Earthquake Strong Motion Research

Author and Co-author(s)	D. Fäh, S. Wiemer, B. Edwards, V. Poggi, D. Roten, R. Grolimund, M. Spada, B. Schechinger, T. Tormann, J. Woessner
Institution	Swiss Seismological Service
Address	Sonneggstrasse 5, CH-8092 Zürich
Telephone, E-mail, Internet	+41-44-633 3857, d.faeh@sed.ethz.ch, www.seismo.ethz.ch
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ABSTRACT

The goal of project «Earthquake Strong Motion Research» was to improve regional and local seismic hazard assessment in Switzerland. The project was split into five sub-tasks. Subproject 1 was focused on the investigation and improvement of ground-motion attenuation models and earthquake source scaling for Switzerland. A variety of new products, methods and models have been developed and published. Highlights of the subproject include the development of methods for automatic site amplification determination; Swiss specific ground-motion prediction models; the investigation of earthquake sources and their 3D crustal distribution; and development of models for amplification, attenuation and vertical-to-horizontal ratio for sites with known velocity profiles. Within subproject 2, we improved the tools for deterministic predictions of ground motion, especially with respect to nonlinear behaviour in sedimentary rocks and soft soils. Records of strong ground motion that are clearly characterised by nonlinear soil behaviour were studied and reproduced using advanced constitutive soil models. Within subproject 3 the earthquake catalogue for the period between 1878 and 1900 was systematically reassessed through historical-critical reintegration of the Annual Reports of the Swiss Seismological Commission. This includes the reconstruction of macroseismic fields from the assessment of local intensities for events with an assumed intensity of V and stronger. In addition, a common database for the compilation of paleo-seismological findings from various research fields was established, and the interdisciplinary reassessment of the period 1964–1974 was finalized. In subproject 4, we present new methodologies to characterize seismogenic source zones in Switzerland, advancing towards more realistic and physically constrained models. For instance, one methodology combined controlled-source seismology and receiver functions to define Moho topography. A general decrease of the *b*-value with depth was observed, which has implications for seismic hazard. We also investigate the resolution capability of 3D seismic data for fault detection and its influence on seismic hazard estimates. Finally, subproject 5 was related to geological disposal repositories with a focus on the possible impacts of strong earthquakes on the repository itself and the infrastructure during the operating phase. We developed an initial conceptual framework to assess the hazard posed by induced earthquakes.

Project goals

The project is split into five 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, nonlinear media;
3. Revision of the Swiss earthquake catalogue 1878–1974;
4. Improved seismotectonic zonation for Switzerland;
5. Earthquake scenarios for deep geological disposal.

Subproject 1 has focused on the development and improvement of earthquake ground-motion attenuation and source-scaling models for Switzerland. The complete understanding in terms of physical parameterization of such models is crucial in order to decouple different effects and build robust predictive models that scale appropriately to large magnitudes. The goal of this subproject was therefore to improve our understanding of existing approaches for ground motion prediction, such as global ground-motion prediction equations (GMPEs) and stochastic simulation models, in addition to developing new approaches and models for the purpose of strong ground motion prediction in Switzerland.

The scope of subproject 2 was to improve deterministic predictions of ground motion, especially with respect to nonlinear behaviour in sedimentary rocks and soft soils. Records of strong ground motion that are clearly characterised by nonlinear soil behaviour were studied and reproduced using advanced constitutive soil models. An important aspect of this subproject was the calibration of dynamic soil properties from standard geotechnical tests, because deterministic prediction models require many parameters, which are difficult to define. A further aim was to study the propagation of body and surface waves in nonlinear materials by performing numerical simulations in three-dimensions.

As instrumental measurements only provide reliable data from seismic activity in Switzerland since 1975, the assessment of seismic hazard chiefly relies on historical records of earthquakes. Subproject 3 therefore targeted the historical-critical improvement of the database of event classes that have not yet been analysed in-depth in the framework of preceding revisions of the earthquake catalogue of Switzerland. A special focus is on the reassessment of intermediate-size earthquakes in the pre- and early-instrumental period of systematic earthquake observation (1878–1974). This includes the analysis of the historical context of the data production to ensure its accurate interpretation.

