geological repository

The overall objective of subtask 3 is to analyze the possible occurrence of induced seismicity due to the repository short and long-term activities. The updates to numerical models as requested by task 1 of the subproject 3 were concluded. A paper presenting a study on induced seismicity accounting for velocity-dependent friction has been published (Urpi et al., 2016). We also updated the so-called seed model to account for a more complete description of fluid flow and geomechanics with a stochastic model. The model called TOUGH2-SEED is presented in a paper that was submitted to an international journal for publication (Rinaldi and Nespoli, 2016).

The application of these models to the nuclear waste disposal is an on-going activity. This also involved an extensive review of publications and reports about experiments performed to mimic repository environment and operations, ranging from the characterization (stress conditions, rock type, size and engineering solutions) of a possible future Swiss repository to the investigation of temperature, pressure and stress changes induced by the emplacement of canisters.

The results available in literature show that the potential for creation of new fractures (i.e. bringing intact rock to failure) is non-existent [12] or negligible, and possibly occurring only for very specific and very unlikely rock parameters [13]. Nevertheless, shear failure on pre-existing and undetectable small features may occur during both deep geological-repository site excavation and operation. Such small fault/fracture reactivation, while not necessarily critical for the operation of the repository, may be important for understanding signals from monitoring tools and the underlying processes.

With regard to the possible seismic activity induced during the construction of the repository, we have continued our study on excavation-induced fault reactivation. We have focused on a simulation specific for a nuclear waste repository in clay material. By assuming typical clay rock properties [12], we have modeled the excavation of three tunnels with diameter 2 m and with an inter-tunnel distance of 40 m. We assume that a fault zone underwent

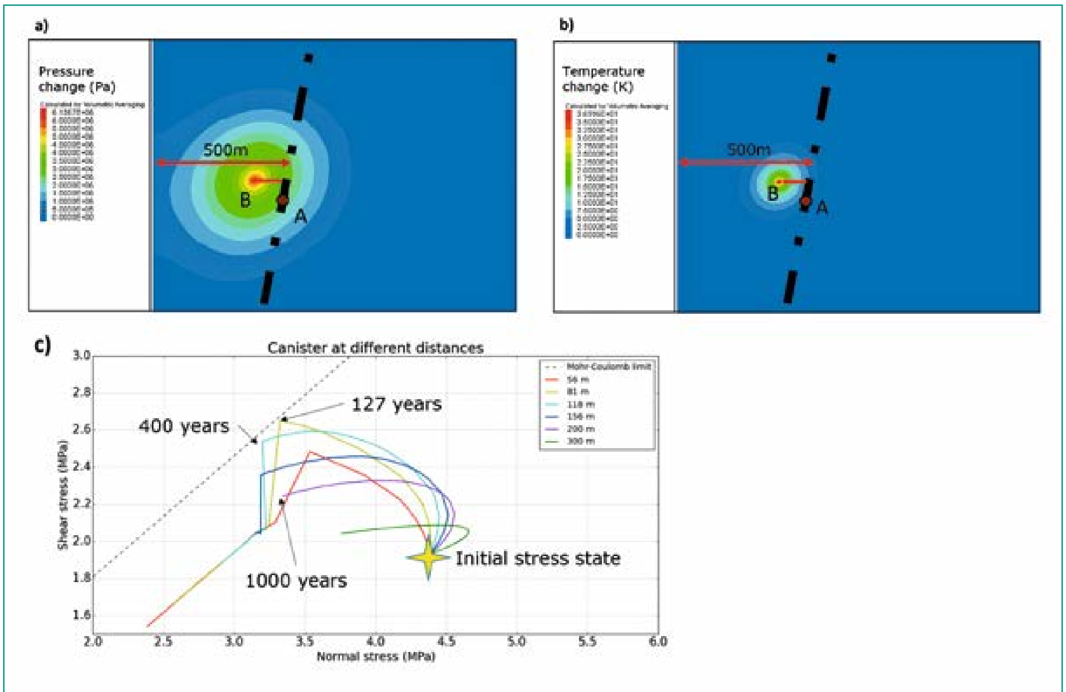



Figure 3:
*(a) Snapshot of the changes in pressure distribution 300 years after canister emplacement; (b) Snapshot of changes in temperature distribution 300 years after canister emplacement. (c) Shear and normal stress evolution. Curves represent evolution over 1000 years. Point A in panel (a) and (b) is the observation point for shear and normal stresses plotted in panel (c). Point A is located on the fault at an elevation of -97.5 m below the canister. Point B represents the canister location whose distance from fault varies according the case (in the example point B is at a distance of 81 m from the fault).*

undetected during site characterization, and such fault zone is placed at a distance of 10 m from the wall of tunnel. During excavation of the three tunnels we calculated the stress evolution at two point placed on the fault plane. We use a Mohr-Coulomb criterion and a strain-softening friction evolution to simulate a sudden slip on the fault if conditions are reached. Assuming an average friction coefficient of 0.6 and a stress ratio of 0.67 between minimum and principal stress (i.e. similar to Mont Terri conditions [12]), results show that the stress changes due to the small tunnels are not critical and the fault is not reactivated. Most of the stress changes occurring on the fault plane are due to the excavation of the tunnel closest to the fault itself, while little stress changes occurred for excavation of the other tunnels. For completeness, simulations were performed also in the case of extreme and unlikely conditions. For example, the fault can theoretically be reactivated if the ratio between the principal stresses is as low as 0.635 and if the frictional coefficient is unrealistically low (0.35). In such conditions, the fault is reactivated as soon as the excavation begins, resulting in a seismic event whose magnitude is only limited by the size of the fault itself.

