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 has focused on the investigation and improvement of ground-motion models and earthquake scaling for Switzerland. Recently, we have focused on the path- and site-specific attenuation properties. Based on Swiss borehole data, we have recognized a clear dependency of the attenuation on the local shallow subsoil conditions. While rather homogeneous hard rock sites are characterized by almost no scattering attenuation, the ground motion tends to be significantly scattered in unconsolidated soft soils. The hard-rock attenuation is dominated mainly by the intrinsic component with only small contribution from scattering. 2D/3D structures such as basins, valleys and ridges play an important role in earthquake hazard in Switzerland. We are presently exploring the role of surface and subsurface topography on ground motion duration. Within subproject 2, we have investigated the effects of small-scale velocity heterogeneities, complex basin geometries and topography on the ground motion, particularly at close distance from the source. The non-linear behavior of shallow soft soils has been a central topic in our research, as we have collected CPT data in Switzerland fundamental to characterize the rheological response of soft materials. We have developed a new numerical code to calculate synthetic broadband seismograms and proposed an inversion scheme for the site-specific calibration of the high-frequency ground motions. Finally, we have started to investigate the physical origin of the local site-attenuation parameter kappa. Within subproject 3, we have studied the potential for induced 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 induced seismicity after the closure of the deep geological repository. Realistic insitu condition and repository geometry 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 sub-projects are:

1. Ground-motion attenuation models and earthquake scaling for Switzerland;
2. Modelling wave propagation in complex, non-linear 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.

The scope of subproject 2 is to improve deterministic predictions of ground motion, especially with respect to near field, to nonlinear behavior in sedimentary rocks and soft soils, and to new trends in modeling 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 (e.g. nuclear waste repositories), develop and validate new modeling 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 prediction in Switzerland. Under the framework of this subproject, ground-motion prediction equations (GMPEs) and site amplification models were developed (Michel et al., 2014; Cauzzi et al., 2015). Recently, Edwards and Fäh (2017) investigated the prediction of strong ground motion at rock sites in Japan, where a wide range of recording-site types were available for analysis. Two different approaches, based on empirical ground motion prediction equations (GMPEs) and stochastic simulations, were followed. Comparisons of empirical GMPE's predictions with the hard-rock data showed that all investigated empirical models lead to an overestimation of median ground motion levels at hard-rock sites in Japan. On the other hand, simulation-based predictions at rock sites were found comparable to observations because site-specific information was included in the simulation procedure. Edwards et al. (2015a), while studying attenuation properties at hard-rock sites in Switzerland, found that the epistemic uncertainty was significant, with different methods leading to very different results. This problem has severe consequences in Vs-kappa adjustments of GMPEs to common reference rock conditions (Bard et al., 2018).

The relevance of the local site-attenuation parameter kappa (κ_0) in engineering practices is well known. Using surface and down-hole stations of the Swiss seismic networks, Pilz & Fäh (2017) computed the path-corrected attenuation parameter (κ_0) at six locations in Switzerland. The intrinsic properties of the wave field 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. It was observed that, for most of the very hard-rock sites, scattering is negligible and intrinsic attenuation is the main controlling factor while weathered, low velocity soft layers can increase the apparent κ_0 due to the combination of scattering and intrinsic attenuation effects. However, the exact relative contribution of both factors is site dependent, and in general still poorly understood.

The influence of the soil layers is not only limited to kappa, but it also affects amplitude and duration of the ground motions measured at the surface during an earthquake. At the same time, 2D/3D structures as deep valleys, basins, ridges and complex topography are known to alter the characteristics of the ground shaking in a complex manner (e.g. Michel et al., 2014; Imperatori and Mai, 2015). It is therefore of utmost importance to derive methods to quantitatively characterize such effects on duration, especially if we consider that they tend to dominate over 1D site-response, in particular at higher frequencies.

