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 subtasks. Subproject 1 focuses on the investigation and improvement of ground motion attenuation models and earthquake source scaling for Switzerland. The analyses show that previously obtained ground motion models perform well but a large uncertainty in assigning attenuation measurements at hard rock sites remains due to the model simplifications, with different methods leading to significantly different results. The development of 2D resonance patterns in alpine sedimentary basins has been investigated through the implementation of new techniques for modal decomposition of the seismic wavefield and by means of numerical modelling. The analysis of recordings at sites with pronounced topography has shown a strong correlation between ground motion polarisation and amplification, at the same time excluding clear relations between the latter and local topographic features. Within subproject 2, we have investigated the effects of smallscale velocity heterogeneities and topography on the ground motion at close distance from the source. The wave field variability induced by these two factors is found to be close to the variability caused by intricate fault rupture processes. Our simulations have shown that 3D velocity models can, on one hand, lead to more reliable source images and, on the other hand, reproduce many complexities found in the observed ground motions only if they are accurate. The potential non-linear behaviour of sites of interest located on soft soils in Switzerland is assessed by coupling field measurements and numerical modelling. Within subproject 3, previous numerical models of injection-induced seismicity were improved, with focus on including physics based assumptions into the numerical approach to simulate induced seismicity. Finally, a study on seismicity induced by tunnel excavation was initiated and has revealed the possibility of triggering small earthquakes on nearby pre-existing faults.

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 is focused on the development and improvement of earthquake ground-motion attenuation and source scaling models for Switzerland. We further develop methods to separate source, path and site effects, implementing alternative parameterization such as the energy magnitude, complex shapes of the source spectrum, or improved distance metrics. We target ground-motion estimates for sites at depth and in the near field, for damaging events as well as for smaller induced earthquakes, based on observations in Switzerland and Japan. Studying the near-surface 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 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. The final goal is to combine models from subproject 1 with deterministic simulations from subproject 2, and to test it with 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 focussed on improving ground-motion prediction and developing new techniques for assessing the geophysical site parameters necessary for accurate estimation of ground motion at the surface.

Building on the ground-motion prediction equations (GMPEs) and site amplification models developed for Switzerland during the previous «Expertengruppe Starkbeben 2010–2014» project (e.g., [1]; [2]; Michel et al., 2014; Cauzzi et al., 2014), we have focused on providing further analyses and refinements. Burjanek et al. (2014) looked for empirical evidence of topographic effects on ground-motion in Switzerland and Japan. They classified sites according to their topographic features and analysed polarization and amplification of the wave-field. They found that topographic effects were present, although much weaker than those related to the S-wave velocity structure of the subsurface. Moreover, a correlation between ground motion polarisation and amplification was observed. As a result, seismic hazard estimates at site with pronounced topography should require a detailed knowledge of the shear-wave velocity profile to assess the state of weathering of the surface material.

Complex subsurface structures can affect the ground motion also by exciting reverberations in the uppermost layers that may modify severely the wave field. The development of 2D resonance patterns in alpine sedimentary basins has been investigated through the implementation of new techniques for modal decomposition of the seismic wave-field and by means of numerical modelling (Ermert et al., 2014; Poggi et al., 2015). These studies have demonstrated the possibility of mapping the relative variation of ground motion along the transversal section of elongated axial-symmetric sedimentary basins (e.g. Rhône Valley) by performing array analysis of ambient vibration recordings. This is essential for the evaluation of site response in such complex environments and particularly for the identification of areas of maximum expected amplification.

