Expertengruppe Starkbeben

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ABSTRACT

The project for the time period 2011/2012 is split into 6 subtasks with the goal to improve regional and local seismic hazard assessment in Switzerland. Subproject 1 was focussed on the development of state-of-the-art earthquake ground-motion modelling, including source-scaling, seismic attenuation and a reference-site velocity-profile for the shaking. The results of this sub-project are related to the further development of research produced during the PEGASOS Refinement Project (PRP). The scaling of the recently developed Swiss stochastic model was successfully tested with a European dataset, and is presently under evaluation with Japanese data. Within subproject 2, we developed site-specific ground motion models based on the quarter-wavelength representation of measured velocity profiles. We developed models for the ratio between vertical and horizontal ground motion, and introduced the quarter-wavelength impedance contrast to account for resonance phenomena. A new method for surface wave analysis for active source experiments has been validated. A new approach was developed in subproject 3 to deepen our understanding of the response of soft soils to strong shaking. The method retrieves dynamic soil properties directly from strong motions recorded on vertical borehole-arrays. Additionally we implemented the Drucker-Prager yield criterion into a 3D finite difference code to account for material non-linearity both in the fault damage zone and in near-surface sediments. Within subproject 4 the examination of historical earthquakes related to the period between 1878 and 1900 showed an unexpected lack of completeness and methodological reliability of existing data. The historical annual reports of the Swiss Seismological Commission represent a wealth of information which are being progressively analysed. In subproject 5, we present a new methodology to combine Controlled-Source Seismology and Receiver Functions to define Moho topography. We document a general decrease of the b-value with depth, and study its implications for seismic hazard. We also investigate the resolution capability of 3D seismic data for fault detection and its influence on the seismic hazard estimate. Sub-project 6 supplements the time-independent hazard estimates with time-varying hazard by assessing the likelihood of further earthquakes during a sequence. In summer 2012 the main research goals were changed to focus on the possible impacts of earthquakes on deep disposal repositories.

Project goals

The project for the time period 2011/2012 is split into 6 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. Estimation of site-specific earthquake ground motion;
3. Modeling of wave propagation in complex, nonlinear media;
4. Revision of the Swiss earthquake catalogue 1878–1960;
5. Improved seismotectonic zonation in probabilistic seismic hazard assessment;
6. Time-varying forecast models and seismic hazard for Switzerland.

In summer 2012, the focus of the projects was adapted to the new needs of ENSI, with particular focus on possible earthquake impacts on deep geological disposal.

Subproject 1 aims to implement, document and further develop ground-motion prediction equations (GMPEs) and stochastic models developed during the PEGASOS Refinement Project at the Swiss Seismological Service (SED). This assures knowledge transfer and continued development beyond PRP. We develop stochastic ground-motion models for existing strong-motion datasets (European, Japanese) in order to test the scaling of earthquake source models and the effect of near and far-field parameterisation adopted in models for Switzerland. Furthermore we aim to improve the understanding of the relation between site velocity-profiles and attenuation (kappa) in relation to the adjustment of GMPEs valid for different regions.

The target of subproject 2 is to find and validate new proxies for site-specific ground motion amplification, based on robust and physically justifiable assumptions. The goal is to calibrate models for site-specific ground motion (e.g., V/H ratios and anelastic amplification functions) based on these newly proposed proxies. Such an approach will reduce the level of uncertainty in the prediction of site-specific ground motion. As a second target of subproject 2, we focus on the development of new techniques for site characterization, such as the combination of active and passive seismics, and the identification of resonance phenomena using innovative approaches.

The scope of subproject 3 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 relies on historical records of earthquakes. Such records are analyzed with historical-critical methods in subproject 4. The main focus is presently on the 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 and the assessment of event parameters such as magnitude and location. To ensure a correct interpretation of historical earthquake records, the historical context of their production is also investigated. New findings relating to large earthquakes for other periods, including yet unknown archival sources, archaeological and palaeo-seismological findings are followed closely.