Early attempts to capture the local effects on duration were based on proxies already employed for the prediction of response spectral ordinates as Vs30 [1]. However it was noticed that the local surface and sub-surface topographical aspect has the biggest impact on the duration response. For instance, sediment-filled valleys can experience much longer ground motions due to the onset of edge-generated surface waves and their entrapment in the sedimentary basin. As a result, local duration response can be used to identify sites with 2D/3D amplification effects [2]. Due to limited number of borehole stations in Switzerland, we have resorted to the world's largest array of borehole stations, the Japanese Kiban-Kyoshin (KiK-Net) network, to analyse the duration response at different sites and to systematically identify those sites with 2D/3D amplification effects.

Building upon available indirect geomorphological proxies for site response (for which [3] is the seminal work), we have identified a set of parameters able to capture the local terrain configuration. These parameters, derived from the quantitative analysis of digital elevation models (DEM) at different scales of investigation, are the normalized topographical index (TPI_{norm}) and the terrain class (Bur-

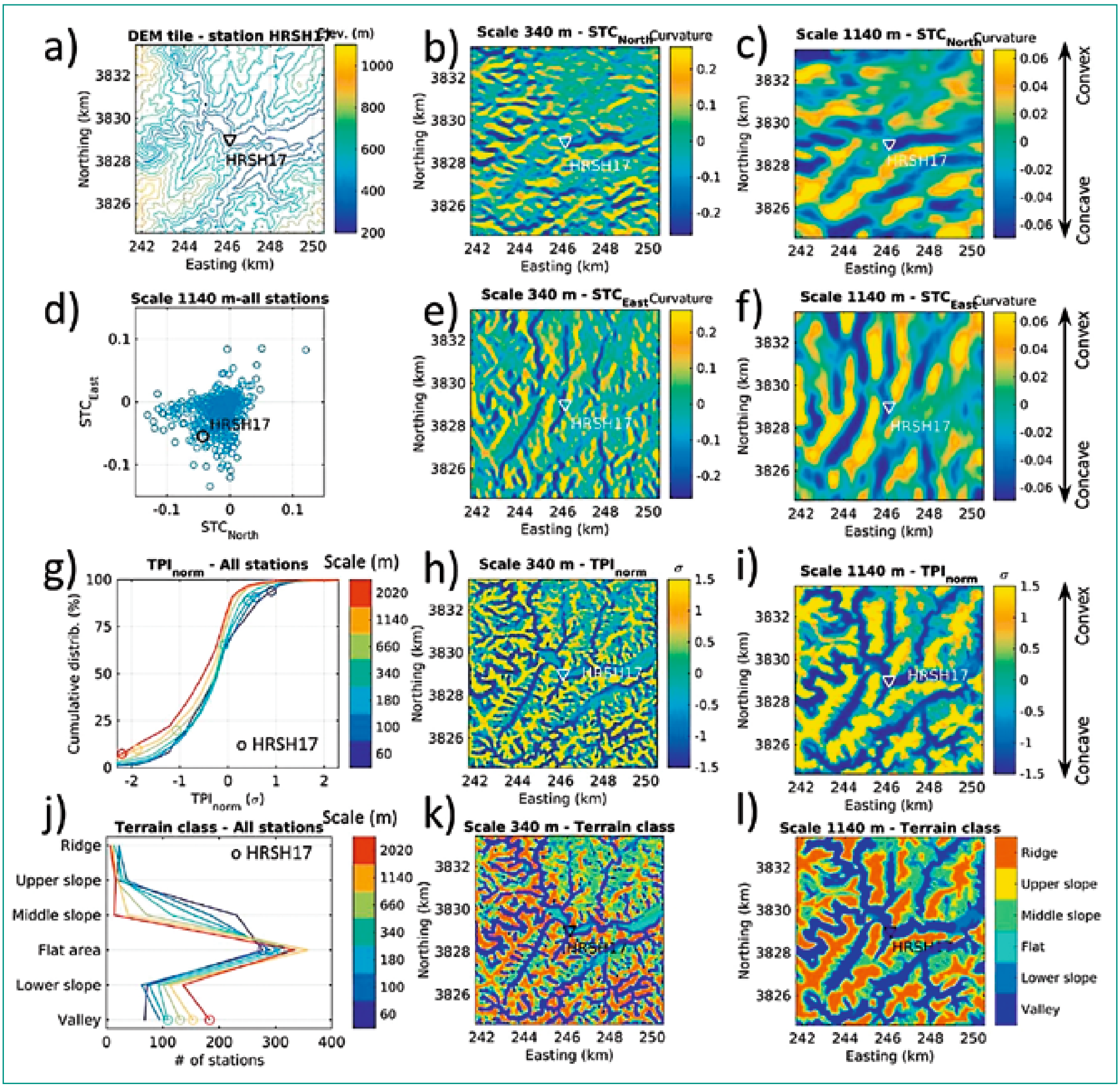

Figure 1: *a) DEM tile covering the area surrounding KiK-Net station HRSH17. b,c) directional smoothed topographical curvature (STC) along northing axis at scales 340 (a) and 1140 m (b); e,f) directional STCs along easting axis; d) directional curvatures in north and east direction at all KiK-net stations; the value of HRSH17 is highlighted. g) cumulative distribution of TPI_{norm} values at all stations for all scales; the values for HRSH17 are indicated with circles. h,i) TPI_{norm} at scale 340 (h) and 1140 m (i) around HRSH17. j) distribution of all Kiknet stations among the terrain classes proposed by Burjanek et al. (2014); the affiliation of HRSH7 is indicated with circles. k,l) terrain classification at scales 340 (k) and 1140 m (l) around HRSH17.*

janek et al., 2014), the smoothed topographical slope [4] and curvature [5] (total, as in [5], and also directional, the latter being an original development for this project).

To analyze the topographical morphology at each KiK-net station, we have used the «Advanced Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2», which we resampled for our purposes on a spatially regular grid of 20 m spacing (Figure 1a). As for the scales of analysis, we selected 7 logarithmically spaced lengths, 60, 100, 180, 340, 660, 1140 and 2020 m. Due to restrictions related to the DEM resolution [3], the computation of curvature alone was limited to the scales 180–2020 m.

