SED – Erdbebenforschung zu Schweizer Kernanlagen

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ABSTRACT

The goal of this project is to improve regional and local seismic hazard assessment in Switzerland. For subproject 1 we focused on the development of an inversion procedure for site-specific near-surface structure that is essential to determine site-specific ground motion amplification properties. Our procedure was thoroughly tested and applied to several Swiss sites. Further, we worked on a stochastic model to characterize high-frequency ground motion at depth relevant for site-specific seismic hazard assessment of deep geological disposals. The analysis of the site-specific ground motion duration patterns was also a topic of our research. Within subproject 2, we developed a library to generate spatially-correlated random perturbations of physical properties as velocity and stress, suitable for large-scale numerical simulations. We have also demonstrated how to validate 3D geophysical models based on cost-effective ambient noise measurements. Last, a procedure to quickly assess the liquefaction potential of a site has been finalized. Within subproject 3, we studied the evolution of pressure and temperature around a geological nuclear waste repository and evaluated the potential for inducing earthquakes. Results, in full 3D, confirmed previous results showing that fault zones located in seismogenic regions few hundreds of meter below the repository are subjected to an increased stress. In the framework of benchmarking activities with other numerical approaches, we also developed a numerical model to account for gas generation. Future implementation will allow modelling gas generation at the full emplacement scale.

Project goals

This science project is split into three subtasks with the main goal to improve regional and local seismic hazard assessment in Switzerland. The sub-projects are:

- Ground motion attenuation models and earthquake scaling for Switzerland;
- Modelling wave propagation in complex, non-linear media and limits of ground motion;
- Induced seismicity and application for a deep geological disposal.

The focus of subproject 1 lies on the development and improvement of earthquake ground motion attenuation and source-scaling models for Switzerland. We target ground motion estimates for sites at depth and at the surface, in the near field, for damaging events and for smaller induced earthquakes as well. The work is based on observations in Switzerland and Japan. Studying the near-surface amplification and attenuation constitutes a key point in our research.

The scope of subproject 2 is to improve deterministic predictions of ground motion, especially with respect to near field, to nonlinear behaviour in sedimentary rocks and soft soils, and to new trends in modelling complex source processes. This includes the calibration of material parameters via field measurements and the development of numerical codes to simulate ground motion in three-dimensional complex media. Results of subproject 1 will be linked to deterministic simulations from subproject 2, and the results will be tested and compared to observed data.

In subproject 3, we move towards a realistic characterization of seismogenic sources for induced earthquakes. The goal is to adapt existing geo-mechanical models to a situation of a deep geological disposal (e.g. nuclear waste repositories), develop and validate new modelling methods, and integrate them in a probabilistic framework for seismic hazard assessment.

Work carried out and results obtained

1. Ground motion attenuation models and earthquake scaling for Switzerland

Subproject 1 is aimed at improving ground motion prediction at Swiss sites. The ground motion prediction equations (GMPEs) and site amplification models for Switzerland were developed within the previous phase of this project (see past ENSI project reports for more details and references). The ground motion attenuation and amplification are closely related to the site-specific near-surface rock and soil structure. Recently, we focused on the development of an inversion method that is capable to infer the near-surface structure and its theoretical amplification including uncertainties. This novel inversion method relies on the probabilistic framework, Bayesian logic, and recent computational methods (Hallo et al., 2019; Hallo et al., under review). A result of the inversion is an extensive ensemble of near-surface models fulfilling rigorous criteria on model complexity (number of layers) and prior site-specific constraints (based on stratigraphic logs, standard penetration tests, bedrock depth, etc.). The performance of this method was tested in terms of inversion of synthetic data modelled in various possible 1D structures. We performed also numerous inversion tests with the real data measured in the vicinity of seismic stations of the Swiss Strong Motion Network (Hobiger et al., submitted). In particular, we tested the method for sites VISP, SAARA, SENGL, and SBAV. As an example in Fig. 1, we show the result of inversion of the surface waves data measured in the vicinity of the SENGL site. The inferred site-specific structure in Fig. 1a-c is supplemented with uncertainty that allows us to evaluate solution reliability. Further, our novel method allows evaluating the posterior probability of the theoretical SH-wave amplification referenced to the Swiss profile [1], which is shown in Fig. 1d. It may predict the site amplification for comparison with the results from empirical spectral modelling [2]. This is of great importance, as it is essential for site-specific seismic hazard assessment. Similarly, we can evaluate the posterior probability of Vs30 that is used routinely for classical GMPE adjustments (Fig. 1e and 1f). This mathematical framework might be applied for the development of the next generation of Swiss stochastic ground motion models.

