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 models and earthquake scaling for Switzerland. Although it is known that soil layering and basin geometry can locally amplify seismic waves, empirical site response estimates are generally limited to locations where nearby reliable reference sites are available. To tackle this restraint, we have resorted to the Japanese network of borehole stations KiK-net, following two parallel procedures to empirically obtain site amplification functions, from the correlation surface-borehole recordings and from the processing of the sole surface waveforms. The systematic collation between the two datasets allows a reasoned comparison of the applied methods, and an in-depth study of the site amplification variability depending on the near-surface configuration. Furthermore, subproject 1 has also aimed at assessing the relevance of nonlinear soil behavior from ground motion recordings and completed the verification of the Swiss stochastic ground-motion model. Within subproject 2, we have produced a new version of a numerical code to generate hybrid broadband synthetic seismograms. The new release has a series of important features, ranging from complex source geometry to multiple scattering models and frequency-dependent spatial correlation of coda waves, which can significantly increase the accuracy of the simulation technique, especially for large earthquakes. We have continued collecting CPT data for the calibration of complex nonlinear soil models. Within subproject 3, we have studied the potential for inducing seismicity in a 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 after the closure of the deep geological repository. Realistic in-situ conditions and nuclear waste repository geometries are being included in our simulations.

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 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 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. Results of subproject 1 will be linked to deterministic simulations from subproject 2, and the results will be tested and compared to observed data.

In subproject 3, we move towards a more realistic characterization of seismogenic sources for induced earthquakes. The goal is to adapt existing geo-mechanical models to a situation of a deep geological disposal, 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

It is well known that local site conditions can strongly affect the amplitude and duration of ground motion during an earthquake. The aim of this work package is developing tools for the robust reconstruction of the local response term of seismic wave propagation, including the assessment of the relevance of nonlinear soil response from ground-motion observations.

The local site amplification can be empirically determined as the ratio between the Fourier spectrum at the target location and the spectrum at a corresponding reference site, i.e. a hard rock location close enough to the station of interest [1]. However, as reliable reference sites can be unavailable, vertical arrays of accelerometers (i.e. borehole stations), with a downhole reference site coupled to a surface instrument, can overcome the difficulty [2], representing the ideal recording configuration for the study of site effects.

Due to the limited number of borehole stations in Switzerland, we resorted to the world's largest array of borehole stations, the Japanese Kiban-Kyoshin (KiK-net) network, consisting of ~700 sites instrumented since 1997. For each station, the Vs profile (from downhole tests) is known. We exploited the rich waveform database of this network to empirically retrieve the horizontal amplification function for each station's site, following two parallel procedures:

- A collation between the Fourier spectra at the surface and at the borehole receiver, thus obtaining a surface-to-borehole (SB) ratio function portraying the amplification due to the soil column between the top and the bottom of the borehole (Figure 1a);
- A second, more complex method involves the estimation of the local amplification function using exclusively the surface accelerometer recordings. Site-specific ground motion residuals relative to spectral modeling of a large number of earthquakes are inverted to retrieve the elastic and anelastic empirical amplification functions [3] (Figure 1b).

Therefore, for most of the 700 KiK-net stations, we obtained two alternative estimates for the local site amplification. The two datasets were first referred to a common bedrock to allow internal and cross-comparison; secondly, they were brought to the Swiss reference bedrock [4] for a proper translation to the Swiss condition. The obtained results are:

- A systematic collation of SB ratios vs. amplification functions from spectral modeling evidenced a good agreement between the two procedures, at least in an intermediate frequency band (Figure 1c). Reliable amplification functions can therefore be obtained at surface stations for the frequency band between about 0.5 and 20 Hz.

- The obtained amplification functions were also sorted according to the station's soil type [5] and the reliability of the provided Vs profile (which determines the soil class). An example for soil class C is given Figures 1a and 1b. This allowed identifying common amplification features for each soil type, and appreciating the relevance of reliable site metadata when these are correlated with local response.

