Expertengruppe Starkbeben

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Duration of the Project	July 2010 to June 2014

ABSTRACT

The project for the time period 2012/2013 is split into 5 subtasks with the goal to improve regional and local seismic hazard assessment in Switzerland. Subproject 1 was focused on the investigation and improvement of ground-motion attenuation models and earthquake source scaling for Switzerland. A variety of novel solutions have been developed and published, including: 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 reference velocity, amplification and attenuation profiles for arbitrary sites, including those at depth. Within subproject 2 we finalized our routine for retrieval of dilatancy parameters from strong motion recordings acquired on vertical arrays, and development continued on the implementation and verification of Drucker-Prager plasticity in a 3D finite difference code. Simulations of wave propagation from an M 7.8 earthquake in a nonlinear medium demonstrate the feasibility of the method to explore physical limits to ground motions during large events. Within subproject 3 the earthquake catalogue for the period between 1878 and 1900 was progressively analysed and the macroseismic information contained in the Annual Reports of the SED systematically integrated into the database for events with an assumed intensity of V and stronger. A common database for the compilation of palaeoseismological findings from various research fields was established and is currently being filled with data. In subproject 4, we present new methodologies to characterize seismogenic source zones in Switzerland, advancing towards more realistic and physically constrained models. Finally subproject 5 is 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 for the time period 2012/2013 is split into 5 subtasks with the main goal to improve regional and local seismic hazard assessment in Switzerland. The sub-projects described in this report are:

1. Ground-motion attenuation models and earthquake scaling for Switzerland;
2. Modelling of wave propagation in complex, non-linear media;
3. Revision of the Swiss earthquake catalogue 1878–1960;
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, with focus on predictions valid for the subsurface. The complete understanding in terms of physical parameterization of such models is crucial in order to decouple different effects: for instance to remove the influence of the near-surface geology from recorded ground-motions. In order to do this we have investigated new parameterizations of stochastic-based simulation models, improved understanding of global ground motion prediction equations (GMPEs) and investigated new methods of magnitude-scaling.

The scope of subproject 2 is 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 will be studied and reproduced using advanced constitutive soil models. Because such models require many parameters, which are difficult to define, an important aspect of this subproject is the calibration of dynamic soil properties from standard geotechnical tests. A further aim is to study the propagation of body and surface waves in nonlinear materials by performing numerical simulations in two- and 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. The main focus of subproject 3 is on the historical-critical revision of the Swiss earthquake catalogue for the period 1878–1960. This includes the extension of the completeness of the event list based on a systematic investigation, the assessment of event parameters such as magnitude and location and the investigation of the historical context of historical earthquake records to ensure their correct interpretation. New findings relating to large earthquakes in other periods, including yet unknown archival sources, archeological and palaeo-seismological findings are followed closely.

Subproject 4 strives to add physical constraints to the generation of improved seismotectonic models for Switzerland and 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

In the previous reporting period, we developed and published a ground-motion prediction model for Switzerland [Edwards and Fäh, 2013a]. This simulation model has now been parameterized for engineering applications using a function dependent on magnitude and distance. We have tested this model against macroseismic intensities of larger historical Swiss earthquakes, determining the best stress-drop to use for the national seismic hazard maps and the ShakeMap system.

The investigation of seismic sources in Switzerland is important to understand how to simulate larger events. As well as investigating wider-European large magnitude earthquakes [Edwards and Fäh, 2013b] we have published the results of our investigation into the 3D spatial distribution of the stress-drop of earthquakes in Switzerland [Goertz-Allmann and Edwards, 2013] (Figure 1). Strong regional variation was found to be related to the Alpine front and areas of uplift.

As well as further developing Swiss-specific models, we have developed implementations of host to target adjustments used for correcting global or regional GMPEs to a Swiss specific, or site-specific target. These Vs-Kappa corrections take into account differences in the local velocity and attenuation between the host (GMPE) and target. Two approaches have been implemented: (1) an approach based on random-vibration theory (RVT), in which both host and target are parameterized in terms of a stochastic model; and (2) a newly developed method [1] based on inverse RVT, allowing the direct estimation of response spectrum compatible Fourier spectra.