The ground motion prediction at depth is needed for the seismic hazard assessment of deep geological disposals. Hence, we are working on the development of depth-to-surface amplification and duration models that may be used for a site-specific prediction of the ground motion at depth. Recently, we draw a physics-based approach to characterize high-frequency ground motion at depth based on the statistical evaluation of depth-to-sur-

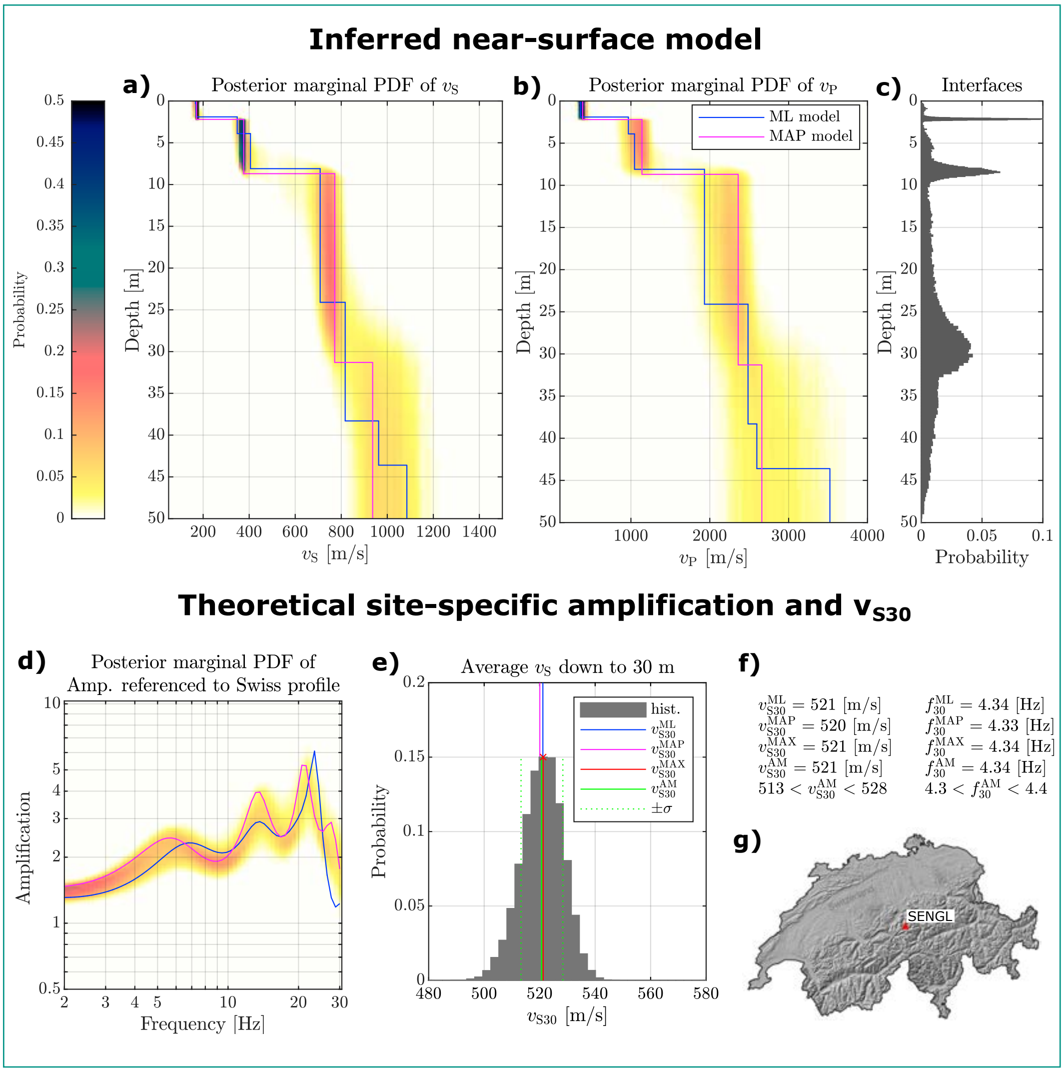

Figure 1: *Application of the novel inversion approach on Swiss data. The near-surface model and theoretical site-specific amplification are inferred from measured ambient vibrations data on the SENGL site, see panel g). In panels a)–c), the site-specific structure is expressed by means of two representative velocity models (ML and MAP model) and posterior probability distribution (signifying uncertainty). The theoretical site-specific amplification in panel d) represents the expected site-specific ground motion amplification referenced to the Swiss reference profile. Panels e) and f) show statistics of Vs30 that is classically used for GMPEs adjustments.*

face SH-wave transfer functions computed in random near-surface models (Hallo et al., 2020). The ensemble of such transfer functions is used for the construction of the stochastic model using Gaussian statistics in the power spectral density (amplification term) and the envelope delay (temporal term). This approach has many applications, such as: the inversion on high-frequency ground motion at depth from surface recordings; the site-specific adjustments on classical ground motion prediction equations; and discrimination of sites with 1D and 2D/3D resonance effects.

We are studying the site-amplification problem also from the point of view of duration, focusing on the lengthening of the ground motion due to local site effects. The expected achievement is twofold: i) we expect the analysis of duration to provide an additional tool to discriminate between sites with 1D or 2D/3D resonance; ii) more importantly, we aim at developing site-specific duration models. As duration models are needed for the translation of Fourier to PSA amplification, the use of site-specific models (in place of the currently employed regional models) would in fact improve the accuracy of such a conversion. In 2020, we have continued the work carried out in 2018 (compiling a database of site condition parameters for the 689 Japanese KiK-net strong-motion stations) and 2019 (determining the significant duration for the ~5200 crustal events recorded by said stations between 1997–2016). In the current year we have