Results from the compiled dataset can be used to derive empirical amplification models for any defini-

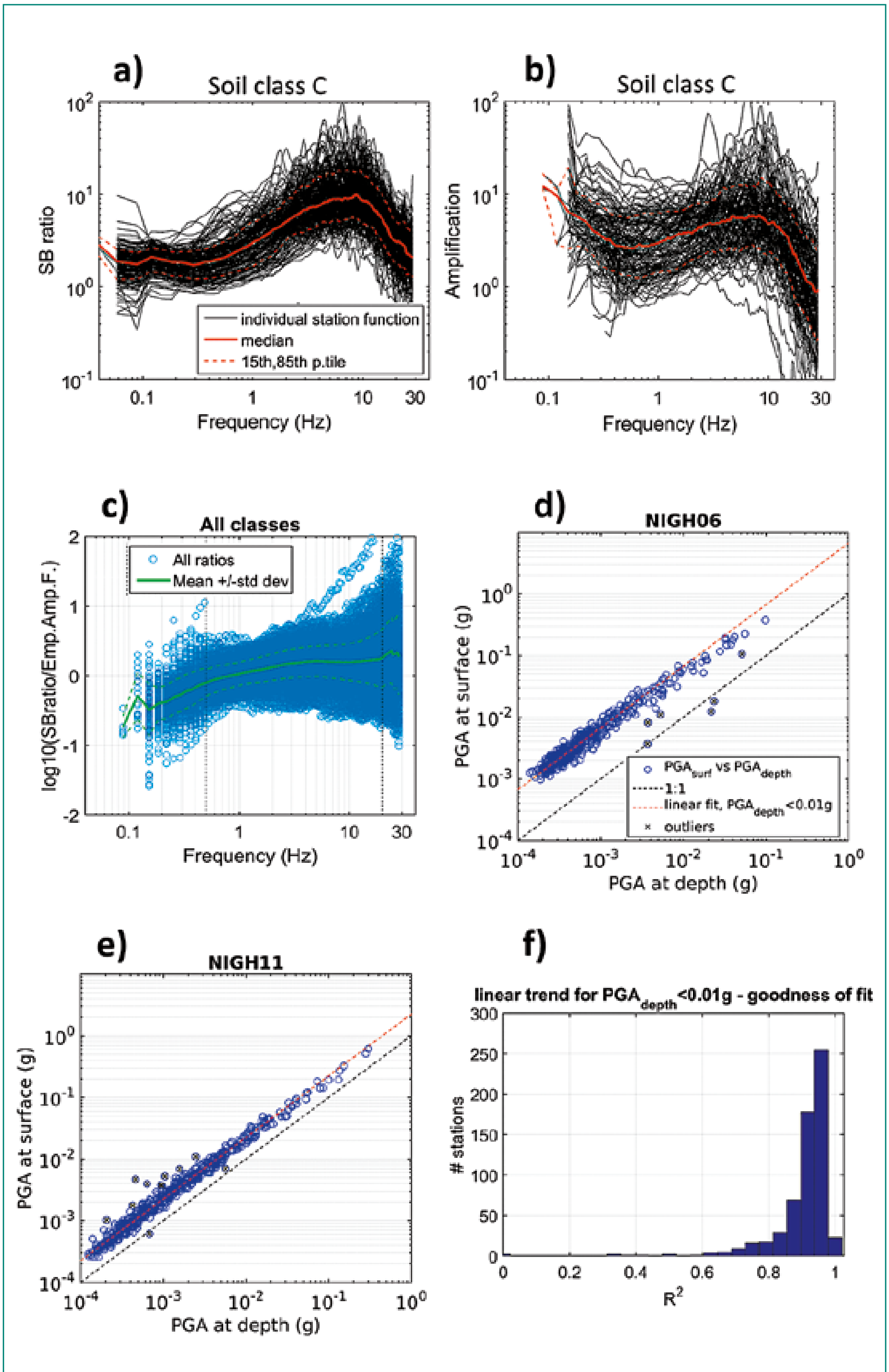

Figure 1: *Envelope of SB ratios (a) and amplification functions from spectral modeling (b) from KiK-net stations belonging to soil class C; c) comparison between all pairs of SB ratios and amplification functions from spectral modeling. d, e) PGA_{surf}–PGA_{depth} couples for two KiK-net station (both C class); f) linear trend at PGA_{depth}<0.01 g, distribution of coefficients R2.*

tion of soil classes or classes of Vs profiles. Related to site-specific attenuation, we finalized the study on near-surface wave scattering attenuation (Pilz and Fäh, 2017), which was a research focus in 2016.

