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Towards a Dynamic Earthquake Risk Framework for Switzerland

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Abstract. Scientists at ETH Zurich from different disciplines are developing a dynamic, harmonised and user-centred earthquake risk framework for Switzerland, relying on a continuously evolving earthquake catalogue generated by the SED using the national seismic networks. This framework uses all available information to assess seismic risk at various stages and facilitates widespread dissemination and communication of the resulting information. Earthquake risk products and services include Operational Earthquake (Loss) Forecasting (OE[L]F), Earthquake Early Warning (EEW), ShakeMaps, Rapid Impact Assessment (RIA), Structural Health Monitoring (SHM), as well as Recovery and Rebuilding Efforts (RRE). Standardisation of products and workflows across various applications is essential for achieving broad adoption, universal recognition, and maximum synergies. In the Swiss dynamic earthquake risk framework, the harmonisation of products into seamless solutions that access the same databases, workflows, and software is a crucial component to ensure standardisation. A user-centred approach utilising quantitative and qualitative social science tools like online surveys and focus groups is a significant innovation featured in all products and services. Here we report on the key considerations and developments of the framework and its components.

Short Summary. We are developing an interdisciplinary dynamic earthquake risk framework for Switzerland for advancing earthquake risk mitigation. It includes various earthquake risk products and services, such as Operational Earthquake Forecasting and Earthquake Early Warning, and adopts a user-centred approach. Standardisation is crucial for widespread adoption and recognition, and the harmonisation of products into seamless solutions that access the same databases, workflows, and software is a crucial component.

Keywords: seismic hazard, seismic risk, seismic network, earthquake forecasting, earthquake early warning, rapid loss assessment, structural health monitoring, recovery and rebuilding efforts, earthquake communication

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1. Introduction

Europe faces a significant earthquake risk due to its tectonic situation, high population density, business value, and the age and condition of buildings (e.g., Danciu *et al.*, 2022; Crowley *et al.*, 2022). This includes areas with moderate seismic activity, such as Switzerland, where earthquakes have the potential to cause significant loss, with projected costs of major events exceeding Euro 100 billion (Wiemer *et al.*, 2016; Wiemer *et al.*, 2023). Building codes and retrofitting are the most effective measures to reduce earthquake risk, but emerging technologies, such as Operational Earthquake Forecasting (OEF) or Earthquake Early Warning (EEW), can also improve resilience by means of reducing exposure (e.g., Cauzzi *et al.*, 2016; Papadopoulos *et al.*, 2023).

The national Seismic Hazard Model (SUIhaz2015; Wiemer *et al.*, 2016) and the recently released first national Earthquake Risk Model of Switzerland (ERM-CH23; Wiemer *et al.*, 2023; Papadopoulos *et al.*, subm.) serve as the basis for tools and systems being developed as part of a dynamic, harmonised and user-centred earthquake risk framework for Switzerland. This framework uses all available information to assess seismic risk at various stages of the earthquake cycle (**Figure 1**), and facilitates widespread dissemination and communication of the resulting information. This involves various services, products, and research developed at the Swiss Seismological Service (SED), the Department of Earth Science, and the Institute of Structural Engineering (IBK) at the Eidgenössische Technische Hochschule (ETH) Zurich, including Operational Earthquake (Loss) Forecasting (OE[L]F), Earthquake Early Warning (EEW), ShakeMaps, Rapid Impact Assessment (RIA), Structural Health Monitoring (SHM), as well as Recovery and Rebuilding Efforts (RRE).

The harmonisation of products and workflows across various applications is crucial for broad adoption and universal recognition of products, as well as to maximise synergies and impact. A crucial component of the Swiss dynamic risk framework is, therefore, the standardisation into seamless products that access the same databases, workflows, and software, and are based on standard models. For instance, the current RIA for Switzerland utilises Swiss ShakeMap (Cauzzi *et al.*, 2015; 2022), which provides ground-motion maps in near real-time and employs the same site amplification layers (Bergamo *et al.*, 2023) used in ERM-CH23. Rapid impact is calculated using OpenQuake (Pagani *et al.*, 2014) for scenario products, RIA, and probabilistic products, while the impact on people and buildings is determined from national building databases and their vulnerability. OELF calculations employ short-term seismicity forecasts in synergy with components of the hazard and risk models utilised for long-term hazard and risk calculations and RIA products. All products are informed by a single, continuously evolving earthquake catalogue as well as continuous waveforms generated by the SED using the national seismic networks.

All products and services feature a significant innovation, namely a user-centred approach that utilises quantitative and qualitative social science tools such as online surveys and focus groups. The visual representation of rapid impact, for instance, was created based on feedback from focus groups and discussions with stakeholders at the federal and cantonal levels, featuring new visualisations of uncertainties. The risk map was adjusted to the public needs which were assessed with a representative, nationwide survey.

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Here we report on the key components of the Swiss dynamic, harmonised and user-centred earthquake risk framework which were mostly developed within the scope of the European Union Horizon 2020 *Real-time earthquake rIsk reduction for a ReSilient Europe* (RISE)[1] project (**Figure 1**). We start with a summary of the seismic hazard and risk in Switzerland and then continue with a description of the recent advancements in seismic monitoring capabilities over the last decade, which are crucial for downstream risk mitigation products and services, on which we focus in the second part of this paper. Finally, we discuss the SED strategy for implementation and communication of earthquake hazard and risk products with the public and stakeholders in Switzerland.

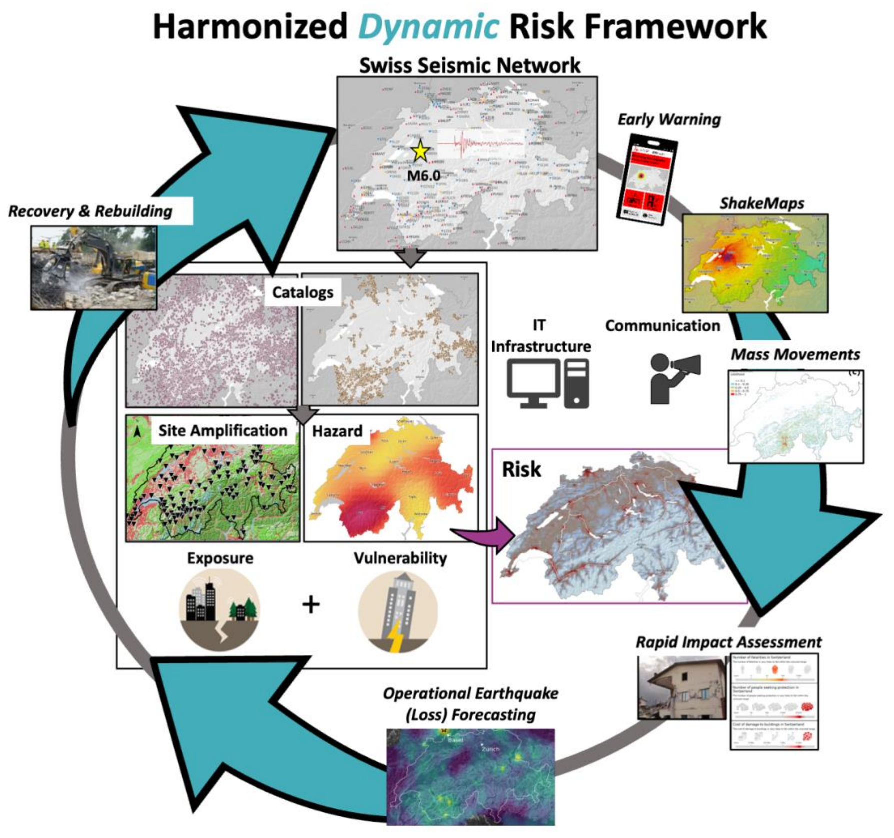

Figure 1: Schematic representation of the dynamic risk concept.

1.1 Seismic Hazard and Risk in Switzerland

Switzerland is exposed to a considerable threat of earthquakes. Around 1000 to 1500 earthquakes are detected in Switzerland and its neighbouring countries every year, including 20 to 30 events that the population feels (**Figure**

[1] http://www.rise-eu.org/home/ last accessed July 2023

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2). SUIhaz2015 (**Figure 3a**; Wiemer *et al.*, 2016), which assesses the likelihood of ground shaking, forecasts that earthquakes of magnitude M >=5 are likely to occur every 8 to 15 years. The severity of impacts on buildings depends on the location and depth of the earthquake. Earthquakes with a magnitude of 6 or greater, which can cause extensive and severe damage, occur on average every 50 to 150 years and can strike any part of Switzerland at any time. The last earthquake of this magnitude occurred close to the town of Sierre in the Upper Valais in 1946 (Fäh *et al.*, 2011). The canton of Valais faces the highest level of seismic hazard in Switzerland, followed by Basel, Grisons, the St. Gallen Rhine Valley, and Central Switzerland.