The main goal of subproject 5 is to move towards a more realistic characterization of seismogenic source zones as one of the primary inputs for probabilistic seismic hazard studies. The seismic source models used in low probability hazard assessment, particularly in regions of moderate and diffuse seismicity such as Switzerland, are somewhat naïve, being based almost exclusively on statistical representations of instrumental and historical earthquake data. To advance the state of the art, we focussed in the reporting period on a more accurate structural representation, improving the understanding of the link between stress, strength and the average earthquake size in the Earth's crust, and through formally integrating information on faults obtained through active seismic surveys as a-priori information in hazard assessment.

The assessment of time-varying hazard and risk is a critical requirement for a seismological service to provide state of the art scientific statements on what type of earthquake activity and shaking to expect during an on-going earthquake sequence and in times of no activity. Subproject 6 focuses on assessing the likelihood of further earthquakes during a sequence to supplement time-independent hazard estimates. The objectives include understanding the productivity of earthquakes clusters within the territory of the Swiss national seismic network, and implementing the forecast models as a real-time application within the SED, technically coordinated with the internal alarm system.

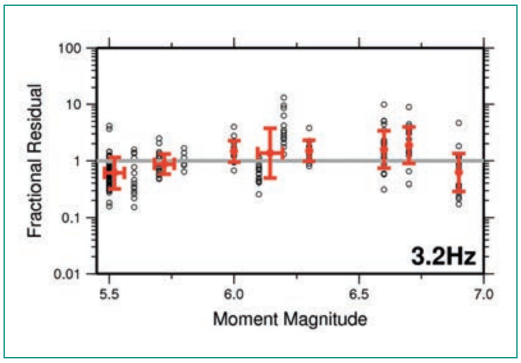

Figure 1:
Residual misfit of simulated ground motion using the Swiss stochastic ground-motion model for a range of large-magnitude Japanese earthquakes at distances up to 50 km.

Work carried out and results obtained

1. Ground-motion attenuation models and earthquake scaling for Switzerland

During the PRP hazard project several GMPEs were determined to be valid for predicting the expected ground-motion resulting from earthquakes in Switzerland. As part of this subproject during 2011/2012 we have implemented and further developed these models at the SED in order to pave the way for a nationwide seismic hazard evaluation. On-going work aims to implement adjustments of these models to Swiss specific sites, in addition to extending their validity to Swiss earthquakes.
Building on from the development of the Swiss Foreland stochastic ground-motion prediction model developed during the PRP we have published an extended model applicable to the whole of Switzerland [Edwards and Fäh, 2013]. The published model accounts for different observations of ground-motion attenuation in the alpine region of Switzerland relating to the different crust thickness and shallower seismicity.
We have performed testing of the [Edwards & Fäh, 2013] model in terms of the scaling of the model to events of higher magnitude than instrumentally observed. The first case was the investigation of the source properties of large magnitude events (5<M<7.6) which have occurred in Europe and the Middle East [Edwards & Fäh, 2012]. In this investigation, we found that the scaling adopted in the Swiss stochastic model, which was designed to be consistent with historical- and macro-seismicity, is consistent with the spread of observations of such large earthquakes. We also found that the use of the effective distance metric (R_{EFF}) is useful for including near-source geometrical effects of finite sources.

Secondly, we have investigated the scaling of the stochastic model and other GMPEs with respect to Japanese strong-motion data (Fig. 1). For the Japanese network, a rock reference profile has been defined, according to the procedure described in [1], which allows an adjustment of the model to different rock profiles. After accounting for site-specific differences in Japan and Switzerland, it was shown that the Swiss model was successful in predicting strong-ground motion of large earthquakes in Japan. The work is still on-going and results will be summarized in year three of the project. The comparison of Japanese data with other existing GMPEs also brought to light an issue with their applicability to sites not typical to the dataset used in their derivation, or indeed the general scaling of such equations to different site conditions. Our analysis showed that, whilst the equations did well in predicting ground-motion at sites typical to the region of origin, for hard-rock sites, as often found in Switzerland, or at depth, the equations did not perform adequately.