cross-referenced the two datasets; first, we have computed for each KiK-net station the average deviation from the distance-dependent median duration of earthquakes, sorted into 0.5 magnitude bins (magnitude range 3–6.5). Consistently with other works in literature (e.g. [3]), we consider this station-specific average deviation (an additive term in logarithmic scale) as representing the site term of duration. Successively, we have regressed these terms against a wide set of site condition indicators, comprising Vs profile-derived proxies (e.g. Vs30, depth-to-engineering bedrock), the site fundamental frequency of resonance (f_0) and topographical slope and curvature evaluated at 7 spatial scales between 60–2020 meters. The most interesting outcomes can be summarized as following:

- The site term may have a significant effect on the overall duration; for most of the stations, the increase/decrease due to local response is comprised within +/- 30 % of the median duration.
- The correlation between lengthening of ground motion and site proxies increases with magnitude. Among the parameters derived from geophysical measurements, the most significant indicators are H800 (depth to engineering bedrock), Vs30 and f_0. As for the topographical parameters, slope and curvature at large scales (1140, 2020 m) best correlate to local duration.

The correlation we observed between curvature and duration of ground motion, however, does not behave as expected; in fact, stations at sites with negative curvature (basins, valleys) show shorter durations than instruments installed in flat areas (null curvature). This can be explained by the fact that terrain curvature is also correlated with the soil stiffness: as illustrated in [4], sharply concave or convex structures are likely to be associated with stiff subsurface materials, while moderate values of curvature generally denote softer soils. Based on this and the previous observations, we conclude that it is difficult to discriminate the prolongation effect of 1D resonance (which appears to be predominant) from that of 2D/3D effects. In the attempt to decouple the two phenomena, we first retrieve for each station the residual from the fitted trend of site duration versus parameters capturing 1D resonance (Vs30, H800). These residuals are then collated with the terrain curvature at the stations' host sites. We observe a slight increase of strong motion duration at sites with a moderate negative curvature. We interpret this behaviour as the prolongation of ground motion due to basin effect and/or edge-generated surface waves occurring at sedimentary basin or valley edges.