In Subproject 4, we move towards a more realistic characterization of the seismogenic source zones for probabilistic seismic hazard studies. This was achieved by focussing on a more accurate structural representation with the link between stress, strength and the average earthquake size. Finally, subproject 5 is related to the definition of possible earthquake impacts on deep geological disposals, the analysis of observations in underground structures, and the issue of induced seismicity.

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 in Switzerland. We have developed a number of products to achieve this aim, and published several articles that improve the understanding of ground-motion in Switzerland. One of the central components of this work has been the development of a stochastic ground-motion simulation model tailored to Swiss seismicity (Edwards & Fäh, 2013a). This model expanded the model developed within the PEGASOS Refinement Project to cover both the Swiss Alps and Swiss Foreland. The model took into account previous studies on Swiss seismicity and ground-motion modelling, such as the definition of a rock reference velocity profile [1] and crustal and near surface attenuation ([2]; Poggi et al., 2013). A report commissioned by ENSI was produced summarising GMPEs and their use in Switzerland (Edwards & Fäh, 2014).

Cauzzi et al. (2014) have recently parameterized the Swiss ground-motion simulation model, such that predictions at various response spectral ordinates can be efficiently generated using only magnitude and source-site distance measures. This has facilitated integration into other products at the Swiss Seismological Service (SED) such as Shake-

Maps and the forthcoming updated national seismic hazard maps. Other related products include the determination of site amplification in Switzerland based on systematic analysis of recorded ground-motions relative to the Swiss simulation model (Edwards et al., 2013). The resulting empirical amplification functions for all of the Swiss real-time seismological stations are incorporated into the SED database and displayed online. The amplification functions have already been used by Michel et al. (2014) to improve the site characterization procedure of newly installed stations within the Swiss Strong-Motion Network and is presently applied for new NAGRA and Mont Terri monitoring stations. A sensitivity analysis was carried out to verify the robustness of the amplification predictions. For that, a synthetic database of seismic stations was produced, including 1D velocity profiles, attenuation models, and corresponding computed SH-wave amplification functions. Synthetic spectra were then produced for a broad range of magnitude/distance combinations. The analysis highlighted the improvements achieved with the updated approaches (Figure 1).

Uncertainty in ground-motion prediction for large events in Switzerland is high due to a lack of data for large earthquakes. We have therefore made numerous tests to calibrate and quantify uncertainty. For the original ground-motion model, macroseismic data, along with intensity to ground-motion conversion equations, were used to calibrate the large-magnitude predictions for Switzerland. Further analysis by Cauzzi et al. (2014) has looked into the issue of calibration in the Alpine and Foreland region specifically, and on the issue of the depth dependence of stress-drop (Goertz-Allmann & Edwards, 2014). The result is a proposed weighting scheme for Alpine and Foreland shallow and deep events which will be incorporated into the current renewal of seismic hazard in Switzerland. Analysis of data from large earthquakes in Europe and the Middle East also provided insights into the stress-parameter suitable for the larger events (Edwards & Fäh 2013b), while comparison with Japanese data has shown that the simulation model used for Switzerland is as good as existing GMPEs at predicting response ordinates for magnitudes up to 7.6.

At the local level, different parametric models for site-specific ground motion have been developed. Firstly, a functional relation to compute vertical-to-horizontal ratio of 5% damped response spectra was calibrated for rock sites (Edwards et al., 2011), based on the calculation of the quarter-wavelength average velocity at the site. The method was subsequently extended to also account for resonance phenomena in soft sediment sites (Poggi et al., 2012a). In a similar manner, two parametric models for near-surface attenuation (kappa) (Poggi et al., 2013) and anelastic site-specific amplification were developed (Poggi et al., 2012b), based on quarter-wavelength concepts and calibrated against empirical amplification functions.

In order to improve the level of detail in assessing geophysical site parameters required for the proper estimation of ground motion at the surface, such as the quarter wavelength parameters, new site-characterization techniques were developed. A novel active seismic approach to analyse surface waves was established, based on the continuous wavelet transform (Poggi et al., 2012c). The method is useful with continuous recordings and