Another focus of our study was the assessment of the relevance of nonlinear soil behavior at high levels of ground motion. Soft soils can exhibit a decrement in shear modulus and an increment in shear damping ratio as the strain level increases [6]. Here again, we analyzed the KiK-net database. In search for empirical evidence of nonlinear soil behavior, we computed orientation-independent [9] h-PGAs for the surface and borehole receivers' recordings at each station (Figure 1d,e). We focused our search on shallow events (hypocentral depth <20 km). The main outcomes are:

- Although we collected more than 80000 pairs of PGA_{surf}-PGA_{depth}, only at 47 stations (out of 689) we recorded three or more exceedances of $PGA_{surf}>0.1$ g (value recognized in literature as the threshold for the onset of nonlinear response). Therefore, the database of shallow events does not yet contain many recordings with levels of ground motion high enough to potentially induce nonlinearity.
- The relation of $\log_{10}(PGA_{surf}) - \log_{10}(PGA_{depth})$ appears to be properly described by a linear relation for the vast majority of KiK-net sites, at least at small strain ($PGA_{depth}<0.01$ g (Figure 1d-f).
- At some sites and at high levels of ground motion ($PGA_{surf}>0.1$ g) we observe a slight deviation from this linear pattern (witnessing potential soil nonlinearity, Figure 1d): however, this deviation does not appear to be strong and it is not consistently noticed at all stations (Figure 1e).

The modest relevance of nonlinearity is evident, when the expected levels of ground motion for Switzerland with 475 years return period are considered [7]. These ground-motion levels are generally below or close to the threshold of potential onset of soil nonlinear behavior observed at some sites. Considering 10000 years return periods, the KiK-net dataset is yet too scarce to establish reliable models for nonlinear soil response.

As a new research field, we started to investigate the site-specific ground-motion duration by analyzing KiK-net and NGA-West 2 data. NGA-West 2 data include a broader range of site-conditions than we find in the KiK-net dataset. Finally, we completed the verification of the Swiss stochastic ground-motion model using Japanese data, by comparing also to published ground-motion prediction equations (Edwards and Fäh, 2017). The results confirm the high quality of the Swiss stochastic model.

2. Modelling of wave propagation in complex, nonlinear media and limits of ground motion

Research in subproject 2 has focussed on improving existing ground-motion modelling techniques and collection of field data to characterise the nonlinear behaviour of soft soils near the surface. Numerical simulations of ground-motion have great potential in seismic hazard studies, as they