The attenuation of seismic waves occurs everywhere in the Earth's crust, although most frequen-

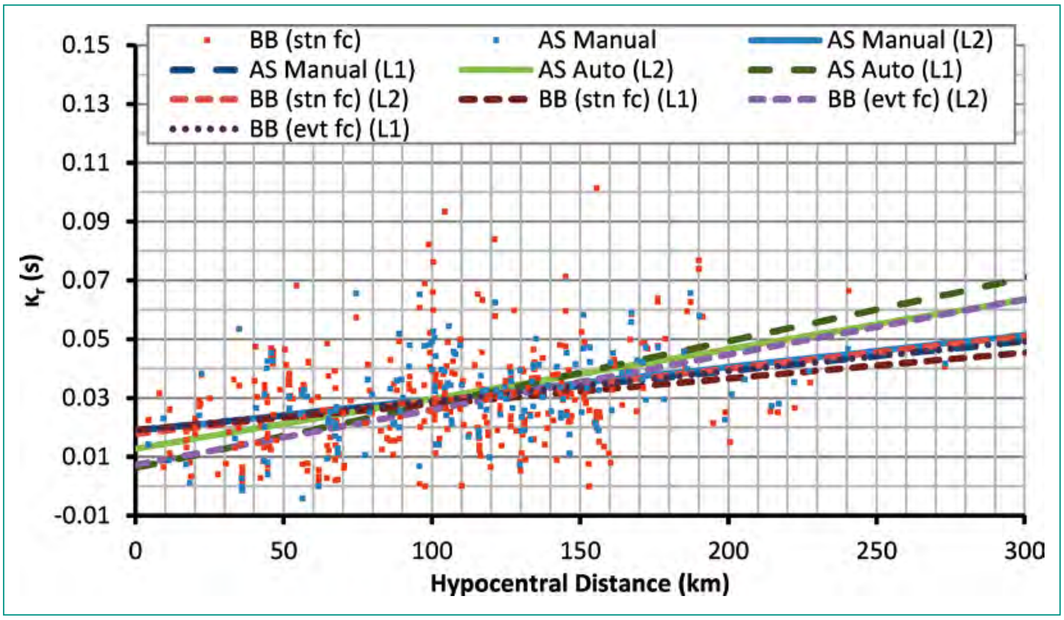

Figure 1: *Comparison of the different path attenuation (Q) and near-surface attenuation (κ_0) models for the seismic station LLS of the Swiss network. For reference, two data sets are plotted: «BB(stn fc)» are the data from the broad-band method, «AS manual» are the data from the manual high-frequency approach. The models are for different fit types («L1» – absolute amplitude; «L2» – least-squares) and for different origin data sets: «BB» indicates broad-band methods, «AS» indicates high-frequency methods. The differences due to the method used to derive the input data κ_r are by far the most significant: for station LLS, κ_0 is measured at zero hypocentral distance and ranges between 0.007 and 0.019 s.*

cies of engineering interest are expected to be dampened mainly as they travel almost vertically in the upper rock or soil layers. Edwards et al. (2015a) investigated this shallow attenuation at hardrock sites. 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 uncertainty in assigning attenuation measurements (kappa) at hard rock sites was significant – with different methods leading to very different results (Figure 1). This is generally due to the model simplifications that are made when measuring attenuation. Multiple methods should be used to estimate kappa – e.g., high-frequency and broadband methods. Edwards et al. (2015a) concluded that epistemic uncertainty to account for these differences (and the resulting host-to-target conversions of global GMPEs to Switzerland) should be included in the hazard logic tree.

Besides natural (purely tectonic-driven) earthquakes, seismic events induced by the exploitation of geothermal systems may play an important role in seismic hazard. Edwards et al. (2015b) investigated the characteristics of a recent moderate earthquake having occurred in Switzerland: the shallow ML 3.5 associated to the geothermal project in St. Gallen. They found that the ground motion model of Cauzzi et al (2014) for Switzerland performed well, although some ground-motions in the near field tended to be underpredicted. This may be due to the shallow source of the event, or due to an underestimation of the local amplification effects. They also found, using an empirical Green's function approach, that the stress-drops of St. Gallen and Basel (geothermal) events were around 3 to 3.5 MPa, consistent with the Swiss stochastic model [1] and the GMPE of Cauzzi et al. (2014). Although the Basel geothermal event had a slightly higher stress-drop (3.5 MPa), this could not be reconciled with the significantly higher damage reports experienced for that event, suggesting that such difference may be related to the human perception of individual phenomena and differences in local site amplification.