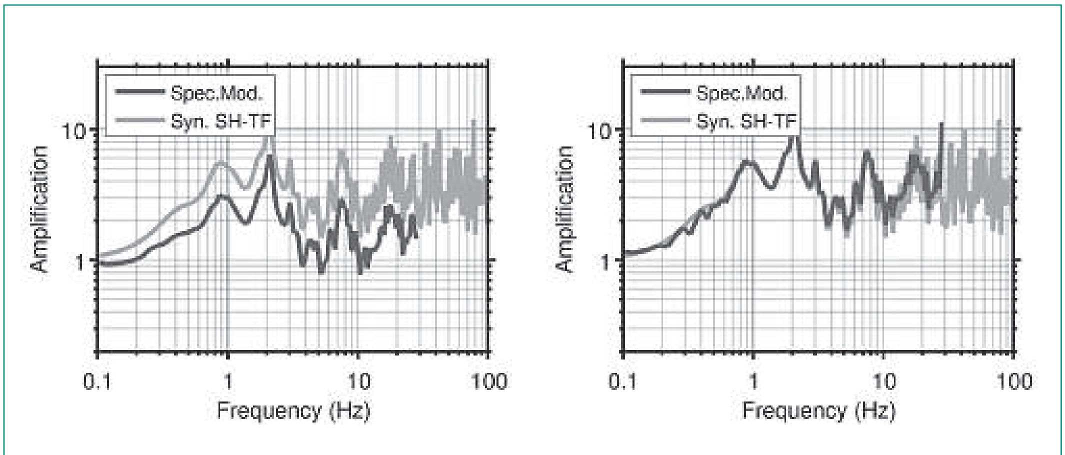
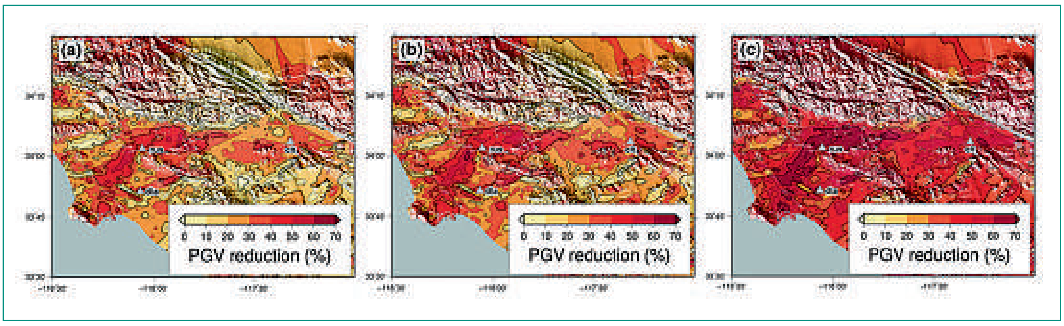


Figure 1: *Comparison of input (Syn. SH-TF) and recovered (Spec. Mod.) site amplification. Left: Approach (classical) detailed in Edwards et al. (2013), with mismatch between the input and recovered explained by the crustal amplification. Right: newly developed (iterative) approach, which takes advantage of input amplification estimations (e.g., quarter wavelength based) and removes the need for a crustal amplification.*

Figure 2:
Reduction in horizontal peak ground velocities (%) obtained with three cohesion models (a), (b), and (c) (Roten et al., 2014a) with respect to the viscoelastic solution.



therefore is complementary to passive seismic acquisition and the processing of ambient vibrations. We have also developed a method to assess resonance characteristics of 2D structures using eigen-decomposition of ambient vibrations recordings (Poggi et al., 2014; Ermert et al., 2014). The method allows us to map regions where large amplifications due to 2D/3D resonances are expected.

In addition to the locally calibrated, region specific ground-motion prediction equation (GMPE), we have developed a conversion scheme of existing GMPEs valid for other regions of the world to Swiss conditions (Edwards et al., 2014a). The conversions account for epistemic uncertainty by including a range of conversion schemes and calibration approaches. One of the most critical parts of this so-called host to target conversion is the near-surface attenuation, defined by the kappa parameter. We have investigated the sources of the significant uncertainty in this parameter by using a number of different analysis approaches (Edwards et al., 2014b).