The separation of the effects of source, path and site on observed ground-motion is important so that we can develop simulation models. We have therefore improved an application for the decoupling of source path and site effects based on a Bayesian approach. The method has been applied to the Japanese KiK-Net database, and the resulting decoupled amplification has been compared with surface-to-borehole ratios. We have published a method employed within the real-time seismic observation network for the determination of site amplification [Edwards et al., 2013]. The implementation continuously analyses recorded earthquakes and updates a database of amplification (elastic and anelastic) for all of the stations connected to the network. The resulting amplifications are displayed on an SED-internal website for easy access.

The definition of a common soil or rock reference is a key issue when predicted or observed ground motion is compared for sites of different characteristics. In order to correct modelled or empirical amplification functions to a common reference, we have developed a simplified method [Edwards et al., 2013] which is based on the use of the quarter-wavelength approximation [2]. The attenuation relevant for an arbitrary velocity profile is also essential to correctly model and interpret amplification, particularly at high frequencies. We extended the approach originally proposed by [2] to simultaneously model both the reference shear-wave velocity profile and the corresponding attenuation ([3]; Poggi et al., 2013). The method has been extensively tested on the Japanese KiK-Net Network by comparing site-specific attenuation measurements with quarter-wavelength average velocities at 36 soil and rock sites. Finally, a parametric model developed with this approach gives us the possibility to estimate anelastic attenuation of a rock site with an arbitrary velocity profile or even Vs30 and provides the base for host-to-target adjustments of real or modelled ground-motion.

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

Research in subproject 2 focuses on both nonlinear behaviour of soft soils near the surface and nonlinearity in the fault zone at depth. A procedure has been developed to retrieve the dilatancy para-

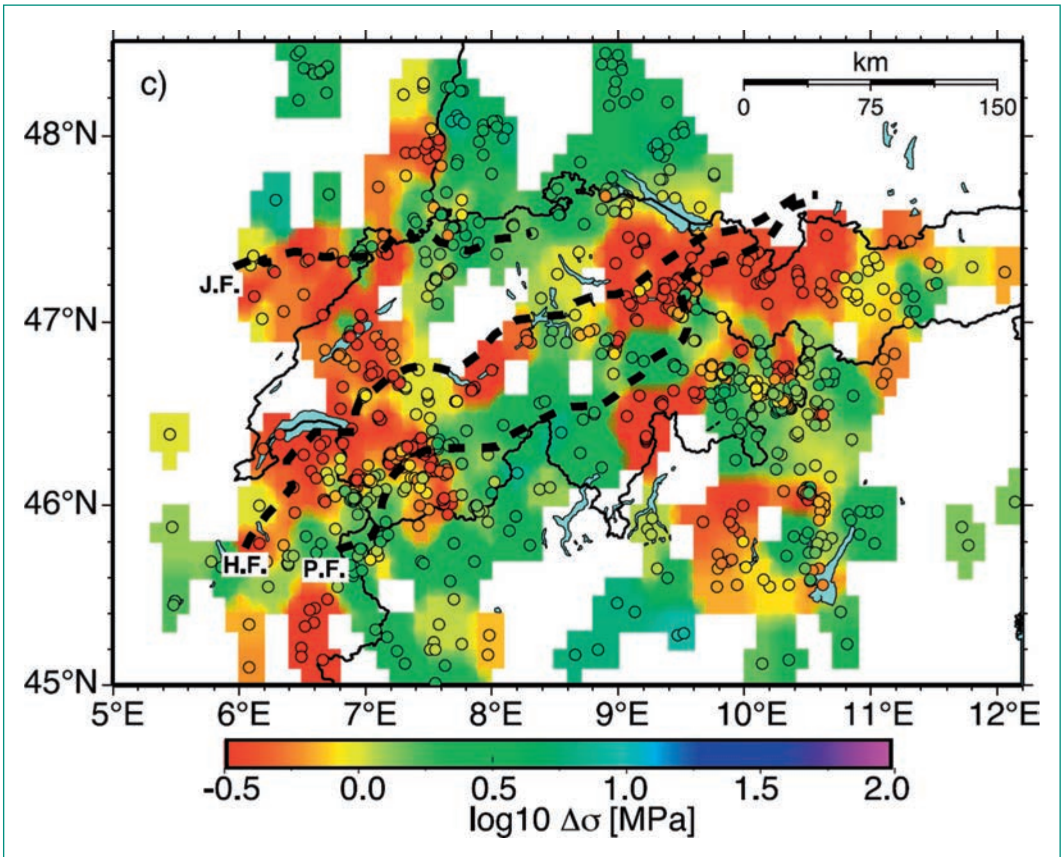
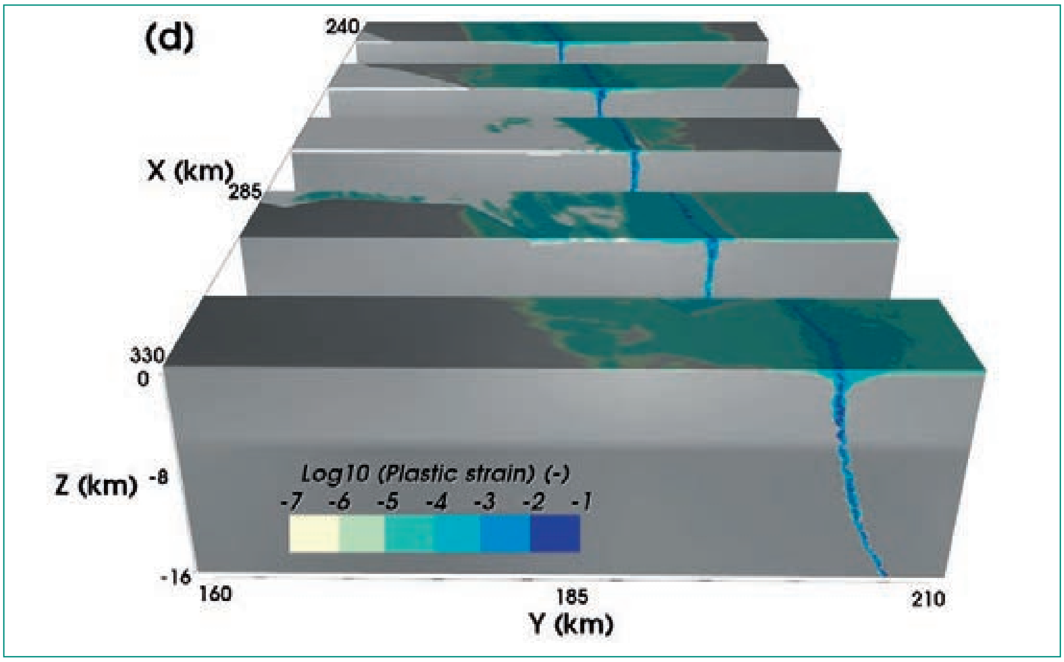