The seismic hazard model SUIHAZ2015 has been implemented in the most recent version of Swiss building code SIA 261 (2020). The 2015 Swiss seismic hazard model updated the hazard model from 2003 (Giardini *et al.*, 2004). The first seismic hazard model for Switzerland used in Swiss building codes until 2003 was the one of Sägesser and Mayer-Rosa (1978) which was based on the historical catalogue available at the time and on macroseismic Intensity.

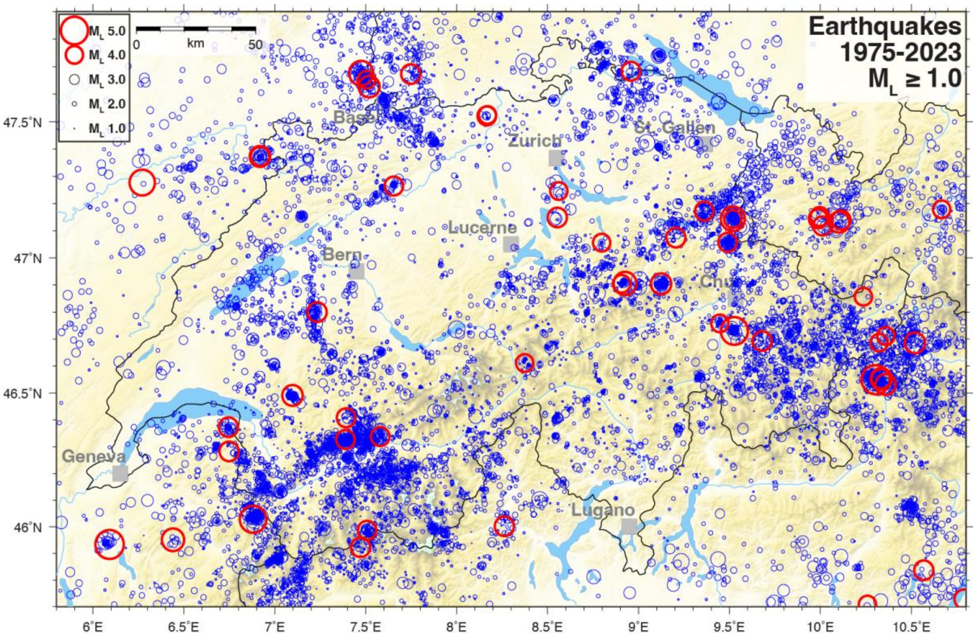

Figure 2: Map of Switzerland and the surrounding area showing all seismicity with ML≥1.0 since 1975 in the SED earthquake catalogue (bulletin locations). Events with ML >= 4.0 are highlighted by bold red circles.

Methods for estimating site-specific amplification and local seismic hazard were developed at SED during the past decades and were implemented in microzonation studies, e.g., as for the region of Basel (e.g., Fäh and Huggenberger, 2006). A number of approaches were developed to estimate site-specific amplification based on geophysical measurements and earthquake recordings (e.g., Edwards *et al.*, 2013; Michel *et al.*, 2017; Poggi *et al.*, 2017; Perron *et al.*, 2022; Panzera *et al.*, 2021, 2022). Recently, a project started to update the microzonation

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for the Basel region. All this experience was used to define the elastic response spectra in the Swiss building code (2020) and to implement a national regulation related to microzonation in SIA 261/1 (2020).

Geographic features, such as large and deep peri-alpine lakes, steep slopes, and alluvial basins with a high-water table, make Switzerland susceptible to secondary hazards (e.g., Fritsche *et al.*, 2012; Fäh *et al.*, 2012). Using geophysical imaging, seismic monitoring, numerical modelling and other techniques, the SED has been conducting research on earthquake-induced hazards, including (i) rockfalls and landslides (e.g., Burjanek *et al.*, 2018; Kleinbrod *et al.*, 2018; Glueer *et al.*, 2021; Häusler *et al.*, 2022); (ii) lake tsunamis (e.g., Strupler *et al.*, 2018; Kremer *et al.*, 2022; Shynkarenko *et al.*, 2022); and (iii) liquefaction (e.g., Fritsche *et al.*, 2012; Roten *et al.*, 2014; Janusz *et al.*, 2022). Findings from these studies have been incorporated into rapid estimates of earthquake-induced mass movements and liquefaction probabilities in Switzerland via the SED ShakeMap application (Cauzzi *et al.*, 2018a; Section 3.3).

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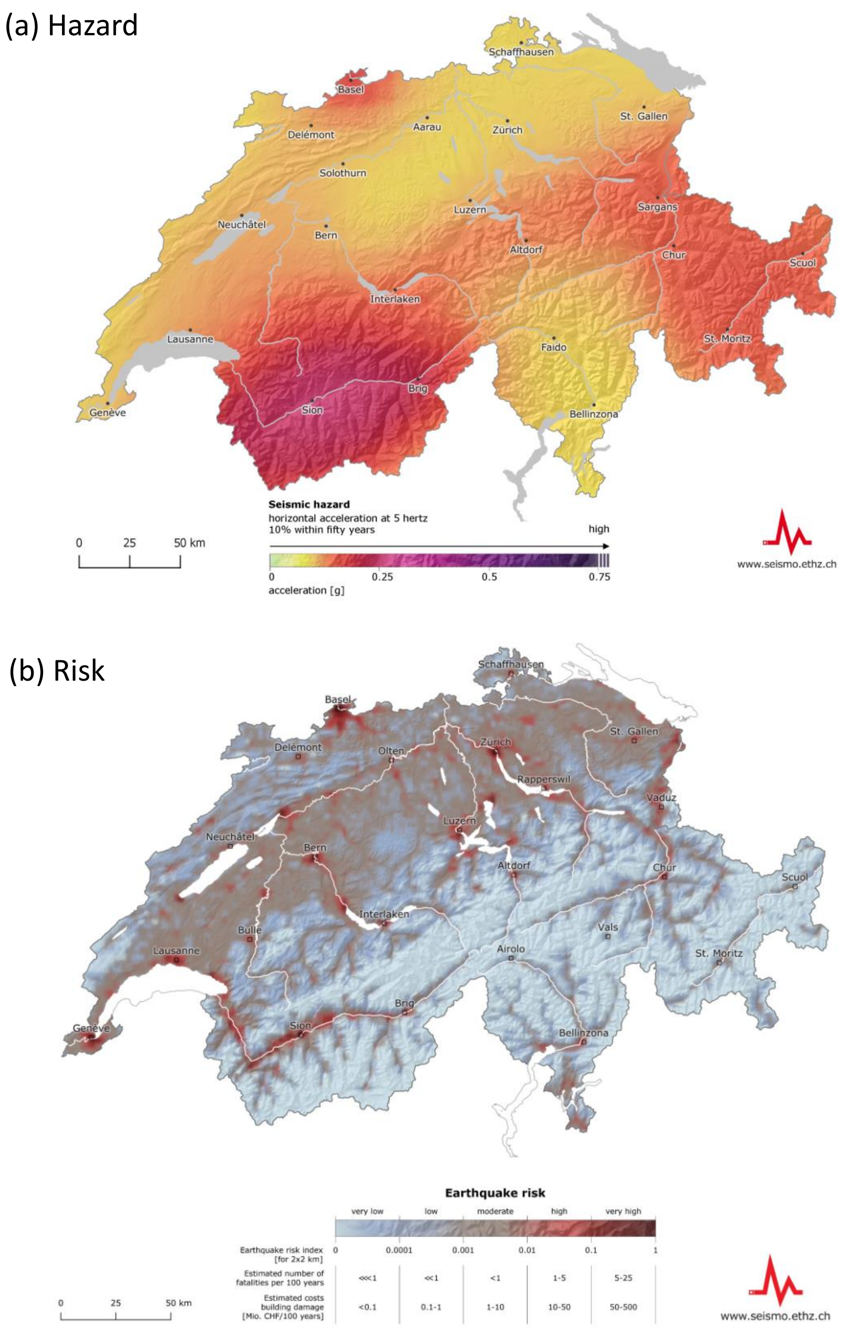

Figure 3: (a) Swiss Hazard Map (SUIhaz2015; @Swiss Seismological Service) showing the horizontal acceleration at 5 Hz; the probability of a building constructed on rocky subsoil experiencing this is 10% within 50 years (i.e., mean return period of 475 years). On average, 5 Hz represents the natural frequency of buildings with two to five floors, which make up the largest proportion of construction in Switzerland. 475 years is the value that underlies the Swiss Seismic Building Codes: an earthquake-resistant residential or office building should be able to withstand an earthquake that occurs where the building is situated within 475 years on average. (b) National Earthquake Risk Model

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of Switzerland (ERM-CH23; @Swiss Seismological Service). The color scale refers to a composite index based on average annual structural/nonstructural loss and fatalities.