2. Modelling of wave propagation in complex, non-linear media

Research in subproject 2 focused on both nonlinear behaviour of soft soils near the surface and nonlinearity in the fault zone at depth. To improve our understanding of nonlinear response near the surface we studied records of strong ground motion that are clearly characterised by cyclic mobility (i.e., effects of pore-water pressure generation that may ultimately lead to soil liquefaction). We selected sites where accelerations were recorded both at the surface and in a borehole, including the Wildlife Liquefaction Array, the vertical arrays at Kushiro Port and Onahama Port, and the KiK-net site FKSH14. A methodology was developed to invert strong ground-motions recorded on such vertical arrays directly for the dilatancy parameters in the Iai et al. [3] cyclic mobility model. Synthetic acceleration time series, obtained by simulating the response of the liquefiable soils with the 1-D finite difference code NOAH [4], were shown to accurately describe the time and frequency evolution of the observations at these sites. Liquefaction resistances derived from strong motions tend to be higher than predictions from field and laboratory tests, and indicate that cyclic mobility effects may occur on soils with a high liquefaction resistance during strong and prolonged shaking [Roten et al., 2013, 2014b].

These case studies illustrate how cyclic mobility may lead to accelerations exceeding 1g on soils that respond distinctively nonlinearly to the shaking, and how advanced constitutive soil models are able to capture this phenomenon. Because the definition of dilatancy parameters in such models remains a challenge, we have developed a method that simplifies the calibration of the Iai et al. [3] cyclic mobility model from laboratory tests [Roten et al., 2011]. A similar method has been derived that allows calibration of dilatancy parameters in the Iai et al. [3] model from results of cone penetration testing. This approach has been used to characterize the soil properties at the location of two strong motion stations in Switzerland, located on the sediments of Lake Lucerne and Lake Neuenburg.

In the framework of subproject 2 nonlinear material behaviour based on Drucker-Prager plasticity was implemented in a 3D finite difference code that simulates spontaneous rupture and wave propagation. By participating in benchmark TPV27 of the SCEC/USGS dynamic rupture code verification project [5] we have successfully verified our implementation of plasticity against a series of independent finite difference and finite element codes.

We have also simulated the ShakeOut earthquake scenario (widely used for drills, assuming an M7.8

earthquake on the southern San Andreas Fault) for a medium governed by Drucker-Prager plasticity. These simulations have shown that plasticity in the fault zone, and, to a lesser extent, nonlinear behaviour in shallow sediments, could reduce the earlier predictions of large long-period ground motions in the Los Angeles basin by 30–70% [Roten et al., 2014a] (Figure 2). These results suggest that the role of plasticity in the saturation of ground motions is not limited to extreme events, such as the maximum physically possible earthquake assumed for Yucca Mountain [6], but remains significant for earthquake scenarios that are considered very plausible.

3. Revision of the Swiss earthquake catalogue 1878–1974

An interdisciplinary study on the period 1964–1974 was completed (Grolimund et al., 2014a). This study addresses the scope and completeness of the relatively scarce documentary data from this period with respect to the administrative, cultural and technological changes at the SED. The results were set into a broader context on risk culture at the SED (Grolimund & Fäh, 2014c). These studies not only provided insights into the reliability of data produced in this period and on the history of the SED and its technological development, but also into the general source material situation in the SED's archives.

The identification and evaluation of relevant historical sources for Switzerland brought to light a considerable potential for improvement of the Swiss earthquake catalogue with respect to its completeness and certainty of events. Due to the loss of a large number of primary sources in the 1950s, the historical Annual Reports of the Swiss Seismological Commission (SEC) are, for most events, our only direct access to the macroseismic investigations performed in Switzerland between 1880 and about 1960. Our analysis showed that the large wealth of information is only partly and inaccurately integrated in the current version of the Earthquake Catalogue of Switzerland (ECOS-09).

For the period of 1880–1900 the database of Earthquake Catalogue of Switzerland ECOS was updated on the basis of the information contained in the Annual Reports of the SEC (Figure 3). The earthquake list was completed with a considerable number of hitherto unknown (generally small) events. Dating errors and duplications were corrected and, in many cases, the appraisal of certainty was adjusted according to historical-critical standards. The descriptive macroseismic information documented in the Annual Reports was systematically integrated into the database for events with an assumed potential epicentral intensity of V (EMS-98) and stronger. Based on this dataset, following the procedures established in the compilation of ECOS-09, individual intensity data points were assessed. In addition the historical context of the production of earthquake information was investigated in order to ensure its correct interpretation. The potential biases and fragmentations of the data resulting from the cultural, theoretical and methodological background of the networks and actors involved could be correlated with specific patterns emerging from the analysis of the macroseismic fields (Grolimund & Fäh, 2014b).