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

Research activity within sub-project 2 has focused on some aspects of ground motion in complex media and on the assessment of liquefaction potential of soft soils. In particular, we have completed the development of a library, called SCARF3D (Imperatori et al., submitted), to generate large-scale random fields that can be used to represent unknown

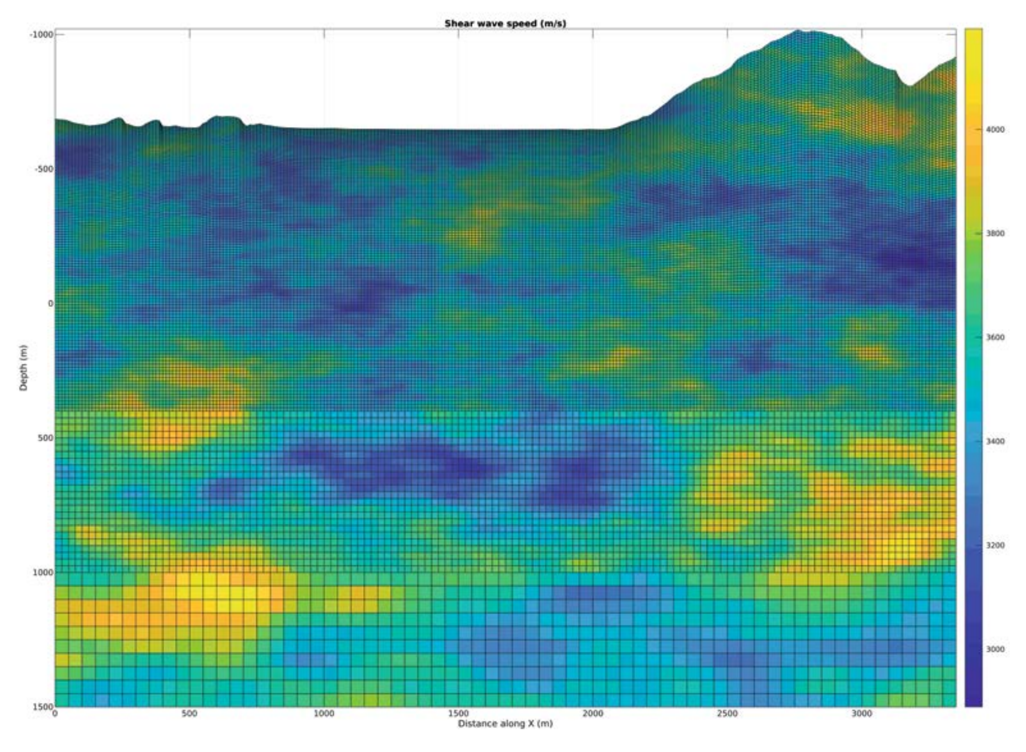

Figure 2: *Sample realization of velocity perturbations on a multiple-refined finite-difference grid. Perturbations are continuous along mesh refinement interfaces. Uppermost grid uses curvilinear coordinates.*

variations of physical parameters. For instance, it has been widely documented that stochastic velocity heterogeneity in the crust and heterogeneous stress distribution on fault planes control many features of the ground motion, as duration, peak amplitude and overall complexity [5]. In the framework of numerical simulations, it is therefore fundamental to calculate these random fields accurately. For large numerical grids, this can be a problematic task [6]. Our library is able to generate in a short time massive spatially-correlated perturbations having the desired statistical characteristics. Perturbations can be non-isotropic, arbitrarily oriented and are computed directly on regular or irregular meshes, as shown in Figure 2. It is expected that many applications will benefit from our library including, for instance, numerical studies of induced seismicity.

A second project focused on the validation of a 3D velocity model for the Visp area, southern Switzerland. Realistic models of the upper crust are key to reliable ground motion simulations and seismic hazard studies, e. g., [7]. Building on an initial geophysical model, we have developed a procedure to validate and further refine its main features based on cost-effective horizontal-to-vertical (H/V) spectral ratios and available standard spectral ratios (SSR). In particular, we simulated deterministically high-frequency ambient noise generated by sources randomly distributed within the alpine basin and verified how closely we reproduced the observed frequency-dependent spectral ratios. An iterative procedure based on data misfit could be used to further refine the initial geophysical model. The final model satisfactorily reproduces most observables.