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 media and nonlinear behaviour of soft soils near the surface. To improve our understanding of ground motion variability in the near-source region (e.g. less than 20 km from the fault), we simulated wave propagation in complex media including small-scale velocity heterogeneities and topography representative of the Swiss alpine region (Imperatori & Mai, 2015). By exploit-

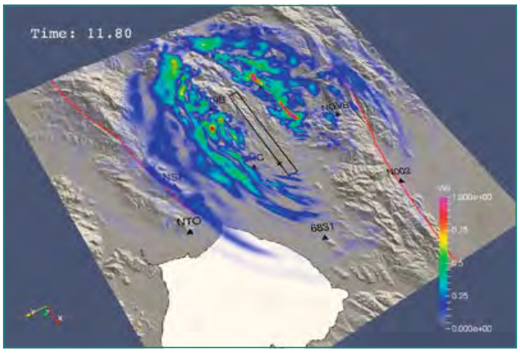

Figure 2:
Snapshot of the simulated peak ground motion velocity 12 seconds after the rupture initiated along the Napa fault (Imperatori, 2015). The complexity of the wave field is mainly controlled by lateral discontinuities in the 3D velocity model.

ing advanced numerical techniques and high-performance computing infrastructures, our simulations covered a wide frequency range, reaching 5Hz. Results showed that both velocity heterogeneities and topography produce a comparable amount of late arrivals (known as coda waves), but of different nature. In particular, while velocity heterogeneities scatter prevalently body waves, irregular topography can affect both body and surface waves. Simulations evidenced also that the ground motion complexity is mainly controlled by the elastic characteristics of the shallowest layers in the Earth's crust. At the same time our study revealed that the ground motion variability due to such propagation effects could be comparable to the variability induced by complex rupture along fault planes. This finding represented an important element of novelty of our study for seismic hazard estimation, as it was generally expected that source effects would dominate ground motions at short epicentral distances.

In the framework of scenario modelling, a realistic description of the causative fault remains essential. A common way to study the key features of faulting is represented by the inversion of recorded seismograms, opportunely low-pass filtered (typical frequency range up to 0.5 Hz). Ordinary inversion studies assume simple 1D media to approximate the impulse response (i.e. Green's functions) of the Earth's crust, therefore neglecting complex 3D wave propagation effects. This may result into inaccurate Green's functions that, in turn, could bias the source image. To clarify this critical issue, we imaged the source responsible of the recent Mw6.0 Napa earthquake by means of Green's functions computed using a regional 1D velocity model and the high-resolution USGS 3D velocity model for the San Francisco Bay Area, thus including basin and topographic effects. Although both source models presented similar characteristics, they showed peculiar differences in terms of energy release close to the surface (Gallovic & Imperatori, 2015). Synthetic tests indicated that 3D velocity models could effectively improve the source imaging, provided their accuracy is high. After retrieving the low-frequency source model, we tried to reproduce the recorded seismograms up to 3 Hz (figure 2) using a recently developed technique to generate kinematic source models releasing high-frequency energy in accordance to dynamic rupture studies [3]. Thanks to the USGS 3D velocity model, we were able to reproduce many features of the observed seismograms, although some discrepancies were found at stations close to secondary sedimentary basins (Imperatori, 2015). This indicated that the USGS velocity model should be improved in some of its parts. More in general, our study pointed out that accurate 3D velocity models are of primary importance for accurate inverse and forward modelling. Regional 3D models might be a direction for future developments in particular regions in Switzerland.

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. The non-linear model of Iai et al. [4] could be used to predict ground motions on such soils and ultimately assess their liquefaction potential for site characterization purposes. Roten et al. (in preparation) have developed a method to calibrate the non-linear soil model of Iai et al. using cone penetration testing (CPT). We plan to apply the procedure of Roten et al. at the location of many strong motion stations in Switzerland. To date we have collected CPT data for three strong motion station in Luzern, Yverdon and Solothurn. Data analyses is progressing.