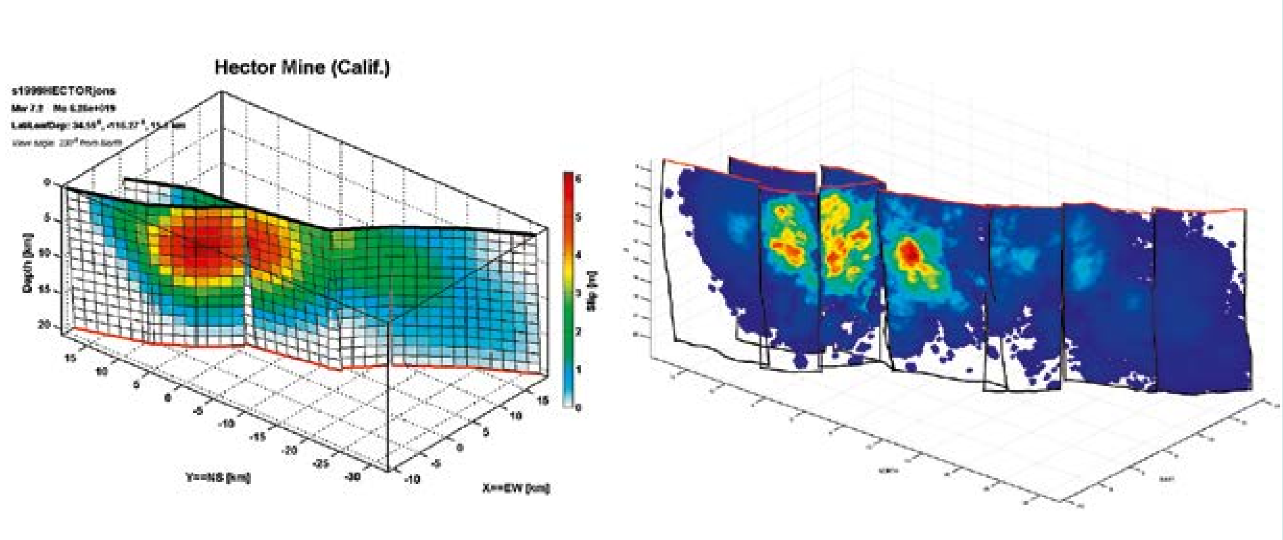

Figure 2: *Left: low-resolution input slip model (Hector Mine earthquake). Right: corresponding high-resolution slip model generated by the code and used in the actual high-frequency calculations. Local perturbations to each fault segment, resulting in variability of strike, dip and rake, are visible as well.*

could lead to a decrease of the epistemic uncertainty. Synthetic time-series may be used to estimate scalar ground-motion intensity measures (e.g. PGA), thus integrating commonly adopted ground motion prediction equations (GMPEs) in areas where the latter are not well constrained. At the same time, they may allow more realistic nonlinear structural dynamic analysis of sensible structures and performance-based earthquake engineering studies. It is highly desirable that these time-series span a wide frequency range, generally up to 10Hz or higher.

It is implied that simulations must be based on a large set of potential rupture models and small-scale velocity perturbations (generally superimposed on a fixed background velocity model, as in [8]) in order to sample the parameter space as much as possible. Fully deterministic simulations at such high frequency, despite the constant increase of computational power, are very demanding and therefore limited to few selected case studies. So-called hybrid broadband techniques are of particular interest because they can reproduce the fundamental features of the ground motion over a wide range of frequencies without being excessively demanding from a computational point of view. These techniques couple low-frequency (< 1Hz) deterministic synthetic seismograms with stochastic high-frequency (> 1Hz) time-series.

We have completely revised an existing hybrid broadband code [9], available on the SCEC broadband platform, by including several new features that are fundamentally necessary for simulating realistic ground-motions. In particular, the high-frequency module itself (> 1Hz) is now based on a mixed deterministic-stochastic approach: the deterministic part is computed using a fast ray theory technique [10], while the stochastic one relies on selectable scattering models [11]. The latter, based on adjustable scattering parameters, controls the appearance of the coda waves. This formulation is meant to reproduce the gradual energy transfer from direct waves, radiated by a complex source model, to coda waves as they travel through the crust. It should be noted that the implemented scattering models are based on the radiative transfer theory and can be used to synthesize only the envelopes of scattered waves. As the exact distribution of small-scale heterogeneities in the crust is unknown, these envelopes are normally «filled» with uncorrelated time-series, representing the actual coda waves. In the new version, we introduce a frequency-dependent coherency model [12] for the coda waves, forcing waveforms at nearby receivers to be partially correlated. Such spatial correlation is particularly important in the context of structural dynamic analysis [13].

The new code can handle complex fault geometries, including multiple fault segments and multi-scale roughness. As evidenced by recent studies [14], fault roughness is also responsible for local variations of strike, dip and rake, contributing to the overall complexity of ground-motions. We have also implemented a methodology [15] for the generation of kinematic rupture models radiating high-frequency energy in agreement with dynamic rupture studies. This feature is particularly useful to reproduce the gradual frequency-dependent directivity loss observed during large seismic events. As a result, the code can be supplied only with a low-resolution slip model and then it automatically generates a high-resolution rupture model used in the high-frequency calculations (an example is shown in Figure 2).