Figure 1 shows indicative results for a sample station (HRSH17) representing a typical example of targeted site (2D/3D concave topographical structures). HRSH17 sits in the sedimentary bottom of a deeply incised valley, approx. 400 m wide (Figure 1a). The computation of directional smoothed curvatures (Figure1b, c – along northing axis e, f – along easting axis) is effective in highlighting convex or concave structures (dark yellow or blue patches) with preferential direction of elongation, typical of a mountain environment (i.e. valleys and ridges). Similar results (quantitative identification of convex or concave features, at different scales) are obtained with TPI_{norm} index (Figure 1h, i), although in this case the directional information is lost. We have also found that the terrain classification we have implemented, following Burjanek et al. (2014; Figure 1k, l), adequately summarizes the complex structure of the topographical surface; for example, bottoms of valleys correctly fall in the «valley» terrain class, and they are surrounded by areas belonging to «ridge» class which actually cover the mountaintops (compare Figure 1k,l with 1a). It should be noted that, as the scale of analysis increases (2^{nd} vs 3^{rd} column in Figure 1), smallerextent features are washed out and large-range patterns gain prominence. Significantly, at small scales (60–180 m) station HRSH17 is classified as «flat area», while in the range 340–2020 m moves to the «valley» category since the wider extent of the investigation now includes the site in a largerscale feature. From our analysis of topographical proxies (Figure 1d, g, j), KiK-net stations appear to be preferentially located in concave structures (valleys, basins), as negative values of TPI_{norm} and curvature are prevalent. This trend becomes progressively more evident as the scale of investigation increases; in other words, stations that are situated in locally flat or elevated areas are embedded in larger-scale concave basins. In terms of terrain classification, we have found that categories ranging from «valley» to «middle slope» are generally well represented at all scales, with only a few sites being assigned to «ridge» or «upper slope» classes. Consistently to what has been observed for TPI_{norm}, the amount of stations belonging to the «higher topography» categories (ridge, upper and middle slope) decreases as the scale of investigation increases. This information, together with other proxies (e.g. geology), will be used to derive duration models for different local conditions.