2. Estimation of site-specific earthquake ground motion

Within the second year of the project we focussed on the validation of the use of the quarter-wavelength parameters (average velocity and impedance contrast) to assess the modification of the ground-motion at the surface. A predictive model to compute vertical-to-horizontal ratio of 5% damped response spectra for both Japanese (KiK-net) and Swiss sites has been finalized [Poggi et. al. 2012a]. Following this approach, a procedure has been introduced to build a predictive model for the anelastic amplification at rock and soft sediment sites. The procedure has been tested on Japanese sites [Poggi et al., 2012b], but an in-depth testing and comparison with the stations of the Swiss seismological network is still on-going.

The estimation of kappa for the correction of GMPEs to local site conditions has proved to be a significant issue. We have worked on the development of predictive relations for kappa based on site characteristics such as Vs30 and the quarter-wavelength velocity. Such relations facilitate the estimation of local attenuation, provided a simple (Vs30) or more detailed (quarter-wavelength average velocity, V_{QWL}) characterisation of the site. The work is still on-going and results will be summarized in year three of the project. Since Vs30 remains the most widely used parameter for seismic site classification, we investigated the relation between V_{QWL} and Vs30. The study resulted in the definition of a model to predict generic quarter-wavelength profiles for a given Vs30-based soil type. This is useful for implementing the newly established ground-motion models also to those sites where Vs30 is the only available information.

A novel seismic approach based on the wavelet transform has been developed for the analysis of surface waves in combination with passive seismics [Poggi et al. 2012c]. The method was successfully applied on two stations of the Swiss network (SEPFL and SLUW) and is presently evaluated for the integration as standard procedure at SED for the characterization of future permanent station deployments. Finally, a method to assess resonance characteristics of 2D velocity structures (e.g., alpine valleys) was developed. The method is a modification of the approach proposed for buildings [2], and consists in performing modal analysis of the basin structure by means of eigenvalue decomposition of the noise wavefield from synchronous array recordings. Such an approach is now used in a Master's project, where it has been successfully used to retrieve the 2D resonance characteristics at two sites.

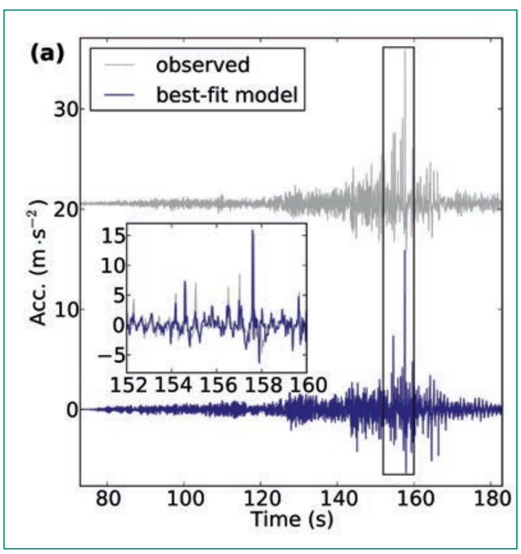

Figure 2: *Observed and simulated acceleration time series in the direction N126°E at OP.*

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

A methodology was developed to invert strong ground-motions recorded on vertical arrays directly for the dilatancy parameters in the Iai et al. [3] cyclic mobility model. We use the effective stress code NOAH [4] to propagate the recorded borehole signal through a medium with unknown dilatancy parameters. The parameter space is sampled with the neighbourhood algorithm to find a model that minimizes the misfit between simulated and observed surface acceleration time series. We applied the method successfully to the Wildlife Liquefaction Array records of the 1987 M_w 6.6 Superstition Hills earthquake [4] and the Kushiro Port records of the 1995 M_w 7.8 Kushiro-oki earthquake. We also inverted the Onahama Port (OP) records of the 2011 M_w 9.1 Tohoku earthquake, which are characterized by high-frequency acceleration pulses of up to 1.5 g and rank among the highest accelerations ever recorded. The inversion method is capable of finding models that reproduce these pulses (Fig. 2), and allows us to indirectly derive the development of excess pore water pressure inside the liquefiable soil. Inverted pore water pressure curves from OP suggest that the sand approached liquefaction at the end of the shaking, which is consistent with sand boils identified at the site (Atsushi Wakai, per. comm., 2012).