In the framework of soil non-linearity, we have refined a procedure developed during the second phase of the ENSI project to quickly estimate the soil liquefaction probability. Our approach extends the standard deterministic procedure of [8] based cone penetration tests (CPT) by considering the probability of peak ground acceleration as provided by ground motion prediction equations (GMPEs) for a target earthquake at a given site. As shown in Hobiger et al. (submitted) this procedure has been applied at many sites in Switzerland.

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

The overall objective of this subtask is to extend the work performed during the previous phase. Here we focus on the geo-mechanical processes that can be present in a deep geological repository due to canisters emplacement, in particular related to fault stability. This includes large model complexity and a stochastic approach to the fault stability analysis. We now employ the newly developed TOUGH3-FLAC3Dv6 approach to simulate a large number of coupled processes occurring in a geological nuclear waste repository ([9], Rinaldi et al., submitted). The new approach allows for simula-

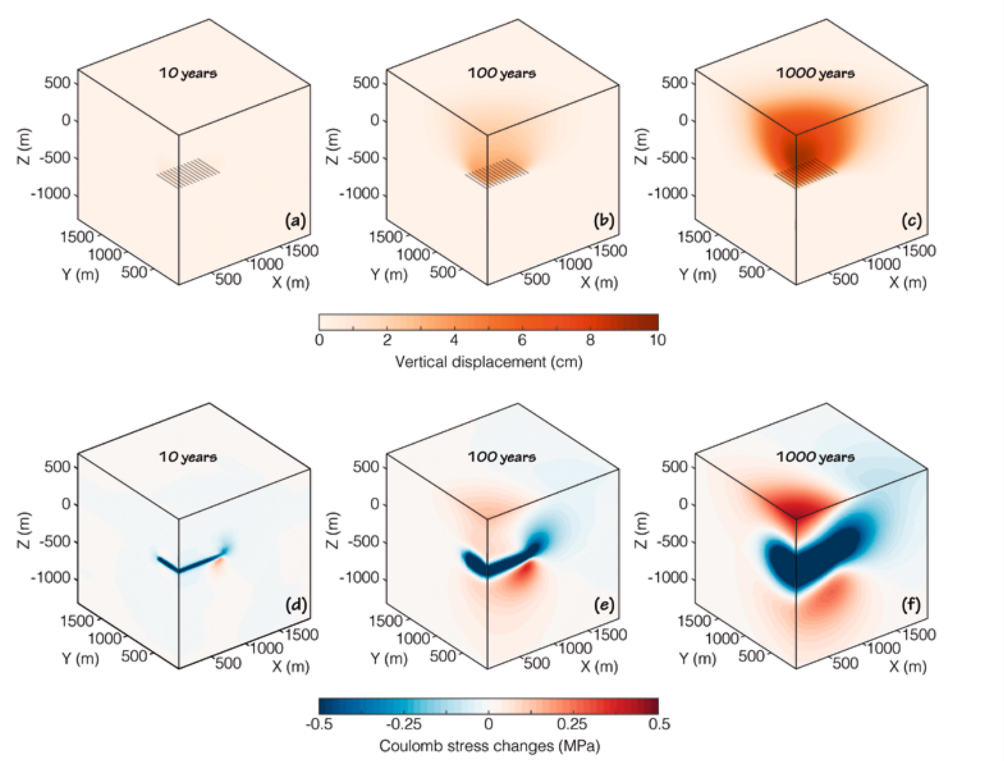

Figure 3:
Distribution of vertical displacement (a,b,c) and Coulomb stress changes (d,e,f) in a deep geological repository for the storage of nuclear waste 10, 100, and 1000 years after emplacement. Coulomb stress is calculated for faults dipping 80° and striking N180°, assuming the north is oriented in the y-direction.

tion with a large number of elements in the computational grid, leading to a more precise description of the coupled processes (e.g thermal pressurization, desaturation and resaturation of the buffer material, and gas generation). The current numerical approach was validated through comparison with analytical solutions, but also through benchmarking with other codes (Friedenberg et al., 2019; Beck et al., 2020). The use of a large mesh allows for more details compared to the previous formulation. The temperature changes due to heat generated by the nuclear waste can be responsible of quite large deformation at ground surface, up to several cm uplift after 1000 years (Fig. 3a, b, and c).