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

Research in subproject 2 has focused on several aspect of ground motion modeling, including realistic heterogeneous media representations, effects of complex subsurface structures and non-linear behavior of soft soils. We have found that velocity heterogeneities represent the major factor influencing ground motion and its variability, and that typical alpine topography can play a minor, although not negligible, role. In particular, Imperatori & Mai (2015) have shown that the ground motion variability due to such propagation effects could be comparable to the variability induced by complex rupture processes along fault planes. The importance of 3D propagation effects (e.g. basin resonance, channeling 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.

We have proposed a new approach to validate 3D velocity models (Imperatori & Gallovic, 2017), especially their shallower parts, based on the presence of unrealistic features in rupture models of moderate and large earthquakes. This study has also evidenced the key role played by the shape of even small geological basins in controlling the amplitude of induced surface waves. In the framework of the limits of ground motion, Vyas et al. (2018) have compared the effects of complex fault rupture processes and velocity heterogeneities in the crust on the coherence of high-amplitude, high-frequency Mach waves. They have found that the latter are sensibly affected by both factors, although their relative contribution depends on the distance from the fault. This study has also high-

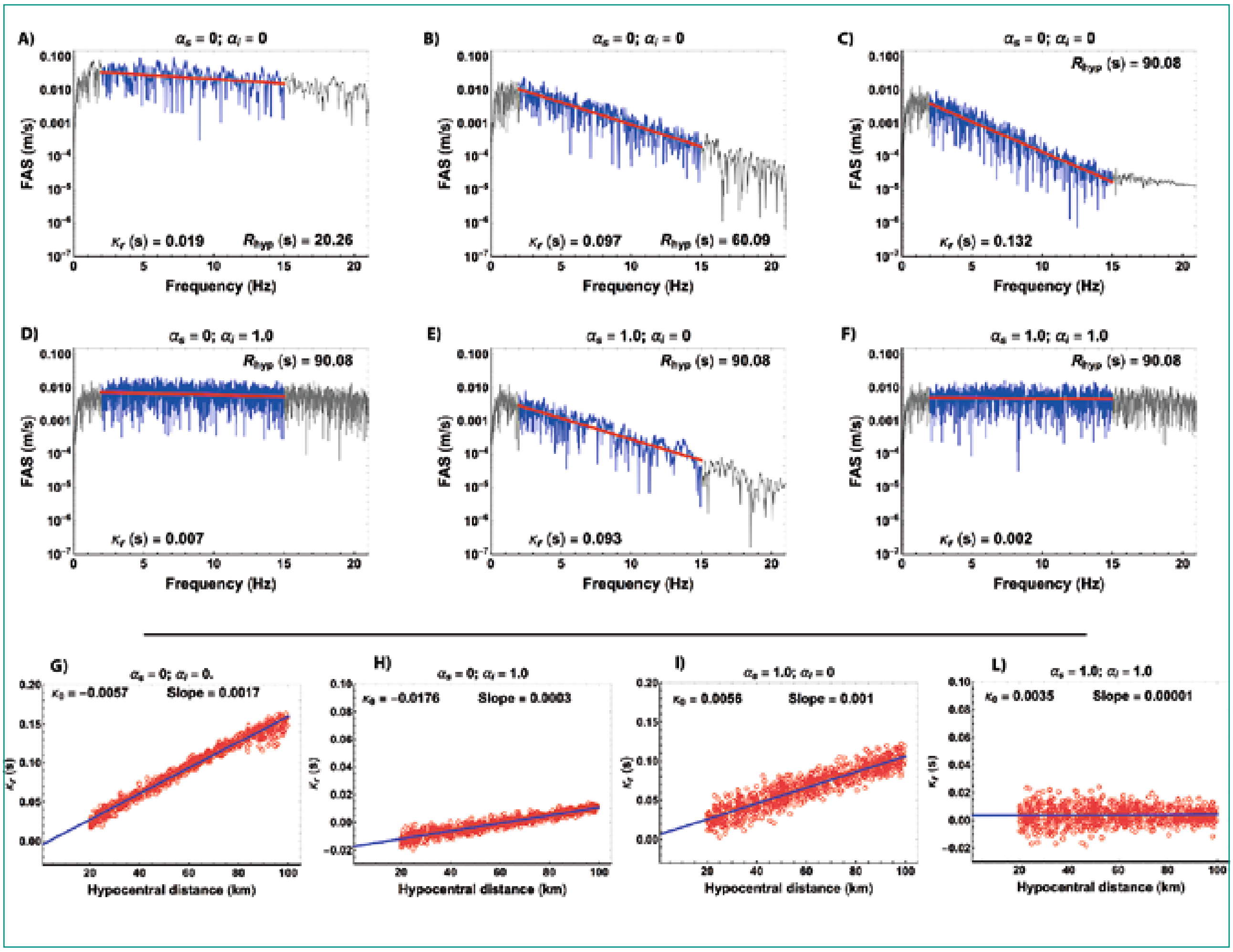

Figure 2 : *From A to C: sample spectra and their linear fit (red line) at three different source-receiver distance ranges for the same scattering/attenuation model. The slope of the line is proportional to kappa. From D to F: as above, but referred to the same source-receiver distance and different scattering/attenuation models. From G to L: kappa estimates as function of distance for different scattering/attenuation models. Intercept marks κ_0. For each model, the amount of scattered/absorbed energy scales with frequency as $f^{(1-\alpha)}$. When α for both scattering and intrinsic attenuation equals 1, these become frequency-independent and spectra do not decay (see case L).*

lighted the possibility that on-fault super-shear rupture speed may occur more often than observed in ground motion recordings.

Numerical simulations of ground motion have great potential in seismic hazard studies, as they could lead to a decrease of the epistemic uncertainty. However, fully deterministic simulations spanning a wide frequency range are still computationally very expensive and are usually limited to few selected cases. We have developed a new numerical code to generate hybrid synthetic seismograms well suitable to explore a large parameter space since it 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 (Imperatori & Fäh, 2017). Recently we have used a preliminary version of the code to produce seismic shaking scenarios in the Po plain sedimentary basin (Northern Italy), a densely populated