A number of paleo-seismological studies carried out in the last few decades in Swiss lakes revealed evidence for potentially seismically triggered mass deposits. So far, the findings have not been systematically collected and combined with data from studies carried out in other scientific disciplines (archeology, speleology, ancient history etc.). In cooperation with the sediment dynamics group at ETH we developed a database which enables the integration of the available data from various origins in a common framework. Finally, a study com-

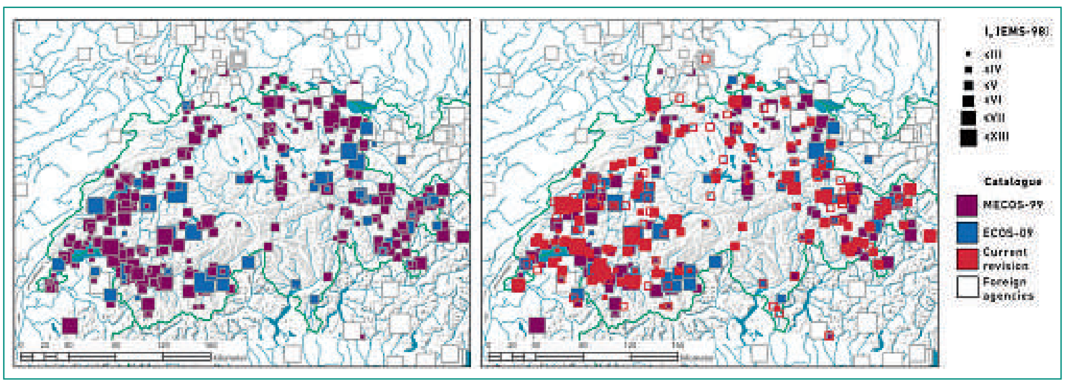


Figure 3:
Event maps 1880–1900 pre-revision status and revised status of the event list. The symbol relates to the epicentral intensity (I_o) in EMS-98 and the catalogue version on which the last modification is based on. Unfilled squares represent new events of unknown I_o.

paring sedimentological «archives» with archeological and historical accounts is currently under revision (Grolimund et al., 2014d).

4. Improved seismotectonic zonation for Switzerland

The overall objective of our research was to move beyond the state of the art defined in the PEGASOS and PRP 'source' (SP1) groups by adding physical-rheological constraints to existing statistical and subjective zonation approaches. This should lead to more realistic characterizations of the seismogenic source zones for probabilistic seismic hazard studies and allow for a more accurate structural representation, linked to realistic representations of stress, strength and the average and maximum possible earthquake size.

The definition and characterization of relevant seismic sources are critical steps in probabilistic seismic hazard assessment (PSHA). This is particularly challenging in low-seismicity regions because observation periods are relatively short, seismicity is often diffuse, and active faults are difficult to identify. In such regions, seismogenic sources are typically represented as areal sources: zones with equal seismic potential. However, observed seismicity is never truly uniformly distributed but clusters at all scales. In Spada et al. (2011), we developed and applied a fractal scaling approach to explore a more realistic characterization of the seismicity distribution within each source zone. For a hypothetical square source zone, we computed hazard curves and hazard maps resulting from simulations of uniformly distributed seismicity, and we compared these with those resulting from simulations of clustered seismicity. We found that the assumption of uniform distribution of events leads to a systematically higher estimate of hazard within the source zone. This overestimation increases for lower probability levels. Of equal importance is the fact that the assumed uniform distribution underestimates the uncertainty of the hazard by up to a factor of three. We applied the fractal scaling approach to the seismicity of Switzerland and measured the fractal dimension of instrumental seismicity for the past 30 years. Using this value for synthetic catalogues we then built a fractal seismic zonation and hazard model. We found that, in general, the assumption of uniform distribution of events overestimates the mean hazard in Switzerland by 3% to 20%, and the uncertainty distribution estimation is 50% to 100% narrower than in fractal distribution, depending on the location and the probability level of interest.

The second goal of our research was to contribute to the development of a high-quality 3D crustal velocity and physical properties model. As a first step, we derived a well-defined model of the crustal/mantle boundary topography, known as the Moho. Below the Moho, the lithosphere is too ductile to allow for brittle failure (i.e., earthquakes), so an improved knowledge of the Moho is an important constraint for seismic hazard assessment. The results were publish by Spada et al. (2013a), and are now used as an input parameter in the new Swiss hazard model.