Figure 1:
Lateral variations of stress drop for using a depth-dependent Q model. The main Alpine fronts are shown by the bold-dashed lines (J.F., Jura Front; H.F., Helvetic Front; P.F., Penninic Front).

Figure 2:
Permanent plastic strain in the southern San Andreas fault zone following the M 7.8 ShakeOut scenario earthquake.



meters of the Iai [4] cyclic mobility model directly from strong ground motion recorded on vertical arrays. During 2012/2013 this method was further improved. A new misfit definition based on the Stockwell transform was introduced, which guides the inversion routine to models that accurately reproduce the frequency-time evolution of the observed signals. We quantified the dilatancy parameters at the Wildlife liquefaction array (WLA), at Kushiro port (KP) and the KiK-Net site FKSH14. 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., 2013a, 2013c]. Development continued on a tool that defines dilatancy parameters from cone penetration tests, which was simplified for easier use by non-specialists. The tool was applied for characterization of nonlinear soil properties at two Swiss strong motion instrument sites.

Continuing efforts have been made in collaboration with the SCEC/USGS dynamic rupture code verification project [5] to verify our implementation of plasticity in the AWP-ODC finite difference code. We have implemented viscoelastic relaxation [6] and shown that it is a condition for convergence of the numerical solution, which has led to the development of a new verification benchmark scheduled for early 2014.

We also simulated the ShakeOut earthquake scenario (widely used for drills, assuming an M 7.8 earthquake on the southern San Andreas fault) for a medium governed by Drucker-Prager plasticity. We showed 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., 2013b, 2013e]. 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 [7], but remains significant for earthquake scenarios that are considered very plausible.

3. Revision of the Swiss earthquake catalogue 1878–1960

In the assessment of earthquakes with a maximum intensity of less than VI (EMS) for the period 1878–1900 we have realized that the large but heterogeneous data pool available in the annual reports of the Swiss Earthquake Commission is only incompletely integrated in the current Earthquake Catalogue of Switzerland (ECOS-09). Most of the information regarding events inherited from the catalogue version MECOS-99 is questionable, as the process of their determination is neither documented nor reproducible and proved to be inconsistent with the critical examination of the information documented in the annual reports. The comparison of each event with its counterpart in the annual reports resulted in the correction of a large number of entries and to the integration of a considerable number of new events, especially in the case of earthquake sequences. We started the reinterpretation of the events based on the reconstruction of their macroseismic field. Currently we have integrated the macroseismic information contained in the annual reports for all events with an assumed intensity of V and V–VI. Moreover, a significant number of yet unconsidered reports were added to previously reassessed larger events.