3. Induced seismicity and application for deep geological repositories

The overall objective of our research was to analyse the possible effects of induced seismicity. The first twelve months have been dedicated to the development of geomechanical models including processes relevant to deep geological repositories, as well as to their application and validation with available data. We validated the geomechanical models with studies of seismicity induced by injection activities, such as enhanced geothermal system and/or CO_2 storage operation. The investigation of these processes allows us to gain insight into the physical mechanisms capable of inducing seismic events.

We proceeded along two modelling approach. The first approach was to improve the geomechanical part of the seed model develop at SED in the past years (e.g. Gischig and Wiemer [5]) by accounting for an improved fluid-flow modelling including thermal effects. We implemented a coupled mechanical-statistical model named TOUGH2-SEED for the study of injection-induced seismicity. Such model accounts for a 3D fluid flow and seismicity on seeds (hypothetical earthquake hypocenters) as well as earthquake–earthquake interactions by means of Coulomb stress transfer. In such case, the deformation induced by one earthquake affects the stress field as well as the permeability. Preliminary results were presented at the TOUGH Symposium 2015. Such geomechanical-statistical model will be applied in the future to studies of relevance for the geological repository of nuclear waste.

The second approach we took was to improve the TOUGH-FLAC modelling, already including fault reactivation (e.g. Rinaldi et al. [6]). This accounts for a more sophisticated friction law to better describe the mechanics of rupture propagation during injection-induced reactivation. We designed a scenario, to investigate how rupture size can be affected by a complex friction coefficient dependent not only on slip distance (slip-weakening) but also on shearing velocity (velocity-weakening or velocity-strengthening). A more accurate modeling of the rupture process will allow the integration of geomechanical modeling into Probabilistic Seismic Hazard Assessment (PSHA). Results were presented at the TOUGH Symposium 2015. The findings will be applied in models related to tunnel excavation for nuclear waste repositories.

Finally, we have started investigating the seismicity induced by tunnel excavation. Relatively intense seismic activity was observed for example during the Gotthard base tunnel excavation, with more than 100 earthquakes recorded during the period 2005–2007, with a maximum local magnitude of 2.4 [7]. Acoustic emissions were also recorded during the construction of tunnel GA04 at the Mont Terri underground rock lab [8]. Considering the massive excavation activity associated to the deep geological disposal for nuclear waste, we decided to create a model to quantify the seismicity induced by tunnelling. We developed our model using the software FLAC-3D, accounting for a tunnel size similar to that in Mont Terri (~5 m radius). We explored a possible scenario that could occur during massive tunnelling, with the tunnel running parallel to an existing fault (Figure 3). Our study indicates that tunnel excavation may induce seismicity characterized by very small magnitude events.