area struck in 2012 by two magnitude 6 earthquakes that caused damage for more than 13 billions Euro [6]. In our study (Van Ede et al., 2018) we were able to reproduce at several sites the main features of the recorded ground motion, especially its overall duration. This investigation has further evidenced that, even in the context of hybrid simulations, realistic 3D velocity models are key to accurate ground-motion predictions. Our modeling has benefitted of an inversion procedure developed to calibrate two fundamental parameters at the core of the broadband code, namely the scattering and the intrinsic attenuation parameter. It should be noted that, in this particular application, both parameters are affected by body and surface waves propagation effects, possibly at several distance ranges, and they cannot be directly compared to the results of Pilz & Fäh (2017). The calibration for each individual target site is performed using a large amount of recordings in order to guarantee that the retrieved quantities reflect the local site conditions as much as possible. We stress out that the inversion procedure can be applied also at Swiss sites where recordings of small earthquakes are available.

Lately, we have established a close collaboration with subproject 1 to determine the physical origin of the local site-attenuation parameter kappa. Although some progress has been made recently [7, 8], a thorough investigation on the nature of kappa is still missing. In our study we have made use of advanced numerical simulations based on the radiative transfer theory (RTT; [9]) taking into account different scattering regimes (isotropic, forward) in 3D. Our numerical approach relies on the generation of random, uncorrelated time-series at a large number of receivers shaped by energy envelopes representing the joint effect of scattering and intrinsic attenuation expressed in terms of parameters η_S and η_I, respectively. These quantities are proportional to the scattered and absorbed energy and both scale with frequency as $f^{(1-\alpha)}$, where α is usually estimated to lie in the range 0.5 to 1. At this early stage of our investigation, we have considered isotropic sources embedded in a half-space and modeled only S body waves as these represent the largest component of coda waves [9]. At the same time, in order to consider all possible combinations of scattering and intrinsic attenuation, we let α vary between 0 and 1.5. By following the original procedure of [10] we computed kappa by fitting the Fourier amplitude spectrum of each time-series. Results, as can be seen in Figure 2, strictly depend on α. We have found that both scattering and intrinsic attenuation control kappa, although in a different fashion. In particular, since scattering translates into longer travel-times, the seismic energy can be (all else equal) more attenuated if scattering is strong (compare Figure 2a and Figure 2b, for instance). This also means that a weakly scattering medium with strong intrinsic attenuation and a weakly attenuating medium with strong scattering properties may lead, in principle, to similar kappa estimates.