These case studies illustrate how cyclic mobility may lead to accelerations exceeding 1 g on soils that respond distinctively nonlinear to the shaking, and how advanced constitutive soil models are able to capture this phenomenon. Because calibration of such models remains a challenge, we have developed a method to calibrate the Iai et al. [3] cyclic mobility model directly from results of cone penetration tests (CPT). This method has been applied to define dilatancy parameters in the lake sediments below the city of Lucerne.

Finally, we have implemented nonlinear material behaviour based on a Drucker-Prager plasticity model in a 3D finite difference code which models wave propagation and spontaneous rupture. We are presently verifying the method against three finite element codes using the SCEC/USGS Spontaneous Rupture Code Verification platform

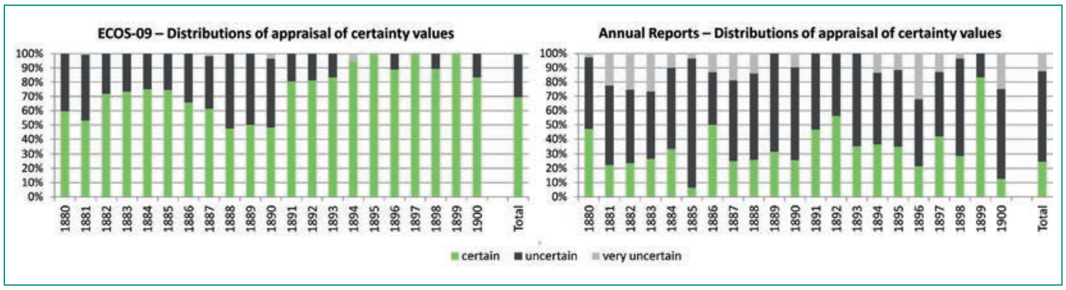

Figure 3:
Distribution of the certainty with the appraisal value. Assessment in ECOS-09 compared with the current historical-critical reassessment from the data compiled in the annual reports of the Swiss Earthquake Commission.

[5]. The elasto-plasticity implementation will allow us to model energy loss inside the fault damage zone at depth as well as hysteretic damping in soft sediments near the surface. These effects become important when predicting ground motions from the maximum physically possible earthquake, which has been attempted for the proposed Yucca Mountain repository using 2D finite element programs [6].

4. Revision of the Swiss earthquake catalogue 1878–1960

The events of 1878–1900 assessed during the reporting period were documented by the Swiss Earthquake Commission (SEC) in annual reports, which contain not only a list of events with their date and time of occurrence, but sometimes descriptions of macroseismic effects as well.

Spot-tests of single years showed a rather incomplete integration of the data contained in the annual reports into the former catalogue versions. Furthermore, the assessments of certainties of occurrence of events and intensities integrated in the current catalogue are not consistent with the criteria of the historical-critical approach applied in ECOS-09 for the period before 1878, and the larger events in the period under review. Thus it was decided to perform a new interpretation of the annual reports' original data by the use of uniform criteria and documentation. Currently our research database is completed with all events described in the annual reports. An overall comparison already shows that besides the integration of a number of yet unknown events, an important number of events will be affected by changes of their appraisal of certainty value (Fig. 3).