The nonlinear 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. Although several techniques to simulate nonlinear soil response exist, their calibration is extremely difficult as they rely on a large number of free parameters. We are in the process of finalising a procedure to calibrate a popular nonlinear soil model [16] by using CPT data. In this context, we have continued our data campaign by collecting CPT measurements in Rennaz, Interlaken and Buochs.

3. Induced seismicity and application for a deep geological repository

The overall objective of this subtask is to investigate the possible occurrence of induced (micro-) seismic events due to the High-Level Waste (HLW) repository construction and disposal activities, as well as due to the Low-Level Waste (LLW) repository construction. The questions we are addressing relate to two fundamental seismological topics:

- The nucleation of a rupture: if a rupture takes place, at which stress state will this happen?
- The propagation of a rupture: will it be a seismic rupture, and of what magnitude?

Our current work focuses on addressing whether conditions for the nucleation of a rupture are possible. We further aim at understanding the effect of temperature increase and subsequent thermal pressurization, as well as addressing issues related to the possible creation of flow paths by reactivation of faults [17].

Our results show that the occurrence of the nucleation and propagation of a rupture can in principle be affected by the repository design (such as thermal load produced by the canisters, geometry and size of the repository) and by the properties and conditions of the hosting formation (for example: in-situ stress condition, elastic properties, frictional behavior, fault size) and an evaluation of the stability of faults close to the HLW repository should be done on the future repository site. Stress and pore pressure perturbation induced by the HLW thermal load can affect the stability of a fault, depending on the in-situ stress state and on the relative position of the fault. The thermal pressurization, i.e. the increase in pore pressure due to the thermal dilatation of the hosting formation, may destabilize the rock mass via reduction of normal effective stress. With respect to the expected size of rupture, it is reasonable to expect that a bound on the magnitude is imposed by the fault dimension. An estimate of the average slip occurring on the fault plane must include the potential secondary effects (surface and tunnel deformations).

The interaction between the thermo-elastic stresses and pore pressure changes in space and time has been investigated for a single tunnel [18] and it is currently extended to include multiple emplacement tunnels. Different stress regimes [19] have been investigated and are presented in Table 1.