The non-linear behavior of soft soils has been another major topic in our research activities. In particular, we have sensibly increased the CPT database necessary to validate an inexpensive but robust procedure to calibrate the large number of free parameters that typically characterize non-linear rheological models. After the latest field campaigns in Wallis (Fully, Collombey, Visp) and Rheintal (Werdenberg, Saxerriet), our database contains 13 high-quality measurements.

3. Induced seismicity and application for a deep geological repository (DGR)

The overall objective of this subtask was 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 have addressed concern 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?

Available studies suggest that the potential for creation of new fractures (i.e. bringing intact rock to failure) is non-existent or negligible [11] and possibly occurring only for unlikely rock parameters [12]. Nevertheless, shear failure on pre-existing, 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 constitute an important monitoring tool to assess the behaviour of the disposal system.

Regarding the construction of a DGR, the influence of tunnel excavation on fault stability has been investigated with a numerical model reproducing suboptimal condition for fault reactivation (i.e. large stress difference, extremely stressed fault close to failure and with low shear strength) and different tunnel diameters, in order to mimic the excavation of both the access and the emplacement tunnels (Rinaldi & Urpi, 2018). Results indicate that micro-seismicity (i.e. events with magnitude smaller than 1) can be triggered by the local stress perturbation induced by the excavation. These small events, not only they do not represent an issue for the safety of the repository, but they would be even beneficial, as they may illuminate previously undetected fractures or faults that could be reactivated at a later stage or affected by thermo-hydromechanical processes after site closure.

In a second step, we have explored the possibility of rupture nucleation during the operation of the DGR. The effect of temperature and pore pressure changes due to the HLW repository is investigated with a synthetic test under plane-strain conditions. A scheme of the model is shown in Figure 3a. Our test has suggested that the occurrence of nuclea-