While seismic hazard in Switzerland has been extensively studied, a formal effort to quantify seismic risk, which assesses the potential impact of earthquakes on both people and structures, as well as the resulting financial losses, was not available in the public domain until recently. In March 2023, the SED in partnership with the Federal Office for the Environment (FOEN) and the Federal Office for Civil Protection (FOCP) released the first National Earthquake Risk Model of Switzerland (ERM-CH23; **Figure 3b**; Wiemer *et al.*, 2023). ERM-CH23 is implemented for use with OpenQuake (Pagani *et al.*, 2014), developed by the Global Earthquake Model (GEM) foundation. As with most contemporary risk models, ERM-CH23 follows a modular structure (Mitchell-Wallace *et al.*, 2017), with five generally decoupled components pertaining to seismic hazard on a reference rock, amplification, structural vulnerability, exposure, and consequence models. These components were developed through collaboration with national and international partners. Unlike past attempts that sought to assess earthquake risk at a continental (Crowley *et al.*, 2021) or global scale (Silva *et al.*, 2020), ERM-CH23 is largely supported by high-quality local data, including a database of more than 2 million building objects that was compiled by the FOEN. Together with ground surveys to assess the frequency of different building materials, conducted by partners at the École Polytechnique Fédérale de Lausanne (EPFL), they underpin the ERM-CH23 exposure model.

ERM-CH23 has been developed to estimate the economic damage in Switzerland caused by earthquakes, which resulted in a projected average cost of CHF 11 to 44 billion for building and contents alone, over a 100-year period. Urban areas, particularly the cities of Basel, Geneva, Zurich, Lucerne, and Bern, face the greatest risk due to their size and the concentration of people and assets that could be impacted by an earthquake. Additionally, these cities contain numerous vulnerable buildings located on soft soil types, which can significantly amplify seismic waves. As a culmination of many years of research and expertise within the SED (e.g., Michel *et al.*, 2017, Hobiger *et al.*, 2021, Bergamo *et al.*, 2021), a national site amplification model (**Figure 4**) has been created as part of ERM-CH23, using geo-spatial prediction techniques constrained on local site response measured at instrumented sites (Bergamo *et al.*, 2023). This model is based on (i) the direct mapping of observed site amplification factors at about 245 seismic stations, extracted with empirical spectral modelling technique (ESM, Edwards *et al.*, 2013); and (ii) layers of site condition indicators (multi-scale topographic slope, estimated bedrock depth, lithological classification of soil; **Figure 4a**). The dataset of empirical amplification factors was finally interpolated over the national territory using site condition proxies as predictor variables and the regression kriging algorithm (Hengl *et al.*, 2007) as a geo-spatial prediction framework. The resulting amplification model consists of four soil response layers for PGV, PSA(1.0s), PSA(0.6s) and PSA(0.3s) (e.g., **Figure 4b**), each with associated maps of epistemic (ϕ_{S2S}) and aleatory (ϕ_{S2S}) variability following the definition in Al Atik *et al.* (2010). The amplification maps for PGV, PSA(1.0s) and PSA(0.3s) were also converted into layers of aggravation or reduction of macroseismic intensity by means of the relations of Faenza & Michelini (2010, 2011).

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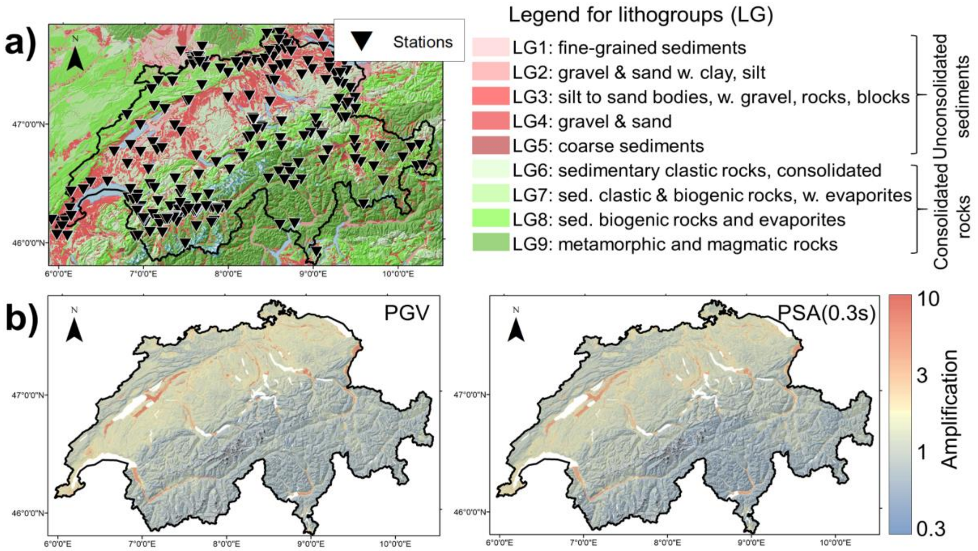

Figure 4: (a) Geographical locations of the 243 (urban) free-field stations having recorded at least 5 earthquakes with signal-to-noise ratios > 3 in the period 2000 – 2021, superimposed on the lithological classification of Switzerland employed to derive the national soil response model. (b) PGV (left) and PSA(0.3s) (right) amplification maps (referred to Vs30 = 1105 m/s), part of the national soil response model (Bergamo et al., 2023).

2. Seismic Monitoring

2.1 Swiss Seismic Network

The Swiss Seismic Network counts today about 220 permanent stations (network code CH; Swiss Seismological Service at ETH Zurich, 1983) with the aim to monitor the seismic activity in Switzerland, support scientific research, and assess seismic risk (Clinton *et al.*, 2011; Diehl *et al.*, 2021b; **Figure 5**). The network is divided into two main groups of stations. The first group is composed of about 50 backbone broadband stations (known as the 'SDSNet') that have very sensitive seismic sensors (velocity instruments, often referred to as "weak-motion") placed in quiet areas with optimal vault conditions. These stations are evenly spread throughout Switzerland and can detect and locate microseismic activity. Each of these sites also has a state-of-the-art force-balance accelerometer (often referred to as "strong-motion" instrument). The second group is composed of approximately 150 strong-motion stations (known as 'SSMNet') that are primarily located in high-risk urban areas of Switzerland, such as Basel and the Rhone Valley in the Valais (e.g., Clinton *et al.*, 2011; Cauzzi & Clinton, 2013). The SSMNet network is concluding a multiannual renewal project (2009 - 2023) which involved the renovation and significant expansion of the network, as well as the systematic site characterization of all newly instrumented sites (Michel *et al.*, 2014; Swiss Seismological Service (SED) at ETH Zurich (2015); Hobiger *et al.*, 2021). In addition to these permanent stations, the network holds another ~70 temporary stations, e.g., for the monitoring of geothermal exploration (Swiss Seismological Service (SED) at ETH Zurich, 2006[2]); aftershocks and seismic sequences (Swiss Seismological Service (SED) at ETH Zurich, 2005[3]), mass movements (Swiss Seismological

[2] https://doi.org/10.12686/SED/NETWORKS/G2 last accessed July 2023
[3] http://networks.seismo.ethz.ch/networks/8d/