With regard to the operational phase of a repository, we account for stresses induced by the canister emplacement (i.e. temperature and fluid pressure). In order to determine the influence of a single emplacement tunnel on fault stability, we used an approach similar to the excavation. Previous results by [13] have shown that a canister emplacement is expected to induce a temperature increase peaking after 50 years and an increase of pore pressure peaking after 100–1000 years (in the immediate surroundings of the emplacement tunnel). Figure 3a and 3b show a snapshot of pressure and temperature distribution 300 years after the canister emplacement.

Such temperature and pressure changes act in synergy to change conditions on a nearby weakness plane, possibly reducing its stability. We assumed unfavorable stress conditions in units lying directly above the Opalinus Clay (normal fault, horizontal minimum tectonic stress 0.61 times the vertical tectonic stress) for a low-cohesion fault (0.5 MPa) [14]. The fault can be reactivated if the canister is emplaced sufficiently close to the fault. As in the case of the excavation study, we assume that a small fault (e.g. with an offset of less than 10 m) underwent undetected during site characterization.

As shown in stress path in Figure 3c, preliminary results suggest that in unfavorable conditions a fault is unstable (i.e. it reactivates seismically or aseismically) if it is located nearby the emplacement tunnel. A magnitude of the possible induced events can be evaluated as function of the dynamic friction and rock properties at the fault. A proper characterization of the seismic vs. aseismic behavior would be possible in the future by the analysis of the faultslip experiment performed in Mont Terri. For the current model, a bound on the magnitude is imposed by the fault size.

## National Cooperation

We initiated collaborations with the Mont Terri Underground Lab and Swisstopo, to model the ongoing Fault Slip experiment at Mont Terri. We cooperated with Engineering Geology group at ETHZ to discuss issues related to deep geological disposals.

## International Cooperation

We have established successful cooperation with the University of Liverpool, UK, and the Disaster Prevention Research Institute, University of Kyoto, Japan. Our work on ground-motion simulations in heterogeneous media was conducted in collaboration with the Charles University of Prague and the King Abdullah University of Science and Technology in Jeddah. The improvement of the hybrid broadband technique has started an active collaboration with the San Diego State University and the University of Canterbury in Christchurch, New Zealand. Research on induced seismicity during operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley.

## Assessment 2016 and Perspectives for 2017

While the project has addressed the questions originally posed, the work has further highlighted the potential for improvements in regional and local seismic hazard assessment in Switzerland and has opened up new questions and directions for future research.

We particularly aim at proposing an empirical site-amplification model based on the physical properties of the site (e.g., the measured velocity profile) and to define the parameters characterizing the effects of frequency-dependent amplification, intrinsic attenuation, scattering and nonlinear soil behavior. Given such information, we facilitate a uniquely referenced site-specific GMPE that could easily be adapted to an arbitrary target site at surface and at depth for hazard analysis.

By adjustment of the Swiss stochastic model to Japanese conditions, we showed that weak-motion data has the potential to allow estimation of strong ground motion, and between- and within-site variability in ground motion. These are critical issues in site-specific seismic hazard analysis, particularly for safety critical structures.

Our research has evidenced that both source and wave propagation phenomena play a key role in seismic hazard analysis at different scales. We plan to further extend our research by investigating the effects of soil nonlinearity on high amplitude Mach waves, which may have a relevant role in generating very large ground motions.

Exploring a large set of scenario is fundamental in earthquake ground motion simulations. For this reason we have improved an existing hybrid broadband simulation technique. We expect to further include more features, also specific to the Swiss region. In particular, we aim to calculate synthetics at depth (e.g. in underground repositories) and to integrate the code with the Swiss stochastic model [1]. We believe that subproject 1 and 3 will greatly benefit from these developments.

After improving the existing model for induced seismicity, we have deepened our understanding of the seismicity that can be induced during repository construction. We have started the analysis of seismicity that could be associated with postclosure behaviour of rocks. We plan to further improve our modelling by accounting for more realistic scenarios for geological disposal as well as realistic frictional laws and 3D geological models.

## Publications in the project 2015–2016


- *Edwards, B. and D. Fäh* (2016). Prediction of Earthquake Ground Motion at Rock Sites: Evaluation of Empirical and Stochastic Approaches. Submitted to Geophys. J. Int.
- *Hobiger, M.,Cornou, C., Bard, P.Y., Le Bihan, N., Imperatori, W.* (2016). Analysis of seismic waves crossing the Santa Clara Valley using the three-component MUSIQUE array algorithm. Geophys. J. Int. 207(1), 439-456.
- *Imperatori, W., Gallovic, F.* (2016). Validation of 3D velocity models using earthquakes with shallow slip: case study of the Mw6.0 2014 South Napa, California, event, accepted in Bulletin of the Seismological Society of America.
- *Imperatori, W., Mai, M.* (2015). The role of topography and lateral velocity heterogeneities on near-source scattering and groundmotion variability, Geophys. J. Int. 202, doi: 10.1093/gji/ggv281
- *Pilz, M., Fäh, D.* (2016). The contribution of scattering to near-surface attenuation. Manuscript under review in Journal of Seismology.
- *Rinaldi, A. P., Nespoli, M.* (2016). TOUGH2-SEED: a coupled fluid flow and mechanical-stochastic approach to model injection-induced seismicity. Computers & Geoscience, in press.
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