A study on the so called «dark ages» of documentation at the SED in the period 1964–1971 in relation to the administrative, cultural and technological changes is currently under review. [Grolimund et al., 2013]. This study 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 source material situation in the SED's archives and the transmission of earthquake data. We could provide compelling evidence that an important collection of primary sources (questionnaires, letters etc.) of the former archives of the Swiss Earthquake Commission relevant for the period of ca. 1878–1955 was disposed of in the late 1950s. A further notable result of our research in the SED's archives is the discovery of unknown historical dia-positives, showing building damage and environmental effects of the 1946 earthquake in Sierre.

For some areas, the recurrence intervals of strong earthquakes largely exceed the time span of historical documentation. For this reason we designed a database to compile palaeoseismological evidence of large prehistorical earthquakes in Switzerland documented in studies from various disciplines. Data is currently progressively integrated in collaboration with the sediment dynamics group of the Institute of Geology at ETH. This integration needs to be completed with archaeological and speleological datasets in the future. In a short note in preparation [Grolimund and Fäh, 2013b], we compare the tentative conclusions on possible palaeo-events in Switzerland with the very few available relevant written sources on seismic events in the Early Middle Ages and the Late Iron Age. The analysis indicates that the location of a very strong 217 BC event indicated in the Catalogue of Strong