In a third study, we explored the hypothesis that the relative size distribution of earthquakes or *b*-value, a key parameter in any PSHA, is inversely proportional to applied shear stress. We tested in Spada et al. (2013b) this hypothesis for seven different continental areas around the world: Northern and Southern California, the Swiss Foreland, Italy, Japan, Turkey and Greece, each derived from regional earthquake catalogues. We document for the first time a monotonic *b*-value decrease between 5–15 km depth. The decrease reverses approximately at the depth of the brittle-ductile transition zone. We translate the observed b-depth gradients into b-differential stress gradients and found clear evidence that b-values are indeed negatively correlated with applied shear stress. Spatial mapping of b-values thus has the potential to act as an indicative stress-meter in the earth crust. The stress drop of earthquakes in Switzerland, as determined by Goertz-Allmann and Edwards (2014), may increase with depth, suggesting stress drop and b-values may also be correlated. These finding are integrated in the upcoming release of the new national seismic hazard model.

We also developed, calibrated and implemented a first order time-dependent model for Switzerland; building upon the Short Term Earthquake Model (STEP) developed at ETH. The model is available on the SED Intranet, updated regularly after significant earthquakes. In another study, we have developed a smooth stochastic earthquake rate model for Switzerland as an alternative to the existing areal source models. The model applies techniques developed by Hiemer et al. [7,8] for California and Europe to Switzerland. The spatial component of the model is based on the kernel density estimation technique, which we applied to both past earthquake locations and slip rates on mapped

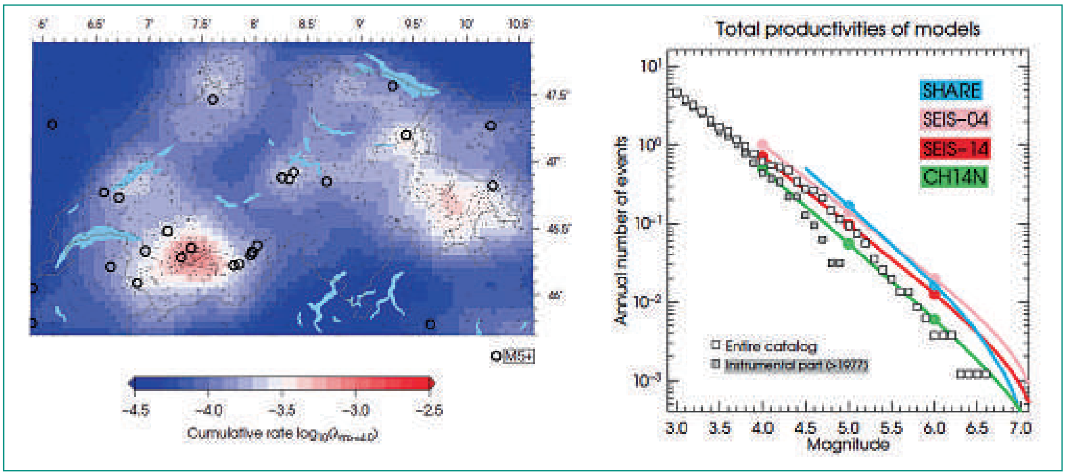


Figure 4:
Left: Map of Switzerland, colour code is the forecasted annual rate of earthquakes with magnitudes greater or equal to 4.5 in each grid cell using the newly constructed smooth seismicity model. Right: Cumulative annual numbers of events observed (black squares) and forecasted by four source models as part of the new Swiss Hazard Model.