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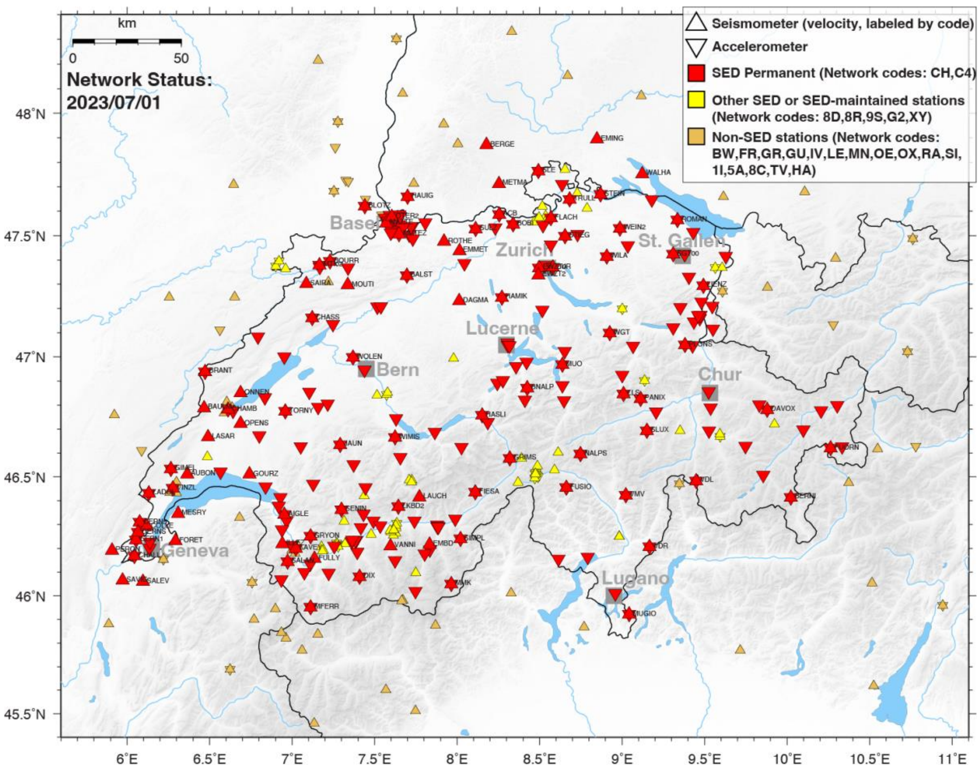
Service (SED) at ETH Zurich, 2012[4]), glaciers (Swiss Seismological Service (SED) at ETH Zurich, 1985[5]), underground rock physics laboratories (Swiss Seismological Service (SED) at ETH Zurich, 2018[6]); as well as for risk studies (Swiss Seismological Service (SED) at ETH Zurich, 2018[7]). The particularly dense network infrastructure in the Valais is host to the Valais Near Fault Observatory (Chiaraluce et al., 2022). An extra ~10 stations inside Switzerland but operated by external providers are included in the SED processing to improve the detection and characterization of seismic events, e.g., related to geothermal exploration (Swiss Seismological Service (SED) at ETH Zurich, 2021[8]). Around 50 stations operated by seismic agencies in neighbouring countries are included for regional real-time monitoring

In the Swiss network, the majority of broadband sensors are Streckeisen STS2 and STS2.5 and Nanometrics T240; the Kinemetrics EpiSensor is deployed for strong-motion. The network uses modern ultra-low latency digitizers (typically Nanometrics Centaur, Taurus, and Kinemetrics Q330), and most sensors are acquired at sampling rates between 200 and 250 sps. A newly developed sensor concept allows the SED to easily deploy large numbers of temporary stations rapidly in more remote locations with real-time streaming.



[4] https://doi.org/10.12686/SED/NETWORKS/XP
[5] https://doi.org/10.12686/sed/networks/4d
[6] https://doi.org/10.12686/SED/NETWORKS/8R
[7] https://doi.org/10.12686/sed/networks/xy
[8] https://doi.org/10.12686/sed/networks/5a

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Figure 5: Map of Switzerland and the surrounding area showing broadband seismometers and strong-motion accelerometers monitored by the Swiss Seismic Network as of July 2023. The map shows permanent and temporary stations operated by the SED, as well as stations operated by external partners in and outside of Switzerland.

2.2 Seismic Data Processing

Over the past 20 years, the number of stations within the Swiss Seismic Network has grown steadily. Data began to be continuously archived in 1999, with the advent of the first broadband sensors. Today, continuous data is standard and the network collects around 20GB of data every day; the total archive size is currently close to 100TB. The Swiss Seismic Network operates a European Integrated Data Archive (EIDA) node (Strollo *et al.*, 2021), and the majority of the waveform data, along with the SED earthquake catalogue, is open and accessible via community-standard International Federation of Digital Seismograph Networks (FDSN) web services for data access and download.

Since 2012, the Swiss Seismic Network has been utilising SeisComP[9], a software developed by the German Research Centre for Geosciences (GFZ) Potsdam and GemPa GmbH[10], for earthquake monitoring and seismic data processing. SeisComP supports real-time data acquisition, archival, and distribution, as well as automated earthquake detection and quantification, manual earthquake review, as well as catalogue management.

Detection and Location: The real-time automated processing at the SED involves event triggering using station-specific short term-average (STA)/long term-average (LTA) thresholds, refined post-picking using Baer (Baer & Kradolfer, 1987) and AIC pickers, association of picks using *scautoloc* or *scanloc* (Grigoli *et al.*, 2018), and location of events with *nonlinloc* (Lomax *et al.*, 2000) using Swiss-specific 1D and 3D velocity models. Several projects have been initiated at the SED over the last decades to improve the existing velocity models at different scales. A first 3D P-wave velocity model for Switzerland was developed by Husen *et al.* (2003), followed by a regional 3D local earthquake tomography (LET) P-wave velocity model by Diehl *et al.* (2009). A refined Pg and Sg LET model (parametrization 10x10x4 km) was computed by Diehl *et al.* (2021a). In their study, Diehl *et al.* (2021a) demonstrated that a sub-kilometer accuracy of epicenters can be achieved in most parts of Switzerland by using Pg and Sg phases in combination with an accurate 3D velocity model and the dense seismic network operated by the SED. Especially in very densely instrumented parts of the network, in which the distance to the closest observing station is smaller than 1.5 times the focal depth for most of the seismicity, the new velocity model also achieves sub-kilometer accuracy of focal depths as demonstrated in Diehl *et al.* (2021a) and Lee *et al.* (2023). This 3D velocity model has been used for relocation and high-resolution seismotectonic interpretations in several recent studies (e.g., Lanza *et al.*, 2022; Diehl *et al.*, 2023) and, since June 2022, is the standard model for bulletin locations by the SED. Furthermore, the LET model was locally improved in southwestern Switzerland by application of a staggered-grid approach, resulting in a 5x5x3 km model parametrization for the region of the Rhone-Simplon Fault Zone (Lee, 2023). The SED is working on an extension of these models to the entire crust, a Swiss-wide 3D Qp and Qs attenuation model, and a new Alpine-wide 3D P-wave crustal model using the data of the AlpArray experiment (e.g., Hetényi *et al.*, 2018).

[9] https://www.seiscomp.de/ last accessed July 2023
[10] https://www.gempa.de/ last accessed July 2023

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Source Characterization: Over the last few years, the SED has updated its strategy for magnitude determination to align it with the latest developments in engineering seismology and seismic hazard studies in Switzerland. This includes the adoption of a new local magnitude relationship MLhc (Edwards *et al.*, 2015; Racine *et al.*, 2020) and the seamless computation of the moment magnitude, Mw, based on spectral fitting, MwSpec (Edwards *et al.*, 2010). Station corrections for local magnitudes have been included, and these changes have been implemented retrospectively for all events since January 1, 2009. Since November 2021, MLhc is the authoritative Swiss-specific local magnitude used by the SED, and its computation has been integrated with SeisComP. Magnitudes are provided for all origins, and the best origin is selected using a SED developed origin score that considers the number of picks, pick residuals, and azimuthal gap. For earthquakes larger than M2.5, alerts are automatically sent to federal and cantonal authorities (Section 4.2), a ShakeMap is created (Section 3.3), and the strong-motion portal[11] is populated. Manual review is performed using the SeisComP *scolv* GUI. For large events with MLhc >3.5, manual moment tensors are calculated using the *scmtv* GUI and published in the annual/bi-annual reports of the SED (e.g., Diehl *et al.*, 2021b). The earthquake catalogue is curated through *scolv*. The SED is currently working on strategies to disseminate and visualise its existing first-motion and moment-tensor catalogues for public access.

Advanced Processing: In addition to the SeisComP standard modules mentioned above, the SED has developed internally, or with support from GemPa, specific modules for advanced processing. These include

- *scwfparam* for providing engineering parameters and input to ShakeMap (Cauzzi *et al.*, 2016);
- *scenvelope*, *scvsmag*, and *scfinder* for EEW (Massin *et al.*, 2021)*;*
- *scdetect* for earthquake detection using template matching (see below);
- *scrtDD* for real-time double difference relocation (see below).

Earthquake Detection from Template Matching - scdetect: Real-time earthquake detection is crucial for the characterization of earthquake sequences. *Scdetect* is *a* highly configurable module for real-time earthquake detection based on template matching using computationally efficient waveform cross-correlation (Armbruster *et al.*, 2022; Mesimeri *et al.*, 2023). The workflow of *scdetect* is fully integrated with the SeisComP architecture and allows users to visualize and refine the detected earthquakes using SeisComP's built-in GUI applications. *Scdetect* is currently being real-time tested in Switzerland in areas of high seismic activity using templates from past earthquake sequences with the goal of detecting small magnitude earthquakes that are missed by the current operational pipelines.