The activities of the SEC have recently caught increased attention not only by SED [Grolimund & Fäh, 2012] but also by historians of culture and science [7, 8]. In the course of our catalogue revision, the theory-oriented approach of these studies will be complemented by a more practice-based perspective. Finally the compilation of the information from the period 1964-1971 was assessed in relation to administrative, cultural and technological changes. A publication related to this period, the so-called «dark ages» of documentation at the SED is in preparation.

Archaeological and sedimentological studies show evidence of tsunami-like events in various Swiss lakes around ca. 300–50 BC. A temporal correlation of those events indicates a possible triggering by a very strong earthquake in the Alpine area. SED organized a workshop with different Swiss research groups to discuss the different palaeoseismological findings and enhance cooperation.

5. Improved seismotectonic zonation in probabilistic seismic hazard assessment

In order to build high-quality 3D crustal models, the first step is to derive a well-defined crustal/mantle boundary topography, known as the Moho. In Spada et al. (2012a), we introduce a new methodology to directly combine controlled-source seismology (CSS) and receiver functions (RF) information, which relies on the strengths of each method. Our results show high frequency undulation in the Moho topography of the Alps at three different interfaces, reflecting the complexity of geodynamical evolution.

In Spada et al. (2012b) we also explore the hypothesis that the relative size distribution of earthquakes, or *b*–value, is inversely proportional to differential stress ($\Delta\sigma$), and hence decrease with depth. We test this expectation for seven different continental areas around the world: Northern and Southern California, the Swiss Foreland, Italy, Japan, Turkey and Greece. We find a general monotonic *b*–value decrease between 5–15 km depth. The decrease stops approximately at the depth of the brittle-ductile transition.

We finally investigate the resolution capability of *3D* seismic data with respect to fault detection in a probabilistic way. With this method, we can assign a probability that a fault of a certain size is detected in a *3D* seismic dataset. Translating the minimum detectable fault size to a moment magnitude of a potential earthquake, we show how the information about faults contained in the image can augment the seismic hazard assessment. If no faults are detected in the seismic image, the maximum possible magnitude in the imaged volume is bounded. In this case, the frequency-magnitude distribution has to be weighted with the probability that a certain sized fault is detected by the seismic image, resulting in a reduction of about 10% of the hazard curve (Fig. 4).

6. Time-varying forecast models and seismic hazard for Switzerland

Time-varying forecast models and the resulting time-varying hazard estimates depend on the calibration of the model to the seismic activity in the target region. These models are able to forecast seismicity rates and exceedance probabilities of a ground shaking parameter on time-scales of days to weeks. The short-term earthquake probability-model uses, in its first stage, generic parameters to forecast seismicity rates which are derived from catalogue data. Generic parameters for the two possible approaches to estimate productivity within the STEP-model [9] are available for other regions. For Switzerland, recalibration of these parameters is necessary. From the available data, we find for the first approach that productivity is smaller compared to Italy and California. However, parameters of the Omori-law cannot be reassessed given the comparatively low-seismicity level, and are taken from estimates of the seismicity in Italy [10].

In the second approach in [9] uses the abundance model and the productivity parameter, or mean abundance, which can be estimated. For this model, we find that the average number of after-shocks for a magnitude M_L=4 event within Switzerland is about a factor 10 smaller than in California and a region of the Apennines. Physical reasons for this smaller productivity are not fully understood and may arise from the state-of-stress, the comparatively low strain rates or the fluid content of the crust. These are hypotheses that are to be investigated in the future.

In addition to the calibration efforts we implemented the two STEP-model approaches as a real-time system. Daily at midnight, the system generates seismicity rate forecasts for magnitude 3–8 for 24-hour windows and, in addition, computes probabilities of exceeding EMS-intensities V, VI and VII. We decided to generate maps depending on the alarm thresholds that are used within the SED. As an example, in case an event of magnitude $3 \le M_L \le 4$ occurs within or close to Switzerland, maps are generated every hour for 5 days. All results are written to a database and maps can be internally accessed on the SED-Intranet as information for the seismologists on duty and may after internal evaluation be publically available.