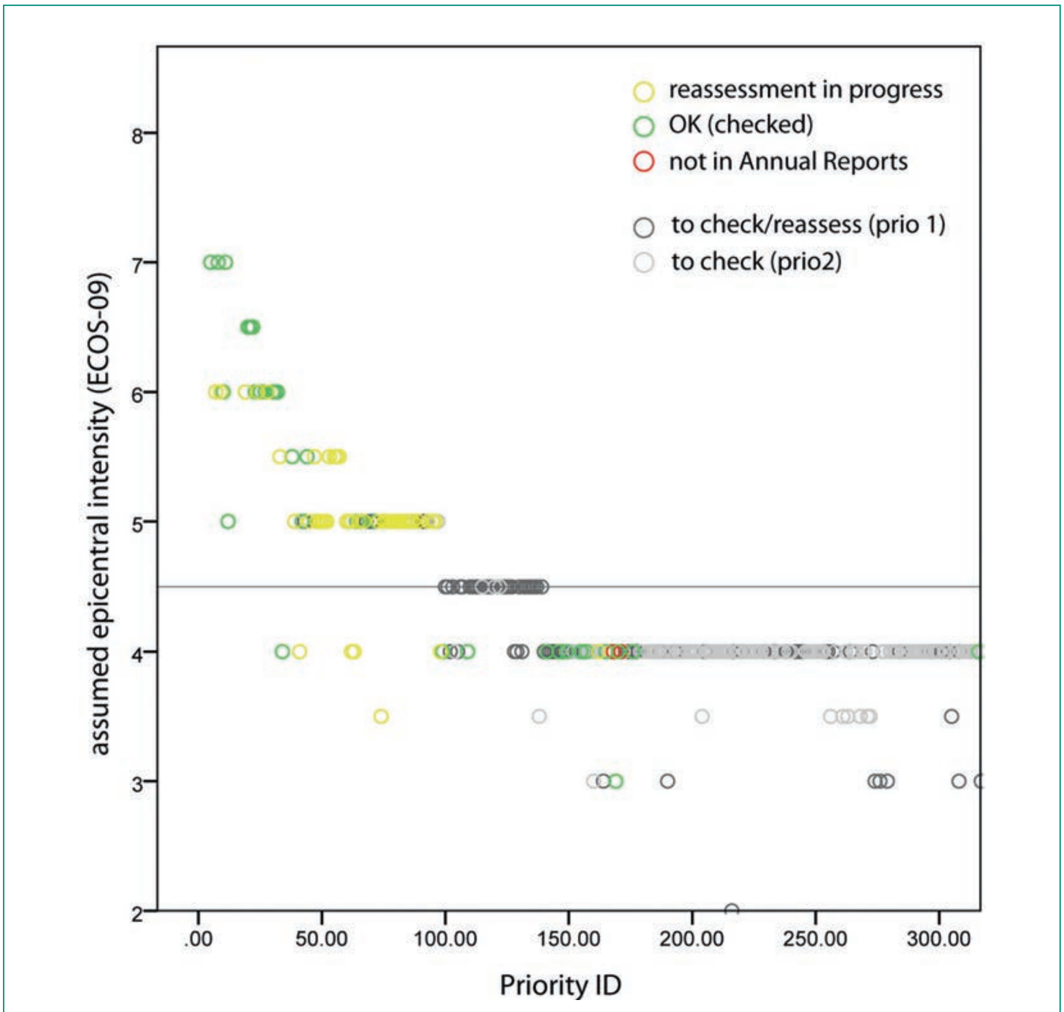
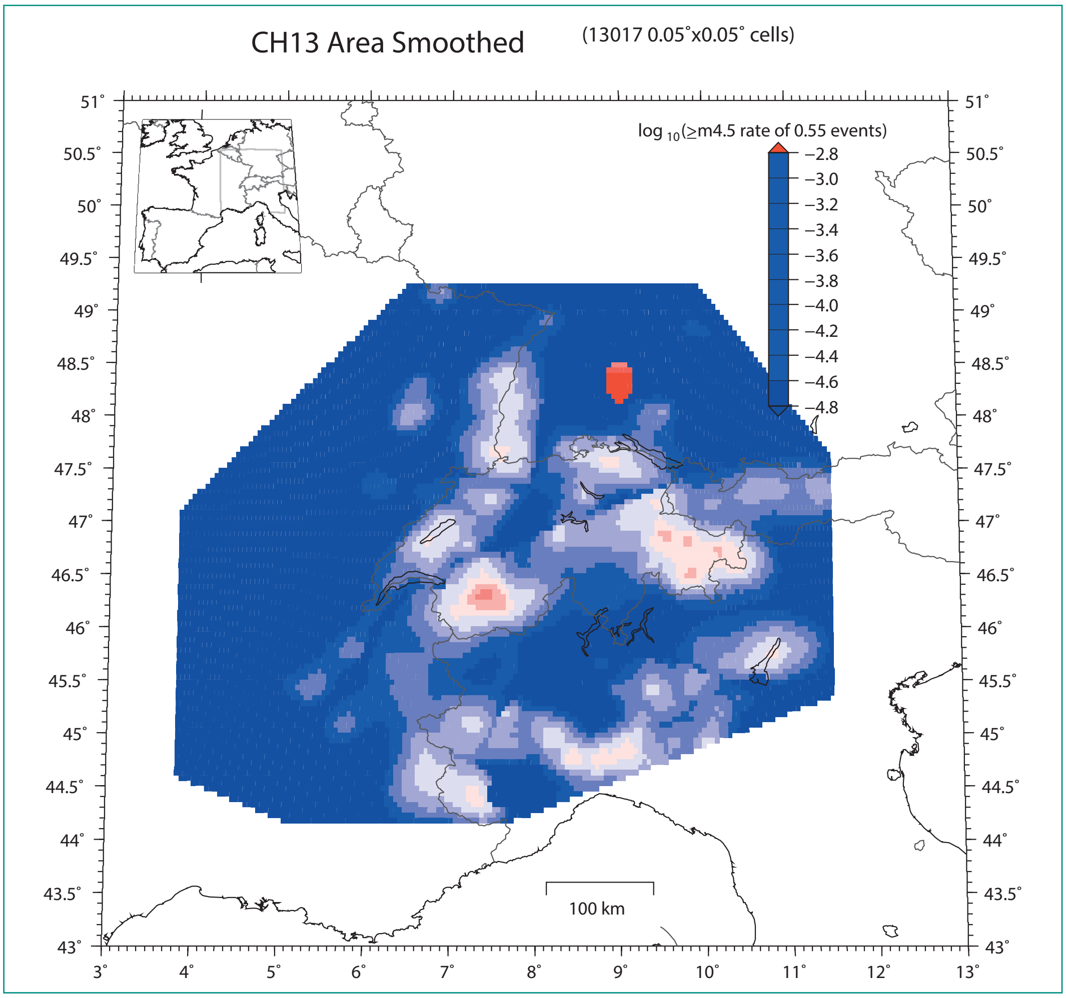


Figure 3: *Events of the period 1879–1900 prioritized with respect to the maximum reported epicentral intensity, the wealth of available macroseismic information and discrepancies between the catalogues.*

Figure 4:
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.