Real-time Double Difference Relocation - scrtDD: To understand the spatio-temporal evolution of natural and induced seismicity, it is essential to have real-time, high-precision hypocenter locations, allowing to determine the geometry and extent of seismically active faults, as well as the volume affected by stimulation procedures.

[11] http://strongmotionportal.seismo.ethz.ch/home/ last accessed July 2023

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The spatio-temporal evolution of seismicity can also provide information about fluid-flow processes and hydraulic properties, including the existence of possible hydraulic connections (e.g., Diehl *et al.*, 2017). Although relative relocation procedures have been developed for decades (e.g., Console & Di Giovambattista, 1987; Waldhauser & Ellsworth, 2000), they are rarely applied in routine, real-time processing. To address this, the SED has developed the *scrtDD* software module, which performs real-time and near-real-time double-difference relocations following the procedures described in Waldhauser & Ellsworth (2000) and Waldhauser (2009) within the SeisComP architecture. The module combines differential times derived from automatic and manual picks as well as waveform cross-correlation with archived data from nearby past events (Scarabello *et al.*, 2020). The differential-time data are subsequently inverted to compute the single-event, relative location of a newly detected earthquake with respect to the double-difference background catalogue following the procedure of Waldhauser (2009). The module also includes the possibility to generate or update a double-difference background catalogue using the standard multi-event double-difference method of Waldhauser & Ellsworth (2000). To ensure that new events are continuously included in the background catalogue and that real-time relocations remain accurate in areas of sparse background seismicity, the SED has implemented both single-event and multi-event relocation procedures in their operational monitoring system since 2021. Currently, the SED is developing and testing concepts for more advanced visualisation and dissemination of SED's double-difference catalogues.

Other advanced methods which are currently being explored and evaluated at the SED, include

Noise interferometry: To monitor variations in mechanical and structural properties in the crust, the SED is applying seismic noise interferometry techniques, which involve reconstructing approximative Green's functions, typically referred to as cross-correlation functions, by correlating continuous ambient seismic noise records (e.g., Nakata *et al.*, 2019). From the cross-correlation functions, ballistic waves are used to image the subsurface (e.g., Obermann *et al.*, 2016; Molinari *et al.*, 2020) and coda waves are used for time-lapse imaging (e.g., Obermann *et al.*, 2013, 2014). Unlike earthquakes, seismic noise offers a constant source of signals that can be recorded anywhere on Earth. The spatial resolution of noise interferometry is primarily limited by the geometry and aperture of the seismic network, as well as the stability in noise excitation across frequency bands. While sparse, noisy stations often only allow the reconstruction of the fundamental-mode surface wave, quiet stations in dense arrays allow the reconstruction of body waves with a much-increased depth resolution. In addition to the monitoring of natural processes, coda wave-based noise interferometry has great potential for the time-lapse monitoring of local engineering applications, such as dams, hydraulic stimulations, or carbon storage. Changes in seismic velocity and waveform similarity at geothermal project sites may help in the future to detect unexpected reservoir dynamics earlier than the microseismic response alone (Obermann *et al.*, 2015; Hillers *et al.*, 2015; Toledo *et al.*, 2022; Sánchez-Pastor *et al.*, 2019). The SED is currently testing this method in Iceland in preparation for potential Carbon Capture and Storage sites in Switzerland.

Fiber-optic deformation sensing: During the past decade, fibre-optic sensing techniques, previously used mostly for perimeter security and infrastructure monitoring applications, have emerged as a new seismic recording paradigm. In particular, Distributed Acoustic Sensing (DAS) offers high spatial resolution at the metre scale, as well as a frequency bandwidth from mHz to kHz (e.g., Lindsey *et al.*, 2020; Paitz *et al.*, 2021). Complementing

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conventional seismometer recordings, DAS fills a niche in cases where kilometre-long fibre-optic cables can either be co-used or easily deployed. The former includes fibre-optic sensing in densely populated cities (Ajo-Franklin *et al.*, 2019, Spica *et al.*, 2020), under water (Spica *et al.*, 2022) or in avalanche-prone regions (Paitz *et al.*, 2023) with the help of telecommunication fibres. This enables urban subsurface imaging with a lateral resolution on the order of 10 m, and the detection of earthquakes and avalanches for monitoring and early warning purposes. On volcanoes, glaciers and ice sheets, fibre-optic cables for sensing applications can often be deployed with relative ease, thereby providing new opportunities for high-resolution studies of volcanic or glacial dynamics (Walter *et al.*, 2020; Klaasen *et al.*, 2021; Jousset *et al.*, 2022). More recent developments in integrated fibre-optic sensing overcome the limited interrogation distance of DAS, typically several tens of kilometres, at the expense of reduced spatial resolution (Marra *et al.*, 2018; Bogris *et al.*, 2022). Applications of integrated sensing for seismic imaging and earthquake characterization, especially in the oceans, are promising but still in their infancy.

Machine learning: Over the last couple of years, machine learning and deep learning techniques have started to rapidly transform earthquake seismology (e.g., Mousavi & Beroza, 2022). Automated seismic processing methods are nowadays capable of producing large data products of high quality that match or even exceed the reliability and fidelity of human processing experts. The SED is actively pursuing research in deep learning-based earthquake science, including event classification, seismicity monitoring methods, site-characterization, planetary seismology, and seismicity forecasts (e.g., Maranò *et al*., 2012; Hammer *et al*., 2013; Meier *et al.*, 2019; Dahmen *et al.*, 2022). This work involves implementing various machine learning models for seismic phase detection, arrival time estimation, signal/noise classification, phase association, first motion polarity classification, and others. The SED uses non-machine learning based methods as benchmarks to evaluate the effectiveness of the new approaches. For all monitoring tasks, the SED plans to compare established and available models against newly-trained models and models transfer-learned using Swiss data. A crucial aspect of these efforts will be the testing of the machine learning methods at various scales of seismicity monitoring, including underground laboratory experiments, geothermal reservoir scales, as well as national and regional monitoring scales.

3. Products and Services

3.1. Operational Earthquake (Loss) Forecasting (OEF & OELF)

Operational Earthquake Forecasting (OEF) and Operational Earthquake Loss Forecasting (OELF) are scientific approaches to forecasting the short-term probability of occurrence and the associated economic and societal impact of earthquakes. OEF utilises statistical analysis of historical earthquake data, seismic activity patterns, and geological features in a specific region to determine the probability of earthquakes above a certain magnitude occurring over a given period. OELF builds upon these OEF probabilities and assesses the potential loss of life, property, and infrastructure that could result.

Earthquake probabilities and the resulting short-term hazard and risk can vary by several orders of magnitude between quiet periods and clustered sequences, such as aftershocks sequences or swarms (van Stiphout *et al.*,

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2010). Unlike long-term earthquake forecasts, which inform long-term risk mitigation measures such as building codes, the operationally calculated short-term earthquake probabilities and the corresponding loss estimates generated by OEF and OELF, respectively, provide crucial information for crisis management in case of a major magnitude event. To complement the long-term earthquake forecasts that are part of SUIhaz2015, the SED is therefore working on an Epidemic-Type Aftershock Sequence (ETAS)-based earthquake forecasting model for Switzerland that describes the temporal fluctuations of earthquake probabilities. ETAS models (Ogata, 1988) are widely used for OEF by agencies worldwide (Marzocchi *et al.*, 2014; Harte, 2019; van der Elst *et al.*, 2022) and partition earthquakes into background seismicity and clusters of aftershocks. In the Swiss case, the background seismicity model is based on the SUIhaz2015 time-independent rate forecast, and clustered seismicity is modelled using ETAS parameters calibrated with the local SED earthquake catalogue. The SED is developing and testing multiple ETAS-based models for Switzerland (Mizrahi *et al.*, in prep.), ranging from simple models that only rely on a comprehensive earthquake catalogue as input to more complex models that consider variations in catalogue completeness and additional information from SUIhaz2015. To evaluate the performance of the models, pseudo-prospective forecasting experiments and retrospective consistency tests (Cattania *et al.*, 2018; Nandan *et al.*, 2021; Bayliss *et al.*, 2022) are being conducted.

Besides the scientific model to probabilistically describe future earthquake occurrence, the SED is also developing the IT infrastructure required to produce automated earthquake and loss forecasts for Switzerland in real-time (see example in **Figure 6**). Both systems are initially operated internally at the SED for evaluation and refinement and will at a later stage be made available to the general public and federal agencies in Switzerland. In particular, the OELF system will provide actionable information to individuals, public authorities, and other stakeholders, based on the updated earthquake rate forecast from the OEF system and ERM-CH23. Strategies for the effective communication of earthquake probabilities and uncertainties to the public are important and have been and continue to be extensively studied at the SED using surveys and discussions with focus groups and stakeholders at the federal and cantonal levels (Section 4.2).