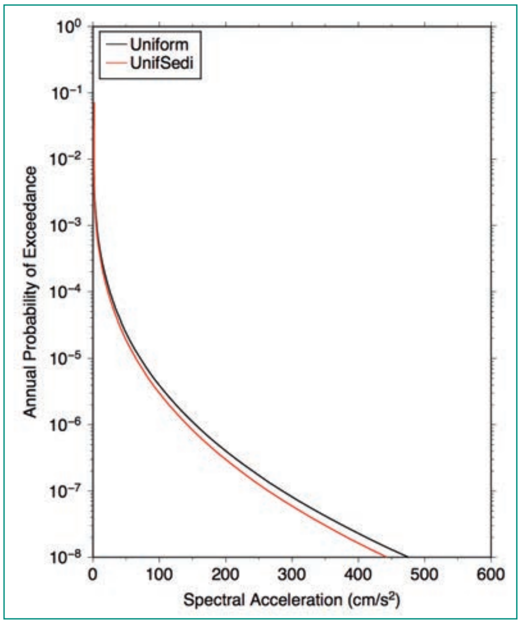

Figure 4: :
Mean hazard curves estimated using the common PSHA (black line) and the one including the method propose here (red line).

National Cooperation

We implemented, validated, and further developed models from the PRP project. Collaboration exists with the Institute of Geotechnical Engineering at ETHZ for calibration of nonlinear material properties. In October 2012 a meeting with members of the Sediment Dynamics Group of the Geological Institute at ETH and the limnology and environmental geology group at the University of Geneva was held to discuss earthquake induced lake-slides and tsunami-events.

International Cooperation

Cooperation was established within the EU-FP7 funded projects SHARE, REAKT and NERA. We are working with the Université Paris EST on the development of advanced constitutive soil models, and with San Diego State University (SDSU) and the San Diego Supercomputing Center (SDSC) in the implementation of numerical algorithms. The international research network in historical seismology was extended at the tri-national meeting in Chambery. 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.

Assessment 2012 and Perspectives for 2013

We have implemented Swiss ground-motion prediction equations (GMPEs), stochastic and V/H models at the Swiss Seismological Service (SED), and are awaiting finalization of the PRP to include Swiss specific modifications. The development of the Swiss stochastic model was successful during 2012, with confirmation of its performance in the case of larger events by testing European and Japanese data. Finally the investigation of kappa in terms of site properties was successful; facilitating the prediction of site attenuation based on characteristics such as Vs-profile at a site.

The project goals of subproject 2 for 2012 have been achieved. The new quarter-wavelength proxies have been validated. Predictive models for amplification and V/H ratios for rock and soft sediment soils have been established. Application of the amplification models for sites in Switzerland is still on-going. In particular, we plan the implementation of a comprehensive tool, which will include all the procedures that have been developed during the project. The developed active seismic methods and the assessment of resonance phenomena will be included in the SED site-characterization procedures.

In subproject 3, the study of ground motion records with clear non-linear signature has led to a novel way of analysing vertical array records, which improves our ability to reproduce cyclic mobility observed in the field. We have faced a delay in the application of an advanced 2D non-linear code to case studies, as its release has been postponed by the developers. Significant progress has been made in the implementation of a nonlinear material model (Drucker-Prager yielding) in a 3D wave propagation code. This code will be further developed in 2013 and validated by reproducing observed ground motion at selected sites. Dynamic soil properties will be defined at more sites where vertical array records are available and simulations of non-linear site response based on advanced constitutive soil models will be performed in 2D once the code is available.

The evaluation and identification of relevant historical sources for the period 1878–1900 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 fact that the discrepancies between historical sources and actual catalogue data are larger than expected, an extension into year 3 of the project was needed.