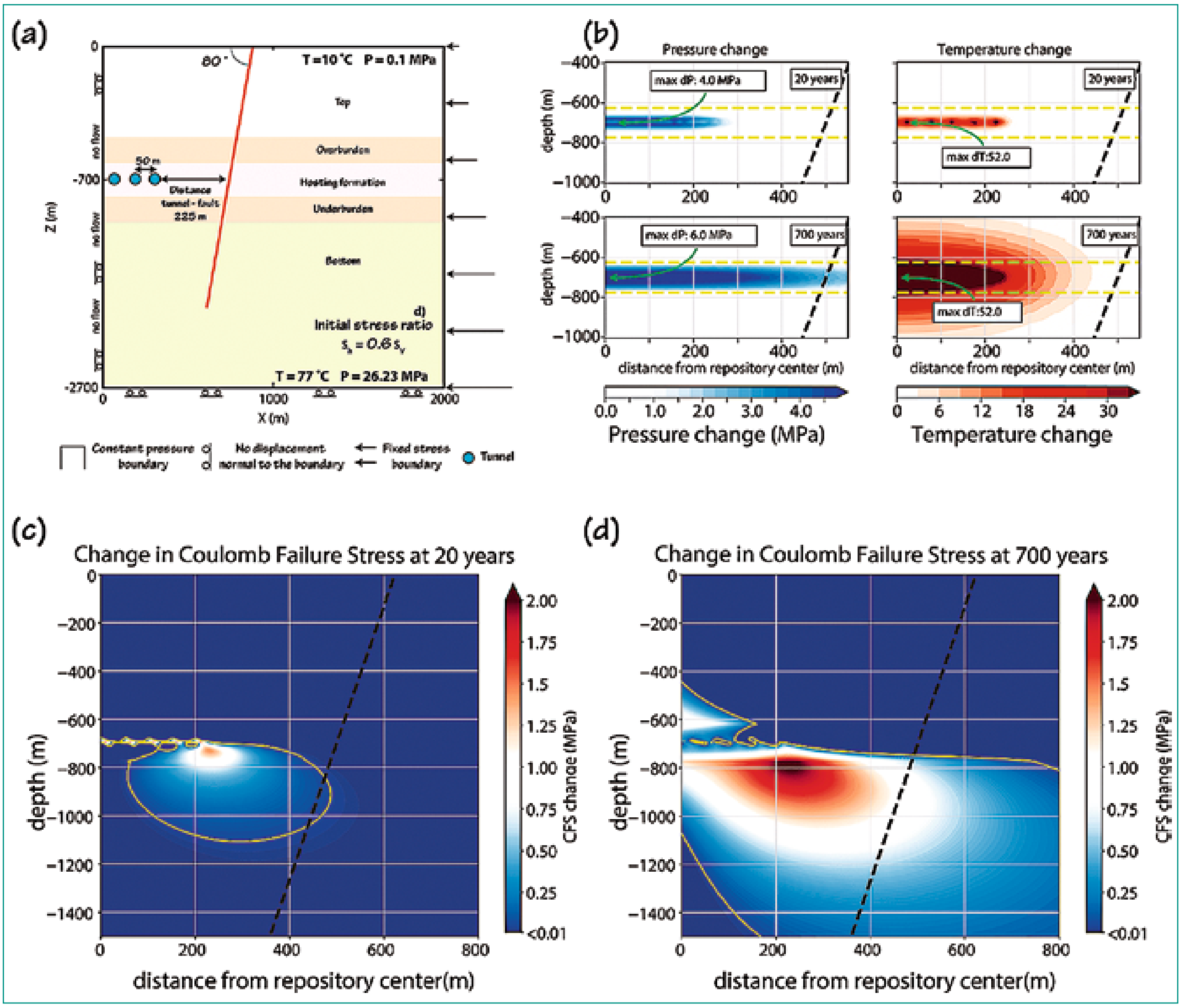

Figure 3: *(a) Schematic representation of the model, including tunnel locations (vertical and horizontal axis are not to scale). (b) Pore pressure and temperature changes at different times. Dashed yellow lines indicates the low-permeability disposal formation, dashed black line the hypothetical location of the fault. (c) and (d) Change in Coulomb Failure stress (change in shear stress plus changes in normal stress times the friction coefficient) at different times, for a fault having dip 80 degrees and in a normal stress environment (vertical stress is the largest). Dashed black lines indicate the hypothetical location of a fault at 275 m distance from the outermost tunnel.*

tion and propagation of a rupture can be affected by two factors: (1) the repository design, such as thermal load produced by the canisters, geometry and size of the repository, and by (2) the properties and conditions of the hosting formation (e.g., in-situ stress condition, elastic properties, frictional behavior, fault size). Moreover, our study has emphasized that the stability of faults close to the HLW repository should be evaluated for the future repository site using site-specific information. 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 and/or by the poro-elastic response (indirect stress changes due to pressurization of the clay hosting the emplacement tunnels) of the farfield rockmass. An example of temperature and pressure evolution for a DGR is visible in Figure 2b, while Figure 2c and 2d represent the change of Coulomb Failure Stress (ΔCFS) at different times, defined as: $\Delta CFS = \Delta\tau + \mu\sigma'_n$ where $\Delta\tau$ is the variation in shear stress, μ is the friction coefficient and σ'_n is the variation in effective normal stress (positive is tensile). A positive value of ΔCFS indicates that the stress state at a certain location approaches the shear strength of a plane of weakness at that location (with defined orientation and slip direction). Concerning the expected size of the rupture, it is reasonable to assume that its maximum in the worst-case scenario is limited by the fault dimension: our model provides a further, smaller bound, based on quasistatic rupture propagation and evaluating slip profile even if the fault slips in its integrity.

The interaction between the thermo-elastic stresses and pore pressure changes in space and time has been investigated for a single tunnel (Urpi et al., 2017) and it has been extended to include multiple emplacement tunnels (Urpi et al., 2018). A sensitivity analysis on different stress ratios, different cohesion values and different repository-fault distances has been carried out. We found a preliminary limiting value for the stress ratio S_h/S_V of 0.63 in a normal stress environment: if lower than this value, our simulations shows that the shear stress may exceed the shear strength in the first centuries of operation, for a fault at less than 300 m distance from the outermost tunnel.