crustal faults. Accordingly, our forecasts rely on the assumption that the occurrence of past seismicity is a good proxy to forecast occurrence of future seismicity, and that future large-magnitude events are more likely to occur in the vicinity of known faults. We computed earthquake rates by estimating the a- and b-value of a truncated Gutenberg-Richter magnitude distribution for the entire study area based on a maximum likelihood approach that considers the spatial and temporal completeness history of the seismic catalogue. Thus the final annual rate of our forecast is purely driven by catalogue data, whereas its spatial component incorporates contributions from both earthquake and fault moment-rate densities. Retrospective and pseudo-prospective testing shows that the new model performs significantly better than the traditional areal source model for Europe. The model applied to Switzerland is shown in Figure 4. The work will form a part of the new Swiss national seismic hazard model to be released in early 2015.
We investigated the fault detection probability in 3D seismic data and the implications for seismic hazard assessment. Information about the existence or absence of faults imaged through 3D seismic surveys should have consequences for the seismic hazard estimation at a site. However, even the most sophisticated site-specific studies conducted in Switzerland (PEGASOS and PRP) do not consider this information, because no established path exists to use it within the constraints of a PSHA. We have developed a probabilistic approach that uses subsurface knowledge from seismic reflection imaging to reduce the uncertainty in seismic hazard estimates. We define a fault detection probability (FDP), which depends on the resolution of the imaging applied as a function of depth, lithology, faulting style, fault orientation etc. The FDP can be used to limit the maximum possible earthquake in a probabilistic sense and again as a function of a range of parameters.

5. Earthquake scenarios for deep geological disposal

This task focused on the definition of possible earthquake impacts on deep geological disposal, the analysis of observations in underground structures, and the problem of induced seismicity. In this context the SED participated in the technical meeting on «Earthquake impact on fracturing and groundwater flows – Considerations for the long-term safety of geological disposals» organized by IRSN in Paris in 2012, and supported ENSI to prepare a summary of possible earthquake impacts on deep geological disposals.
Using synergies with ongoing and independently funded research related to deep geothermal energy we have made substantial progress on setting up a framework to model earthquakes induced near deep geological repositories. Because a fully coupled thermo-, hydro-, and geomechanical computational framework to assess induced earthquakes in a probabilistic sense is currently both unconstrained and computationally expensive, we have developed and partially calibrated a so-called «hybrid» approach (Goertz-Allmann and Wiemer, 2013; Gischig and Wiemer, 2013). In this approach, first order physical constraints such as pore pressure variation and strain are modelled explicitly, while geomechanical coupling is achieved through a calibrated model of stochastic seed faults. Their size-distribution and failure is distributed assuming an inverse relationship between applied shear stresses and size-dis-

tribution. This allows first order predictions on the likelihood of felt earthquakes as a function of depth, faulting regime, cohesion or coefficient of friction to be made. It also represents a conceptual framework in which to build improved seismogenic source models (subproject 4). Using the work by Mignan et al. (2015), and the GMPE related efforts discussed in subproject 1, we are also able to convert forecasted, time dependent earthquake rates into hazard, specifically calibrated for induced and very shallow events.

National Cooperation

Collaboration with the Institute of Geotechnical Engineering at ETHZ was essential for calibration of nonlinear material properties. A working group for paleo-seismology with members of the Sediment Dynamics Group of the Geological Institute at ETH was established in order to collect findings related to paleo-earthquakes. In connection with questions relevant to the history of science, knowledge and environment, we collaborated with the chair for the history of technology at the D-GESS department at ETHZ and with the ETHZ University Archives. Finally, the SED started a co-operation with Engineering Geology to discuss issues related to deep geological disposals.

International Cooperation

Successful cooperation was established with the University Joseph Fourier in Grenoble and with the University of Potsdam resulting in common research activities for the development of improved GMPEs. We coordinated with IFSTAR (Paris) the work on the calibration of nonlinear soil properties from strong motion records. The implementation of Drucker-Prager plasticity in AWP-ODC was done in collaboration with San Diego State University and the San Diego Supercomputing Center. For the verification of the method against other codes we collaborate with the United States Geological Survey (USGS) and the Southern California Earthquake Center (SCEC). We cooperated with European groups working on historical earthquakes and contributed to workshops in France and Germany. Work on induced seismicity and probabilistic fault imaging was embedded in the framework of the EU Projects GEISER and IMAGE. Work on short term forecasting was conducted in collaboration with the EU project REAKT, where time-dependent forecast models are being evaluated independently.

Assessment of the project

The project «Earthquake Strong Motion Research (2010–2014)» was successfully concluded, having addressed a diverse range of topics in seismic hazard and engineering seismology. The numerous studies undertaken within the framework of the project have led to the production of a variety of publications, products and reports. These studies included specific problems intrinsic to seismic hazard assessment for long return periods, which are required for today's nuclear facilities and for the long-term safety of geological disposals. Diverse internal, national and international collaborations have been developed and continue to provide benefits beyond the end of the project. 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.

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