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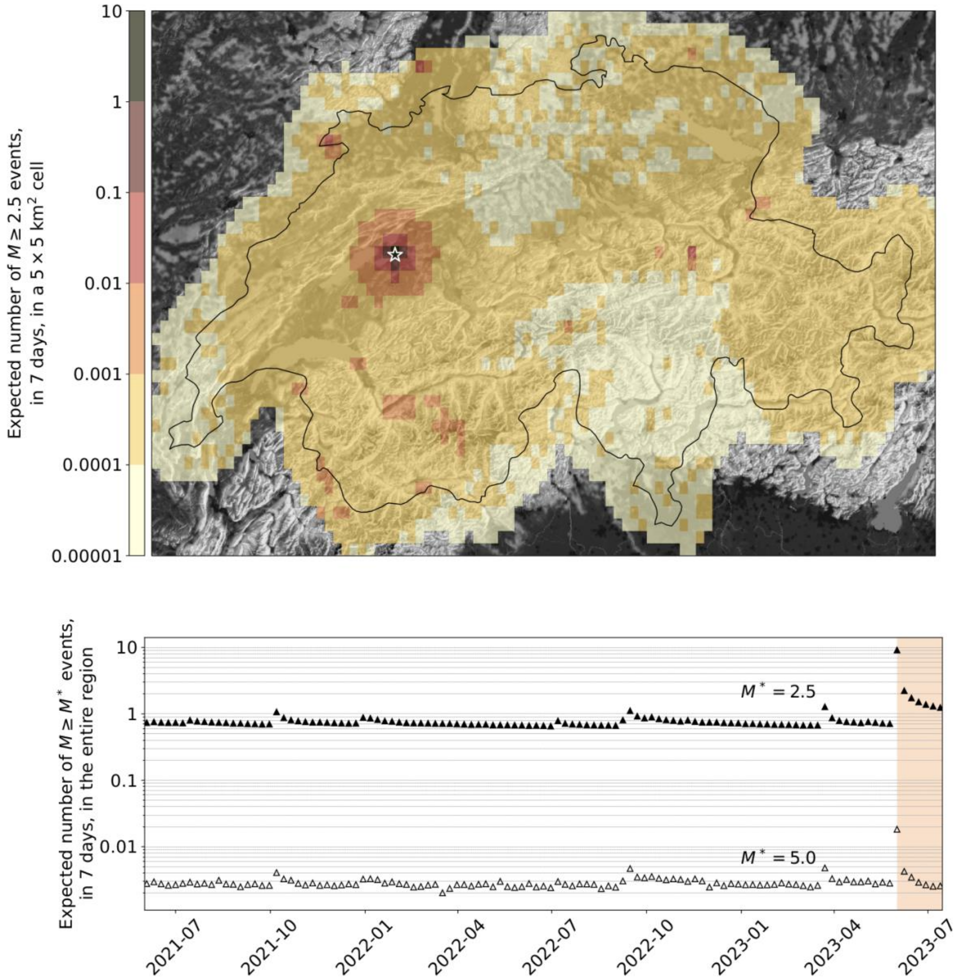

Figure 6: Time-dependent earthquake forecast for Switzerland after a hypothetical Mw 6.0 earthquake near Bern, Switzerland, at midnight on June 1, 2023 (white star in top panel). Top: Spatial distribution of the expected number of felt earthquakes (ML ≥ 2.5) in the first 7 days following the event, per 0.05°x0.05° grid cell (roughly 5x5 km²). Bottom: Temporal evolution of 7-day forecasts for the entire region shown in the top panel. The filled and empty triangles represent the expected number of ML ≥ 2.5 and ML ≥ 5.0 earthquakes, respectively. The shaded background marks the time interval after the occurrence of the Mw 6.0 event.

3.2 Earthquake Early Warning (EEW)

Earthquake early warning (EEW) systems are designed to rapidly detect earthquakes and provide people and automated systems with time to prepare and take protective action before strong shaking arrives (e.g., Allen *et al.*, 2009; Cremen & Galasso, 2020). Although the EEW provided alert times are short (depending on the distance between the earthquake and the location to be warned), they are considered sufficient to allow taking cover, stopping trains or elevators, shutting down industrial processes, or triggering automated shutdown systems. EEW is considered an important tool for earthquake risk reduction and disaster management, as it may help to reduce the number of casualties and damage to infrastructure and buildings during an earthquake, as well as to minimise social and economic disruption (e.g., Papadopoulos *et al.*, 2023).

For around one decade, the SED has been developing open-source software and methods for EEW using a set of SeisComP modules (such as *scenvelope*, *scvsmag*, and *scfinder*), known as the ETHZ-SED SeisComP EEW (ESE) system (Massin *et al.*, 2021). The core of ESE is formed by the Virtual Seismologist (VS; Cua, 2005) and Finite-Fault Rupture Detector (FinDer; Böse *et al.*, 2012) algorithms. VS provides fast EEW magnitudes using existing SeisComP detection and location modules, while FinDer identifies fault rupture extent by matching growing patterns of observed high-frequency seismic acceleration amplitudes with modelled templates. The SED is currently developing a new SeisComP module to compare the observed and predicted ground-motion envelopes with the goal to select origins and magnitudes from the independent VS and FinDer source parameter estimates, while suppressing false alerts (Jozinović *et al.*, subm.).

In Switzerland, VS and FinDer are not yet used for public alerting, but rather for testing and demonstration of EEW. VS uses phase picks to provide fast locations and magnitudes for any event detected by the Swiss Seismic Network, while FinDer is typically activated only for earthquakes with magnitudes greater than 3.5. The median delay for the first VS (since 2014) and FinDer (since 2017) alert is 8.7 and 7 seconds, respectively, but earthquakes are frequently detected in as little as 4 to 6 seconds when they occur in areas with a high station density (see example in **Figure 7**). Typically, it takes 3.5 seconds for the P-waves to propagate from the hypocenter to the fourth closest station in the Swiss Seismic Network. The SED continues to optimise the Swiss Seismic Network for EEW, although the benefit from further station densification appears limited (Böse *et al.*, 2022). Despite the rare occurrence of large earthquakes in Switzerland, a recent public survey shows that 70% of the Swiss population would like rapid notifications for all earthquakes that are felt, even if they have a low damage potential (Dallo *et al.*, 2022a). Future mass notifications for EEW in Switzerland could be enabled either through the Swiss multi-hazard *Alertswiss* and *MeteoSwiss* platforms, which can receive and display push notifications on mobile devices, or through cell broadcast once available.

3.3 Swiss ShakeMaps

Ground-motion maps provide critical information on the severity and distribution of ground shaking generated by an earthquake. The SED has been utilising the ShakeMap® application (Worden *et al.*, 2020) in Switzerland for approximately 15 years and is a core founder and contributor to the European ShakeMap initiative that promotes international collaboration and harmonisation of ShakeMap procedures in the greater European region (Cauzzi *et al.*, 2018b). ShakeMap rapidly maps seismic shaking information based on recorded and predicted intensity measures, such as peak ground acceleration (PGA) and peak ground velocity (PGV), 5%-damped pseudo-acceleration spectral ordinates (PSA), and macroseismic intensity levels, including amplification due to local site effects.

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The SED ShakeMap framework is updated regularly and employs ground-motion models specific to Switzerland, ground-motion-to-intensity conversion equations, and site amplification models (which are the same as those used in ERM-CH23; Section 1.1) that allow for accurate and reliable ground shaking estimates across the Swiss alpine and northern foreland regions (Cauzzi *et al.*, 2015). The SED maintains an archive of instrumental ShakeMaps for events with a magnitude larger than 2.5 that occurred since 1991 and an atlas of large historical ShakeMaps (see example in **Figure 7**). There are plans to include rapid finite-fault information in the SED ShakeMaps in the near future (Böse *et al.*, 2012).

ShakeMaps are an important tool for earthquake response and recovery efforts. At the SED, ShakeMaps serve multiple purposes. They are used (i) to inform the Swiss public about the severity of ground shaking and affected areas; (ii) to estimate the likelihood of earthquake-triggered mass movements for significant events, following a set of geospatial susceptibility proxies and peak ground acceleration (Cauzzi *et al.*, 2018); and (iii) to rapidly assess the potential damage caused by ground shaking as part of the SED RIA system (Section 3.4).