Currently, our 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. The fault is assumed as a large structure (>1000 meters length along dip) cutting through the Opalinus Clay. The combined poro- and thermo-elastic stress perturbations affect the fault stability at depth, 200 m below the Clay formation: no direct perturbation of pressure or temperature on the fault plane is necessary to initiate slip movement.

The rupture behavior (aseismic or seismic) and its propagation depend on the in-situ rheological properties. Assuming that the fault material allows for seismic slip and that the fault is critically stressed due to the background natural tectonic stress, a fault located at less than 300 m from the repository will induce a microseism with an equivalent moment magnitude between a minimum of 0.55 (if the fault is cohesionless) and of 2.4 (if the cohesion value is 0.4 MPa and drops to 0 during slip).

This result must be considered as an approximate value. Indeed, we have assumed the same properties for the fault as for the Opalinus Clay but, at the simulated depth of reactivation, frictional properties could be different. This may lead to different results, either allowing for larger accumulation of elastic energy or lower release of seismic energy or no shear movement at all. Evaluation of the stress state and of the rheological properties of the formations below the repository formation are key ingredients to evaluate the possible occurrence of induced seismicity.

National Cooperation

We had active collaborations with the Mont Terri Underground Lab and Swisstopo to model the on-going Fault Slip experiment at Mont Terri. We co-operated with Engineering Geology group at ETHZ to discuss issues related to deep geological disposals, such as the influence of different constitutive models to capture the rheological behaviour of clay at depth and to correctly represent the tunnel excavation in the numerical model.

International Cooperation

We established active collaborations with the University Joseph Fourier in Grenoble and the University of Potsdam, resulting in common research activities for the development of improved GMPEs (in particular duration and Fourier models). We have strengthened our cooperation with the Disaster Prevention Research Institute, University of Kyoto, Japan. Ground-motion simulations were conducted in collaboration with the Charles University of Prague, the King Abdullah University of Science and Technology in Jeddah and the San Diego State University. We have started collaboration with IFSTTAR, fostered by a workshop held at the SED, focusing on the nature of kappa based on finite-difference simulations in complex media. Research on induced seismicity during operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. An on-going discussion with the experts at the Canadian Nuclear Safety Commission regarding model parameters and goal continued during the year.

Assessment 2018 and Perspectives for 2019

We have compiled a dataset of topographic parameters for seismic stations in Japan based on a large amount of borehole sites. In a second step we will study the correlation of site-specific duration with these parameters together with geological parameters. This will allow us to calibrate ground-motion duration models using various site-proxies. The developed methodology will be then applied to the Swiss network. We emphasize that duration is fundamental to move from models in the Fourier domain to models in the response-spectral domain. A Fourier spectral amplification model will be proposed using a similar approach. It is also important to note that an improved duration model is required to update the Swiss stochastic model of Edwards and Fäh (2013). In the context of ground motion modelling, we have applied a preliminary version of the broadband code to scenario simulations in the Po plain basin. Results will be used to further refine the code. We have developed an inversion procedure to calibrate scattering and intrinsic attenuation parameters for each target location. We have started an investigation on the nature of the local site attenuation parameter kappa supported by advanced numerical models. We will make use of Monte Carlo simulation techniques to extend our study to more realistic three-dimensional media featuring basins and topography. Our ultimate goal is to apply these techniques to Swiss sites in order to produce robust estimates of scattering and intrinsic attenuation at regional and local scale and to establish a link with available measurements of kappa. Such estimates may serve as a basis for accurate hybrid ground motion simulations in Switzerland.

We have developed a forward numerical model to assess the occurrence of seismicity with the post-closure behaviour of the repository. Numerical simulations with different simplified models of the repository design, as well as different in-situ stress regimes, have been initiated and a 3D model will be completed in the following year. This model will account for frictional laws derived from the latest published data and for heterogeneities in the hosting formation properties as derived from 3D geological models.

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