Italian Earthquakes [8] and the interpretation of the 563 AD Tauredunum-event at lake Geneva as a rock fall in the Earthquake Catalogue of Switzerland [9] might have to be reassessed.

4. Improved seismotectonic zonation for Switzerland

Seismogenic source models are the starting point of the assessment of seismic hazard. The objective of our research is to move beyond the state of the art defined in the PEGASOS and PRP «source» groups by adding physical-rheological constraints to existing statistical and subjective zonation approaches. The analysis of the crustal structure using combined controlled-source seismology and receiver function information to derive 3D Moho topography beneath the alpine region has been completed and published [Spada et al., 2013a]. Together with related efforts to determine crustal structures and high-resolution earthquake location, these findings will allow for a much more accurate correlation of seismicity and structure (rheology and faults), forming the basis of numerical model building.

The finding that the relative earthquake size distribution of earthquakes varies systematically with depth, as predicted by laboratory measurements and by the strength profile of the crust, has been finalised and published [Spada et al., 2013b]. Results for Switzerland are currently being implemented in OpenQuake in order to evaluate the hazard sensitivity; it will likely be a part of the upcoming release of the new national seismic hazard model. Efforts to quantify the resolution ability of 3D seismic surveys in order to integrate this information in a quantitative sense into probabilistic hazard studies are progressing. This new technique, which we call Probabilistic Seismic Fault Imaging has been further refined by adding filters that account for faulting styles, depth, dependent imaging resolution etc., a publication on the topic is currently in preparation [Schechinger et. al., 2013]. Work related to time-dependent models for Switzerland has been completed; the model is available on the SED Intranet, updated regularly after significant earthquakes.

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. [10, 11] for California and Europe to Switzerland [Woessner et al., 2013]. The model applies techniques for California [10] and Europe [11] 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 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 be completed with a publication and will form a part of the new Swiss national seismic hazard model to be released in 2014.

5. Earthquake scenarios for deep geological disposal

This task is related to 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 on November 22–23rd 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. 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-distribution (an extension of Mohr-Coulomb Failure theory). 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). For example, this model qualitatively predicts the depth-dependence of the relative earthquake size distribution (b-value) observed in Switzerland [Spada et al., 2013a]. Using the work by Mignan et al. [2013], 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 is continuing with the Institute of Geotechnical Engineering at ETHZ for calibration of nonlinear material properties. A working group for palaeoseismology with members of the Sediment Dynamics Group of the Geological Institute at ETH was established. Finally, the SED started a cooperation with Engineering Geology (Florian Amann) with a common workshop on October 7, 2013.

International Cooperation

We hosted Sanjay Bora, a PhD student from Universität Potsdam, who was working on new generation GMPE development, supervised by Professor Frank Scherbaum. Sanjay presented the results of his PhD studies, which focused on how to predict ground-motion using models of earthquake Fourier spectra and duration using RVT. We established a cooperation and began working together on the RESORCE Database (Reference Database for seismic ground motion in Europe).

We are working with Fabian Bonilla from IFSTAR 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 the workshop «Macroseismicity: Sharing and use of historical data», April 3rd 2013 in Paris. A working meeting with the newly established historical seismology group at the Landeserdbebendienst Baden-Württemberg took place on October 29, 2013.

Work on induced seismicity and probabilistic fault imaging was embedded in the framework of the EU Projects GEISER and IMAGE, results were shown at the European Geothermal Congress in Pisa, June 6, 2013. Work on short term forecasting was conducted in collaboration with the EU project REAKT, where time-dependent forecast models are being evaluated independently. Results were presented at the 2nd annual REAKT meeting in Zurich, October 23, 2013.

Assessment 2013 and Perspectives for 2014

The reporting period 2013 has been very successful, with several publications related to subproject 1. We have made significant progress in the ability to determine Swiss or site-specific ground-motion in terms of horizontal and vertical components, including sites at depth, and improved our understanding of how to decouple the earthquake source, path and site effects. For 2014 we plan to further refine the implementations determined so far, and specifically focus on the impact of buried locations on the seismic wave-field.