Subproject 5 is making progress in line with the work planned. The work performed so far defines critical boundary conditions for defining more advanced seismogenic source models for Switzerland. The next steps will be (1) to develop a reference Vp *3D* crustal model based on *CSS* and *RF* information; (2) to include the regional behavior of *b* in depth into probabilistic seismic hazard assessment studies in order to quantify its impact; (3) to complete the framework for integrating fault imaging information, and to summarize the work in a publication and study the implications for surface faulting probabilities.

Public access to the updated time-varying hazard and rate forecasts implemented in subproject 6 will be internally discussed before this information will eventually be open. The models are running in real-time and as soon as sequences have been recorded, the forecasts will be tested with currently used evaluation methods.

Finally, in 2013 the main focus of the project will be on possible earthquake impacts on deep geological disposals according to the new research plan.

Publications in the reporting period

- *Edwards, B. & D. Fäh (2013).* A Stochastic Ground-Motion Model for Switzerland. Bulletin of the Seismological Society of America 103 (1), 78–98.

- *Edwards, B. & D. Fäh (2012).* Measurements of Stress Parameter and Site Attenuation from Recordings of Large Earthquakes in Europe and the Middle East. Submitted to Geophysical Journal International.
- *Edwards, B., V. Poggi and D. Fäh (2011).* A Predictive Equation for the Vertical-to-Horizontal Ratio of Ground Motion at Rock Sites Based on Shear-Wave Velocity Profiles from Japan and Switzerland, Bulletin of the Seismological Society of America 101, 2998-3019.
- *Edwards, B., V. Poggi & D. Fäh (2011).* A Predictive Equation for the Vertical to Horizontal Ratio of Ground-Motion at Rock Sites Based on Shear Wave Velocity Profiles. Proceedings of the 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Strong Ground Motion, Santa Barbara, California.
- *Edwards, B., D. Fäh & D. Giardini (2011).* A Stochastic Ground-Motion Model for Switzerland. Proceedings of the 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Strong Ground Motion, Santa Barbara, California.
- *Grolimund, R. & D. Fäh (2012).* History matters: bref aperçu de la sismologie historique en Suisse. In: Gazette des Archives, Paris (in press).
- *Poggi, V., B. Edwards & D. Fäh., (2012).* Characterizing the vertical to horizontal ratio of ground-motion at soft sediment sites. Bulletin of the Seismological Society of America 102, 2741-2756.
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- *Poggi, V., D. Fäh. & D. Giardini (2012c).* Time–Frequency–Wavenumber Analysis of Surface Waves Using the Continuous Wavelet Transform. Pure and applied Geophysics. DOI: 10.1007/s00024-012-0505-5.
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- *Sellami, S., R. Grolimund, & D. Fäh (2012).* Earthquakes in Switzerland and surroundings 1964-1974: a «dark age» of earthquake documentation at the Swiss Seismological Service. In prepara-tion.
- *Spada, M., I. Bianchi, E. Kissling, N. Piana Agostinetti, & S. Wiemer (2012a).* Combining Controlled-Source Seismology and Receiver Function information to derive 3D Moho topography for Italy. Revised for Geophysical Journal International.
- *Spada, M., T. Tormann, S. Wiemer, & B. Enescu (2012b).* Generic dependence of the frequency-size distribution of earthquakes on depth and its relation to the strength profile of the crust. Submitted to Geophysical Research Letter.

Conference contributions in the reporting period

- *Poggi, V., B. Edwards & D. Fäh (2012).* Effect of surface average shear-wave velocity on the vertical-to-horizontal ratio of the ground motion: comparing rock and soft sediment sites. 33rd General Assembly of the European Seismological Commission, August 19–24, Moscow, Russia.
- *Edwards, B. & D. Fäh (2012).* A Stochastic Ground-Motion Model for Switzerland. Seismological Society of America Annual Meeting 17–19 April 2012, San Diego, CA, In: Seismological Research Letters, 83, 456–457.
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- *Roten, D., D. Fäh & F. Bonilla, (2012).* Development of excess pore water pressure in liquefiable soils inferred from vertical array records. Annual

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