We also evaluated the potential for fault reactivation. Starting from the changes in the full stress tensor, we evaluate the Coulomb Stress change as $\Delta CFS = \Delta\tau + \mu(\Delta\sigma_n + \Delta p)$, as where $\Delta\tau$ is the change in shear stress, μ is the coefficient of friction, $\Delta\sigma_n$ is the change in normal stress (negative when compressive) and Δp is the change in pore pressure.

Shear and normal stresses are calculated for faults striking parallel to the tunnels and with 80° dip angle toward the repository (i.e. strike N180°). Figures 3d–f show how the repository itself is undergoing stress shadow (negative Coulomb stress changes), meaning that failure is hindered. At early times, the thermal pressurization is causing only more compression and stabilizing faults in the near repository region (Fig. 3d). Failure of the considered fault orientation is, however, favoured at greater depth, where more seismogenic faults could be present. This is linked to the shear transfer caused by temperature changes, and it is then particularly relevant when the thermal effect starts distributing outside the clay formation (e.g. at 100 or 1000 years – Fig. 3e–f). These results are valid for steeply dipping faults and are in good agreement with a recent 2D study on fault reactivation during disposal of nuclear waste at depth [9]. The current model does not account yet for gas generation, although we investigated the potential for this process through numerical benchmarking. Results show that accounting for two-phase fluid flow, as well as for realistic retention curves (i.e. phase-relative permeability and capillary pressure) could strongly affect the modelled pressure and temperature evolution, as well as the expected deformation in the vicinity of an emplacement tunnel.

National Cooperation

We actively cooperated with researchers involved in the Swiss Strong Motion Network renewal project. Code development benefited of the infrastructures at the Swiss Supercomputing Center. The development and validation of the geophysical model for Visp involved Swisstopo and the Canton of Wallis. We also collaborated with various teams performing experiments at the Mont Terri Underground Lab (FS-B, GT, CS-D).

International Cooperation

Our research on probabilistic inversion was carried out with the Australian National University and Charles University of Prague. Collaboration with King Abdullah University of Science and Technology (KAUST) fostered the development of the random field generator. Research on induced seismicity during operational phase is currently carried out in collaboration with the Lawrence Berkeley National Laboratory (LBNL) in Berkeley. We also took part to international initiatives to benchmark and validate numerical models (BENVASIM, DECOVALEX).

Assessment 2020 and Perspectives for 2021

Future work in subproject 1 will involve the application of a physical-based stochastic model to characterize high-frequency ground motion at depth on Japanese and Swiss data. We have planned also some improvements to the stochastic ground motion model for Switzerland. In particular, we expect to verify the influence of the finite-extent source model on ground motion predictions and to test inversion strategies for the next generation stochastic model. As for the analysis of strong motion duration, we plan to extend this study to Swiss stations, and verify the consistency with the results already obtained from the Japanese network. In subproject 2, we finalized a library to efficiently generate random fields with multiple hardware support. It can be used in subproject 1 to, e.g., extend the study on high-frequency ground motion at depth towards more complex models and in subproject 3 to, e.g., produce more realistic initial stress conditions. We have also developed a strategy to validate 3D geophysical models based on cost-effective noise measurements. In the framework of subproject 3, we recently published a paper on seismicity induced by tunnelling activities and improved our modelling capabilities of stress evolution in a deep geological repository. The latter is critical for a proper assessment of the potential for induced seismicity. Future work will focus on gas generation effects in 3D models. The resulting stress field will then be used as input for the stochastic model presented in the past, and more effort will be dedicated to the study of potential effects of stress evolution in the distribution (temporal and spatial) of the seismicity.

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