In subproject 2, the inversion of vertical array records for dilatancy parameters has been concluded successfully for three sites. Development on the plasticity implementation in the 3D finite difference code AWP-ODC has continued and a number of production runs have been completed. During 2014 we will participate in the SCEC/USGS code verification benchmark to verify the implementation of Drucker-Prager plasticity in AWP-ODC against a number of finite element codes. New developments will include a GPU-version of the finite difference code with plasticity that will take advantage of the next generation of supercomputers. Nonlinear response of soft soils will be studied by using the 2D version of the fully nonlinear code NOAH.

Due to the unexpectedly incomplete integration of the data contained in the Annual Reports of the Swiss Earthquake Commission and the relatively large amount of heterogeneous data available describing weaker earthquakes our progress was slower than initially planned in subproject 3. We expect to be able to process all intensity greater than or equal to V events until 1912 by the end of the project, which corresponds the year of the dissolution of the Swiss Earthquake Commission.

The efforts related to improving seismogenic source models (subtask 4) are immediately useful as they can be implemented in the next generation Swiss national hazard model. They will also be used for the baseline for the next generation of modelling tools and ultimately for the upcoming PSHA of deep underground repositories. Work related to probabilistic fault imaging will be completed by June 2014 with a publication submitted by then.

With respect to subtask 5, induced seismicity, we plan by June 2014 to have implemented a first application of these new tools explicitly targeted at deep geological repositories. Using the strain footprint of the repository as an input, we will compute probabilistic scenarios and perform first order sensitivity analyses that can help guide the decisions on future research needs in this domain.

Publications in the reporting period

- *Edwards, B. and D. Fäh (2013a).* A Stochastic Ground-Motion Model for Switzerland, Bulletin of the Seismological Society of America 103, 78–98, doi: 10.1785/0120110331.
- *Edwards, B. and D. Fäh (2013b).* Measurements of stress parameter and site attenuation from recordings of moderate to large earthquakes in Europe and the Middle East, Geophysical Journal International 194, 1190–1202, doi: 10.1093/gji/ggt158.

- *Edwards, B., Michel, C., Poggi V. and Fäh, D., (2013).* Determination of Site Amplification from Regional Seismicity: Application to the Swiss National Seismic Networks. Seism. Res. Lett., Volume 84, Issue 4, 611–621.
- *Goertz-Allmann, B.P. and B. Edwards (2013).* Constraints on crustal attenuation and three-dimensional spatial distribution of stress drop in Switzerland, Geophysical Journal International, doi: 10.1093/gji/ggt384.
- *Grolimund, R. and D. Fäh (2013a).* History matters: bref aperçu de la sismologie historique en Suisse. In: Gazette des Archives 103(2), Paris.
- *Grolimund, R. and D. Fäh (2013b).* Evidences for very Large (Pre)historic Alpine Earthquakes in both Natural and Historical Archives – a Workshop Report. In preparation.
- *Grolimund, R., Sellami, S., Fäh, D. and N. Deichmann (2013).* Earthquakes in Switzerland and Surroundings 1964–1974. Submitted to Swiss Journal of Geosciences.
- *Mignan, A., D. Landwing, B. Mena and S. Wiemer (2013).* Induced seismicity risk assessment for the 2006 Basel, Switzerland, Enhanced Geothermal System project: Role of parameter uncertainty on risk mitigation, Geothermics, under revision.
- *Poggi, V., Edwards, B. and Fäh, D., (2013).* Reference S-wave velocity profile and attenuation models for ground-motion prediction equations: application to Japan, Bull. Seim. Soc. Am., Volume 103, Issue 5, 2645–2656.
- *Roten, D., D. Fäh and F. Bonilla (2013a).* High-frequency ground motion amplification during the 2011 Tohoku earthquake explained by soil dilatancy. Geophys. J. Int., 193 (2), doi:10.193/gji/ggt001
- *Roten, D., Olsen, K.B., Day, S.M., and Fäh, D. (2013b).* Effects of fault zone plasticity could lead to revision of southern San Andreas earthquake scenarios, to be submitted.
- *Roten, D., Fäh, D., and Bonilla, L.F. (2013c).* Quantification of cyclic mobility parameters in liquefiable soils from inversion of vertical array records, to be submitted to Bull. Seism. Soc. Am.
- *Schechinger, B. Goertz, and A. Wiemer, S. (2013).* Integrating Probabilistic Fault Imaging into Probabilistic Seismic Hazard Assessment, Geophysics, in preparation.
- *Spada, M., E. Kissling, I. Bianci, and S. Wiemer (2013a).* Combining Controlled-Source Seismology and Receiver Function information to derive a 3D crustal model for Italy, Geophys J Int, 194, 2, 1050–1068, DOI: 10.1093/gji/ggt148.
- *Spada, M., T. Tormann, S. Wiemer, and B. Enescu (2013b).* Generic dependence of the frequency-size distribution of earthquakes on depth and its relation to the strength profile of the crust, Geophys Res Lett. DOI: 10.1029/2012GL054198.
- *Woessner, J., S. Hiemer, S. Wiemer and E. Kissling (2013).* A smooth seismicity forecast model for Switzerland, Swiss Journal of Geoscience, in preparation.