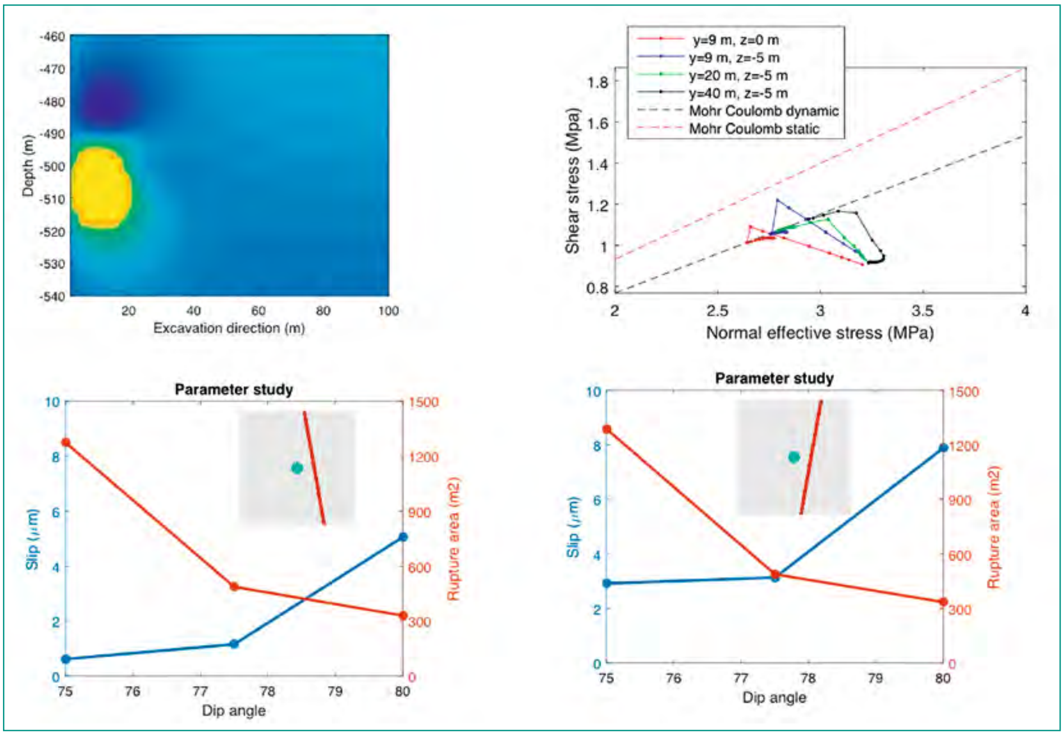

Figure 3:

FLAC-3D simulation of seismicity induced by tunnel excavation and sensitivity analysis on fault dip. Top left: rupture area (yellow) of a base-case simulation. Top right: stress variation on the fault zone at different distances from the excavating front. Bottom row: sensitivity analysis of fault slip and rupture area as a function of the fault dip angle.

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 to discuss issues related to deep geological disposals. Collaboration with the Institute of Geotechnical Engineering at ETHZ was successful in relation to borehole installations to study nonlinear soil response.

International Cooperation

Successful cooperation continued with the University Joseph Fourier in Grenoble and the University of Potsdam resulting in common research activities for the development of improved GMPEs. Our work on ground-motion simulations in complex media was conducted in collaboration with the Charles University of Prague and the King Abdullah University of Science and Technology in Jeddah. The validation of the USGS Bay Area 3D velocity model has established cooperation with the United State Geological Survey (USGS). We collaborate with the Lawrence Livermore National Laboratory (LLNL) in Livermore to further develop a finite-difference method to compute synthetic seismograms. Research on induced seismicity was carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley and the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Bologna.

Assessment 2015 and Perspectives for 2016

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 directions for research.

For example, hard rock sites, forming the basis for hazard maps, are accompanied by a significant level of uncertainty when assessing attenuation values (kappa). This is mainly due the general lack of consensus regarding the dependence of attenuation on the wave-field characteristics and parameters of the local ground conditions. Previous results will enable us to verify the correlation of various profile parameters with attenuation and to clarify the physical significance of the empirical attenuation parameter kappa. Moreover, numerical simulations of high frequency seismic waves in complex media will help develop relationships between site-specific attenuation and near-surface geophysical parameters and structural heterogeneities in well-known environments. This, in turn, may help derive more constrained region specific ground-motion prediction equations.

Our research has also evidenced that accurate deterministic seismic hazard assessment studies should be based on realistic, detailed 3D velocity models. Such models are needed to better understand the key features of the rupture process and to reproduce the complexity of the observed seismic wave field. At the same time, high-frequency deterministic simulations have shown that hybrid methods commonly used in the engineering community to calculate synthetic seismograms must be improved, as they cannot fully reproduce all the features of realistic ground motions. We expect to further develop these techniques according to our results.

We have started improving existing models to predict injection-induced seismicity by implementing more accurate fluid flow equations and friction laws. These models will be used to study the seismicity induced during tunnel excavation and quantify the probability that the associated small earthquakes may trigger larger events. We target to model ground motions due to induced seismicity at nearby sites for deep geological disposals and to generate catalogues of injection-induced seismicity.

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