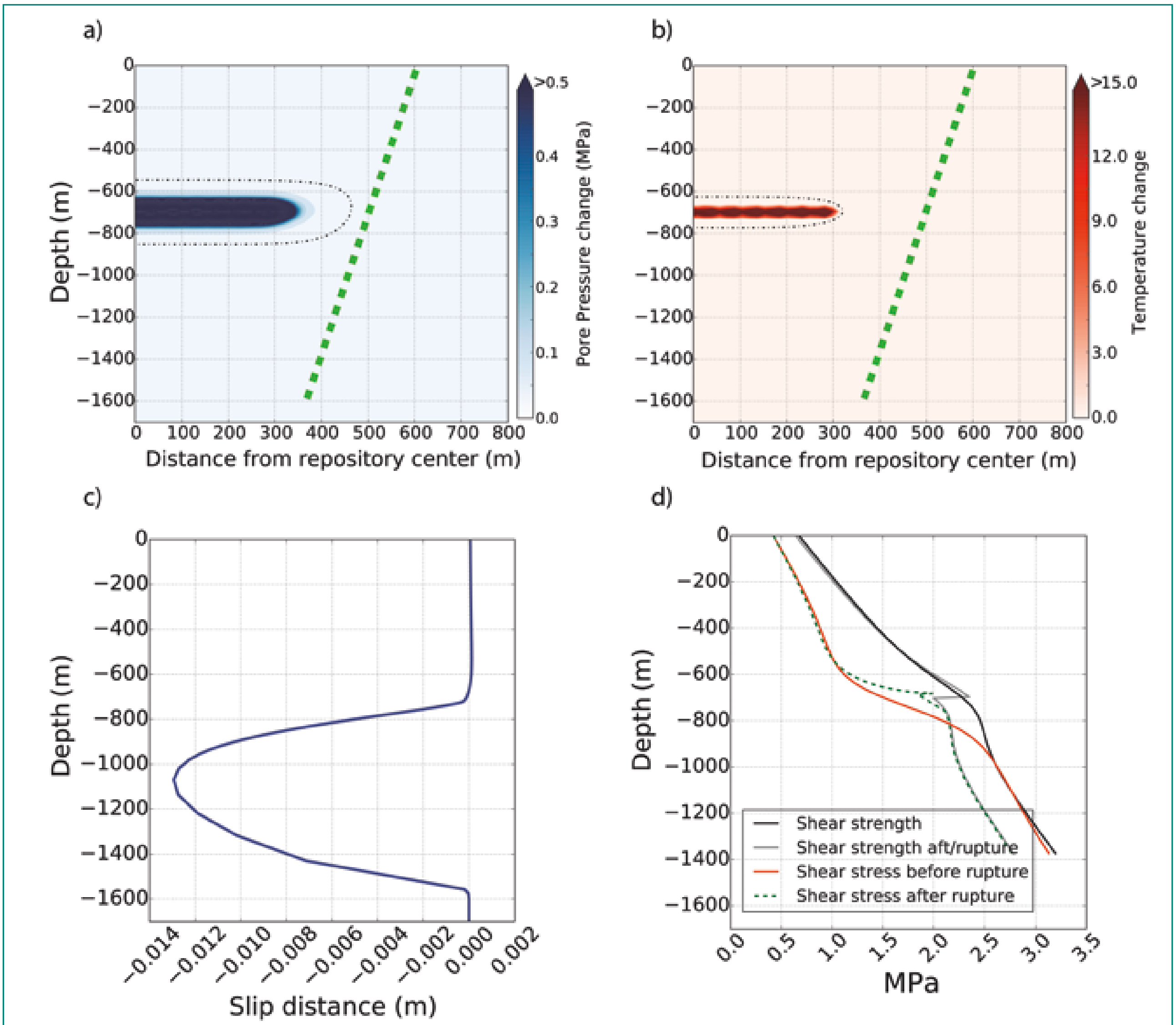

Figure 3: *a) Snapshot of the pressure field 100 years after canister emplacement (capped at 0.5 MPa), the thin dashed line represents 0.5 MPa pressure increase after 500 years. b) Temperature distribution (scale capped at 15 °C), the dashed black line represents 15 °C change after 500 years. Dashed green line in a) and b) represents the fault location. c) Shear displacement along the fault after reactivation. d) Shear stress and shear strength profiles, before and after fault reactivation: kink in shear stress after rupture corresponds with the tip of the moving section of the fault, having no shear displacement.*

	GMmax	GMref	GMmin
Stress regime	Reverse	Strike Slip	Strike Slip
Maximum stress at 900 m	Horizontal 41.1 MPa	Horizontal 28.3 MPa	Horizontal 23.7 MPa
Minimum stress at 900 m	Vertical 22.1 MPa	Horizontal 21.0 MPa	Horizontal 17.5 MPa

Table 1: *Stress state for three different possible in-situ conditions. GMmax refers to a scenario where S_{Hmax} is limited by the residual strength of the Opalinus Clay, GMref refers to a scenario where a moderate horizontal tectonic load is present and GMmin to a scenario where S_{hmin} is controlled by overconsolidation.*

The currently used model represents a plane strain vertical section; therefore, the rupture process is limited to take place in the vertical direction. Reactivation of the fault zone occurs, following a Mohr-Coulomb criterion, and sudden slip is simulated by means of a strain-softening friction law. The hosting formation follows an elastic rheology. Elastoplastic behavior will be included in the future. The fault is assumed as a large structure (>1000 meters length along dip) cutting through the Opalinus Clay.