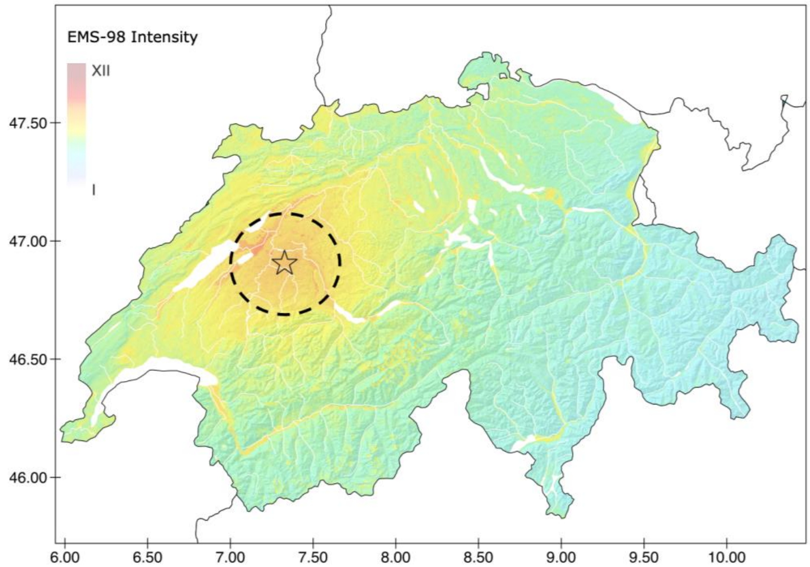

Figure 7: Swiss ShakeMap for a hypothetical Mw 6.0 earthquake near Bern. Dashed circle shows the 30-km-large no-alert-zone centred on the epicentre where EEW could probably not be provided before strong shaking initiates.

3.4 Rapid Impact Assessment (RIA)

Rapid Impact Assessment (RIA) involves the gathering and analysis of information to quickly assess the damage and impact of an earthquake (or other) disaster. RIA systems shall provide decision-makers with timely and accurate information to guide their response and recovery efforts. The RIA processing chain involves (i) the assessment of the extent and severity of the damage; (ii) the evaluation of the needs of the affected population; and (iii) the identification of priority areas for response. RIA efforts in Switzerland currently focus on the first step.

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The SED RIA system uses OpenQuake's scenario calculator (Pagani *et al.*, 2014) and Swiss ShakeMaps (Section 3.3). Once an earthquake's location and magnitude are determined, a ShakeMap is created and the RIA calculator activated. Monte Carlo simulations are then used to generate multiple ground-motion field realisations at the location of the building assets in the ERM-CH23 exposure model. Damage and loss estimates are derived using the vulnerability functions associated with each asset and the simulated ground-motion values. The SED RIA system estimates various types of losses (damage, economic loss, injuries, deaths, and shelter needs) at the national, cantonal, and municipal levels. These estimates are compiled in a standard format (Section 4.2), which includes a map of ground shaking and visualisations of losses - along with associated uncertainties - at different scales. In the future, the SED RIA system will become fully integrated and synchronised with the Swiss Seismic Network operations and perform near-real-time calculations for every earthquake with magnitude M > 3.0 within a specified radius around Switzerland. For now, the RIA results (see example in **Figure 8**) are shared internally at the SED for verification, but will soon be made available to the public.

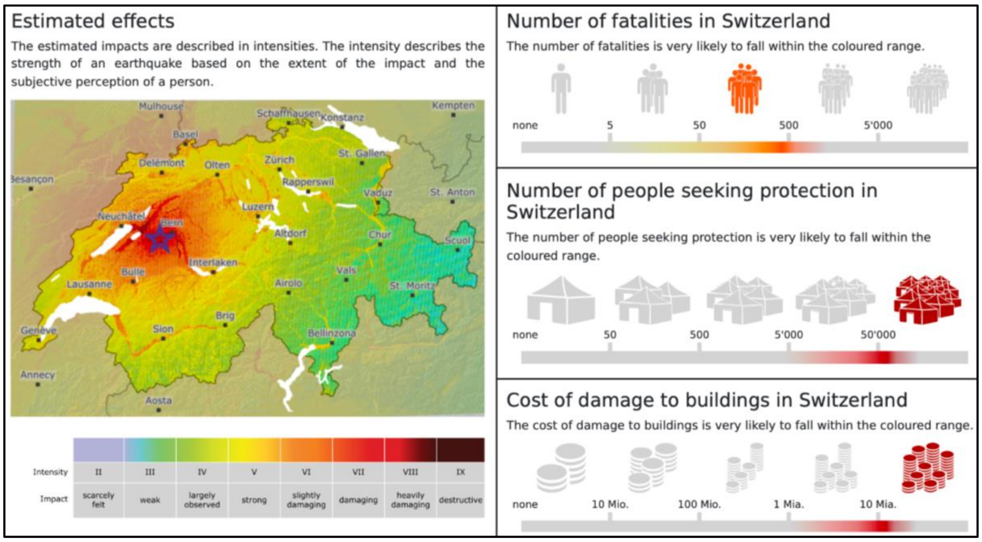

Figure 8: Exemplary Rapid Impact Assessment (RIA; @Swiss Seismological Service) output (here national level estimate) for a hypothetical Mw 6.0 earthquake near Bern. See http://www.seismo.ethz.ch/static/ERM-CH23/scenario/Bern_M6_0_en.pdf for full report.

3.5 Seismic Hazard Web Platform and Services

Among other dynamic and operational earthquake-related services, the SED is actively involved in the development, maintenance, and hosting of a web platform that grants access to a wide range of earthquake hazard datasets, input models, results, documentation, and information at both the national and regional levels. This web platform, accessible at http://hazard.efehr.org, is an integral part of the European Facilities of the Earthquake Hazard and Risk (EFEHR) network of federated services. Moreover, the earthquake-related hazard data, products,

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and services are designed to be interoperable with the newly developed EPOS ICS-C platform (Haslinger *et al.*, 2022).

The hazard platform comprises three individual web applications that enable users to interactively explore and retrieve hazard curves, hazard spectra, and hazard maps. Through a user-friendly interface, users can access hazard data and related metadata. The platform streamlines the retrieval of hazard maps, which can be disseminated to users through multiple avenues, including customised services offering ASCII data, file downloads featuring compressed ESRI shapefiles, and adherence to the OGC standards, which facilitate the distribution of projected map images.

The EFEHR web portal serves as a gateway to various seismic hazard models, including the 1999 Global Hazard Map of the Global Seismic Hazard Assessment Program (GSHAP, Giardini, 1999), the 2013 European Seismic Hazard Model (ESHM13, Woessner *et al.*, 2015), the 2014 Earthquake Model of the Middle East (EMME14, Giardini, 2017), the 2015 Swiss Hazard Model (SUIhaz15; Wiemer *et al.*, 2016), and the 2020 European Seismic Hazard Model (ESHM20; Danciu *et al.*, 2021). Furthermore, this platform will be the principal repository for results and datasets related to the ERM-CH23 (Wiemer *et al.*, 2023).

3.6 Structural Health Monitoring (SHM)

Due to slow retrofit and replacement rates of existing buildings, slow uptake of modern earthquake resistance standards, and the intensity of extreme events, earthquakes pose a significant threat to the built environment. Post-earthquake inspections are necessary to assess the damage to buildings and ensure safe shelter for the population. Current expert-conducted visual inspections suffer from possible subjectivity and delay recovery. However, recent advances in sensor development offer reliable and cost-effective sensing hardware, making broad monitoring of multiple conventional buildings realistic. Structural Health Monitoring (SHM) provides tools to analyse these sensor data and to translate vibration data into meaningful information about the structural state of a building. Damage-sensitive features (DSFs) can be extracted from continuous measurements and contribute to the detection and localization of earthquake-induced damage (e.g., Reuland *et al.*, 2023a).

Several approaches to overcome the scarcity of real-world dynamic monitoring data of both healthy and damaged structures have been developed at the Chair of Structural Mechanics and Monitoring, ETH Zurich: (i) SHM-based fragility functions relate probabilities of a structure to reach a given damage state to DSFs and can provide near-real-time damage tags (Reuland *et al.*, 2021; Reuland *et al.*, 2023b); (ii) a machine-learning methodology relying on domain adaptation has been successfully used to transfer a damage-state classification from simulated training data to real measurements from experimentation (Martakis *et al.*, 2023); and (iii) a framework for automated detection of faulty sensors has also been developed to ensure that sensors are functional and record valuable data during earthquakes (Martakis *et al.*, 2022a). Furthermore, monitoring data from buildings can contribute to earthquake preparedness by reducing uncertainty and regional variability of capacity curves used to derive fragility functions (Martakis *et al.*, 2022b). After successful testing on individual buildings, SHM-based rapid loss

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assessment has been recently integrated into a regional demonstrator (Nievas *et al.*, 2023). Integrating monitoring data and engineering models into a robust framework will pave the way to make SHM-based real-time building tagging operational in Switzerland and elsewhere.