Conference contributions in the reporting period

- *Edwards, B., V. Poggi, D. Fäh.* Improving Referenced Ground-Motion Prediction through Physically-Based Site-Specific Adjustments. Seismological Society of America Annual Meeting, 17–19 April 2013, Salt Lake City, Utah.
- *Edwards, B., V. Poggi, and D. Fäh. A Kappa.* Model to Predict the Attenuation Characteristics of Gradient-Like Velocity Profiles. Seismological Society of America Annual Meeting, 17–19 April 2013, Salt Lake City, Utah.
- *Poggi, V., B. Edwards and D. Fäh.* Combined estimation of kappa and shear-wave velocity profile of the Japanese rock reference. European Geosciences Union General Assembly, Vienna, Austria, 7–12 April 2013.
- *Roten, D., Olsen, K.B., Day, S.M., Dalguer, L.A. and Fäh, D. (2013d).* Large-scale 3D simulations of spontaneous rupture and wave propagation in complex, 3D media, Annual meeting of the Seismological Society of America, April 17–19, Salt Lake City, Utah.
- *Roten, D., Olsen, K.B., Day, S.M., and Fäh, D (2013e).* The Shakeout earthquake scenario with plasticity. Annual meeting of the Southern California Earthquake Center, September 8–11, 2013, Palm Springs, CA, poster #217.

References

[1] *Al Atik, L., A. Kottke, N. Abrahamson, and J. Hollenback:* Kappa scaling of ground motion prediction equations using IRVT approach, Bull. Seism. Soc. America, 2013, in press.

[2] *Poggi, V., Edwards B., & Fäh D.:* Derivation of a Reference Shear-Wave Velocity Model from Empirical Site Amplification, Bull. Seis. Soc. Am. 101, 258–274, 2011.

[3] *Poggi, V., B. Edwards & D. Fäh:* The quarter-wavelength average velocity: a review of some past and recent application develop-

ments, Proceedings of the 15th WCEE, Lisbon, 2012.

[4] *Iai, S., Matsunaga, Y., & Kameoka, T.:* Strain space plasticity model for cyclic mobility, Report of the Port and Harbour Research Institute, 29, 27–56, 1990.

[5] *Harris et al.:* The SCEC/USGS Dynamic Earthquake Rupture Code Verification Exercise, Seism. Res. Lett., 80 (1), 119–126, 2009.

[6] *Andrews, DJ.* Rupture dynamics with energy loss outside the slip zone, J. Geophys. Res, 110(B1), B01307, 2005.

[7] *Andrews, D.J., Hanks, T. C. & Whitney, J. W.:* Physical Limits on Ground Motion at Yucca Mountain, Bull. Seism. Soc. Am., 97(6), 1771–1792, 2007.

[8] *Guidoboni, E. et al (Eds.):* CFTI4 MED Catalogue of Strong Earthquakes in Italy 461 B.C. – 1997 and Mediterranean Area 760 B.C. – 1500, Milano/Bologna, 2007.

[9] *Gisler, M., Fäh, D. & Masciadri, V.:* «Terrae motus factus est». Earthquakes in Switzerland before A.D. 1000. A Critical Approach. Natural Hazards, 43, 63–79, 2007.

[10] *Hiemer, S. J. Woessner, R. Basili, L. Danciu & Wiemer S.:* A smoothed stochastic earthquake rate model considering seismicity and fault moment release for Europe, submitted to Geophys J Int, 2013a.

[11] *Hiemer, S., Jackson, D. D., Wang, Q., Kagan, Y. Y., Woessner, J., Zechar, J. D., & Wiemer, S.:* A Stochastic Forecast of California Earthquakes Based on Fault Slip and Smoothed Seismicity. Bulletin of the Seismological Society of America, 103(2A), 799–810, 2013b.