Considering elastic behavior for the hosting formation, a rupture on the assumed fault plane may only be induced by the repository stress and pressure perturbation if the stress state corresponds to the GMmax scenario (Table 1). As presented in [18], the plastic behavior of the Opalinus Clay can affect stress distribution and fault reactivation timing. Therefore, other scenarios will be investigated considering the elastoplastic behavior of the hosting formation. Results in Figure 3 show that conditions for fault reactivation are reached in the formation below the Opalinus Clay as a combination of stress arching due to the thermal expansion of the hosting formation and pore pressure field perturbation in the unit below the argillaceous formation. With respect to distance, this can happen when a fault is at a distance of 200 meters from the edge of the emplacement area. The induced fault reactivation does not extend along the complete length of the fault. The thermal expansion stabilizes the portion of the fault lying at the same depth as the emplacement tunnels. In the case analyzed (Fig. 3c-d), the rupture is confined to the zone of increased shear stress (with respect to the in-situ stress condition) due to the thermo-elastic stress perturbation.

Assuming that the fault reactivation occurs with a seismic energy release, and assuming that the ruptured area has circular shape, the resulting moment magnitude with the calculated slip distribution is 1.8. This result must be considered as an approximate value. Indeed, we assumed the same properties for the fault as for the Opalinus Clay, but at the simulated depth of reactivation such properties could be different: a higher cohesion or friction coefficient would reduce the rupture length.

National Cooperation

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

International Cooperation

We have strengthened cooperation with 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 the operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. Comparison of approaches and results with the Canadian Nuclear Safety Commission has been initiated.

Assessment 2017 and Perspectives for 2018

We have compiled a dataset combining site-amplification functions and measured velocity profiles, which can be used to derive empirical amplification models for any definition of soil classes or classes of Vs profiles. Related to site-specific attenuation, we finalized the study on near-surface wave scattering attenuation (Pilz and Fäh, 2017), which was a research focus in 2016. Moreover, we completed the verification of the Swiss stochastic ground-motion model using Japanese data, by comparing also to published ground prediction equations

(Edwards and Fäh, 2017). The results confirm the high quality of the Swiss stochastic model. Recently, [20] have developed a new technique for predicting response spectra ordinates, which utilizes two separate empirical models for FAS (Fourier Amplitude Spectrum) and duration of ground motion. We plan to develop an empirical frequency-dependent duration model and an empirical FAS model calibrated upon Swiss and/or Japanese data. High-frequency ground-motions in the near source region are mainly controlled by stress drop. The apparent stress conditions and source dynamics are related to the total energy released during an earthquake. Thus, we also plan to estimate energy magnitude for Swiss earthquakes. An energy magnitude is expected to reduce the aleatory variability at higher frequencies.

We have thoroughly revised an existing technique to compute broadband synthetic seismograms by adding a series of features concerning the source and wave propagation part. The code is now able to handle both small and large seismic sources, reproducing their frequency-dependent effects on ground motions as the loss of radiation pattern and directivity. Coda waves are based upon advanced scattering models and are characterized by realistic spatial correlation patterns. We plan to complete the implementation of some relevant features in the broadband code, mainly the possibility to model ground-motion at depth in order to make our code a valuable tool for seismic hazard assessment for underground nuclear waste repositories. At the same time, we will fully validate the code by simulating relevant past earthquakes. We expect to extend our research by investigating the effects of soil nonlinearity. This may be carried out by working on numerical simulations and observed recordings: in particular, simulations may be used to evaluate the effects of nonlinearity on high amplitude Mach waves, while recordings from the vertical array in Visp may provide further details on the nonlinear response of soft soils.

We have started to simulate induced seismicity that could be associated with post-closure behaviour of a repository. Numerical simulation of different repository designs as well as different in-situ stress regimes have been initiated and will be completed in the following year, accounting for frictional laws derived from the latest published data and for heterogeneities in the hosting formation properties derived from 3D geological models.

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- *Graupner, B.J., J. Rutqvist, Y. Guglielmi, T.S. Nguyen, J.-W. Park, W.-J. Shiu, L. Urpi, G. Ziefle (2017)*. Modelling the induced slip of a fault in argillaceous rock. 7th Clay Conference, Davos, Switzerland, 24–27 September, 2017.
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