3.7 Recovery and Rebuilding Efforts (RRE)

Recovery and Rebuilding Efforts (RRE) refer to the process of restoring a community or region to its pre-disaster condition after a natural or man-made disaster. The recovery phase begins immediately after the event and focuses on providing immediate assistance to affected people, restoring critical infrastructure such as power, water, and transportation systems, and providing temporary housing for those displaced by the disaster. The rebuilding phase involves longer-term efforts to repair or replace damaged infrastructure, such as roads, bridges, and buildings, and to help affected individuals and communities recover from the economic and social impact of the disaster.

Resilient communities have the ability to quickly recover from extreme events, and retrofitting measures can help decrease the risk of earthquakes and reduce repair efforts. Still, RRE is crucial to restoring community functions and minimising negative social and economic impacts. Recovery models and resilience assessment tools can simulate recovery trajectories and guide decision-makers towards effective actions. The iRe-CoDeS (interdependent Resilience Compositional Demand and Supply) framework developed at ETH Zurich (Blagojević *et al.*, 2022), offers the capacity to perform such analyses and has been integrated with OpenQuake software for regional hazard and risk assessment.

Early loss assessment is often incomplete and imprecise, which hinders response efforts. To improve decision-making, a dynamic update of regional post-earthquake damage estimates is proposed in iRe-CoDeS. Gaussian Process inference models are used to fuse early inspection data with a pre-existing earthquake risk model (such as ERM-CH23; Bodenmann *et al.*, 2023), reducing uncertainty and improving regional building damage estimates. By combining regional recovery and resilience assessment tools with this framework, uncertainty in recovery trajectories can be reduced, and real-time what-if analyses can inform decision-makers on the state of the community during recovery and optimal resource deployment. The iRe-CoDeS model can be updated with early inspection information after an earthquake, providing recommendations for recovery efforts and remaining recovery time.

4. Operation and Communication

4.1. Operation

Providing operational services demands a high level of service availability. To achieve this, the SED provides appropriate hardware solutions, invests in professional software engineering, and provides for 24/7 IT on-call duty backup. The seismic processing data centre at the SED is the operational service with the longest history and

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most mature setup, and provides the template for new services as they are added to the operational ecosystem. High availability services are achieved by operating two identical software versions on fully redundant and physically separated hardware, a primary and backup system. If any issues arise on the primary system, the backup system can immediately become primary. A third server is also supported for development and prototyping. Databases are also fully replicated and backed-up, and when database information is provided to the public, it is accessed only via replicated databases to remove the possibility of external loads compromising the operational systems.

To react to operational and seismic crises, the SED operates three 24/7 on-call teams, dedicated to technical IT-related issues, immediate review of all seismic events with M>2.5, and for handling inquiries from authorities, media and the public for Swiss and international events. To provide internal and external seismic alerts, an in-house developed alarm system enables the duty seismologists to take prompt action when an earthquake occurs. The seismic alerts are automatically activated when an earthquake above a specific magnitude is detected within or in proximity of Switzerland. Web portals enable the public distribution of products generated by these operational services via direct access or APIs.

The SED conforms to international community standards in data formats, metadata and dissemination services where possible (such as FDSN mseed, stationXML and web services), and indeed is at the cutting edge in developing now standards, for example the SED curates the quakeML (Schorlemmer *et al.*, 2011) data model, ensuring that earthquake information is easily accessible and shareable. The integration of harmonised data and processes is at the heart of effective dynamic earthquake risk management and mitigation strategies.

4.2 Communication and Societal Perspective

As a federal agency, the SED is responsible for informing the public, authorities, and media about earthquakes in Switzerland, and providing warnings when needed. For this purpose, the SED monitors ground shaking 24/7 in Switzerland and neighbouring countries (Section 2.1). Details (including time, location, magnitude, and possible impacts) of a detected earthquake are published on the SED webpage within 90 seconds. Federal and cantonal authorities are informed automatically if the magnitude is 2.5 or larger. A team of on-call duty seismologists assesses every recorded earthquake and takes further actions if needed, and is available for media requests. The SED also engages in science communication during quiet times to transfer knowledge about earthquakes and related topics. To ensure effective communication, the SED interacts with societal stakeholders and co-develops and evaluates various information products, including those presented in this article. The SED also contributes to the training of future earthquake experts through teaching efforts at ETH Zurich and beyond.

Recently, the SED has been shifting from hazard to risk communication, which should increase societies' preparedness and disaster resilience. To ensure effectiveness, it is important that communication products are designed by an interdisciplinary expert group and then tested with the relevant end-users before releasing them

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publicly. In preparation of the ERM-CH23 release in March 2023, the SED has tested various output formats for risk products with professional stakeholders of the society and the general public:

- Marti *et al.* (2023) showed that people and professionals consider RIA reports and risk scenarios to be very important, although they appeared similarly challenged to correctly interpret the information provided. To represent the uncertainties of the model estimates, the simplest visualisation using ranges was the most understandable and the most popular (see **Figure 8**).

- Regarding EEW systems, a public survey conducted by the SED in Switzerland (Dallo *et al.*, 2022a), revealed that the Swiss public wants to receive EEW alerts for all felt events (even if they are not damaging) and their preferences align with those in other countries. EEW alerts with pictograms have the strongest effect in motivating people to take action, even if that is not necessarily what they like best.

- The SED has collaborated with the Winton Center at the University of Cambridge to test OEF communications with the general public in Italy, Switzerland, and California in the US. A survey of Dryhurst *et al.* (2022) found that people in all three countries provided similar answers. Maps representing OEF probabilities as different coloured isoline compartments could mislead the public. The best information combination for OEF communication is a geographical map showing the forecast area, textual information about the current absolute chance of an earthquake, and a risk ladder to provide context.

- Dallo *et al.* (2022b) conducted three online surveys with various experiments and virtual focus groups to improve communication of earthquake information on multi-hazard platforms, such as *MeteoSwiss* and *Alertswiss* (Section 3.2). The results indicated that people prefer a combination of visual and textual information, pictorial and textual behavioural recommendations, interactive features, consideration of data privacy issues, messages with time indication and action-keywords, as well as clearly distinguishable icons of the epicentre and the person’s location (Valenzuela Rodríguez, 2021).

When designing information campaigns, it is important to consider people’s personal factors, which can influence their interpretation of the information provided, their design preferences, and their perceived usefulness. To achieve successful campaigns, key factors to consider include regular communication, context, channel choice, risk communicator training, and community-based approaches (Marti *et al.*, 2020). A significant challenge is to provide personalised notifications to end-users while still addressing their concerns about data privacy.

5. Conclusions and Outlook

The SED is developing and implementing a harmonised and dynamic risk framework that centres around the users’ needs and considers earthquake hazard and risk as a constantly evolving, integrated concept. Significant advancements in seismic observation in Switzerland were made over the past decade, including the

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implementation of denser seismic networks and advanced data processing. They pave the path to enhance tools for earthquake forecasting, early warning, and rapid impact assessment and to harmonise them such that they are consistent, understandable and synergetic. We believe that by profiting from advances in scientific understanding and the dramatically changing technological capabilities, earthquake hazard and risk should be appreciated not as a constant in time, but as an evolving, integrated and dynamic risk (**Figure 1**).

According to our concept, the dynamic risk that a structure is exposed to depends on its structural type, location, occupancy, soil conditions, and topography, while people's risk is affected by their exact location within a structure. However, dynamic risk also includes changes with time; for example, risk increases with rapid urbanisation and building stock changes or when a seismic sequence is active nearby, and can be observed by improved dynamic geophysical understanding of faulting and earthquake processes. EEW in the concept of dynamic risk is a sudden and short-term change in this risk environment (seconds to minutes); i.e. the time between rupture initiation and the arrival of damaging waves. RIA is likewise a defined state in dynamic risk: some buildings may be damaged by the preceding events thus changing their vulnerability in an environment of evolving seismic hazard because of an ongoing seismic sequence. Exposure of people has greatly changed, and the chance of another damaging earthquake is orders of magnitude higher than during a 'normal' day.

As data, models, and computing resources increase, dynamic and operational earthquake-related services will become increasingly available and important in assessing and mitigating earthquake risks. As described in previous sections, the SED provides key operational services, such as earthquake monitoring, ShakeMaps, EEW, OEF, RIA, and computational infrastructure. The seismic network and ShakeMap system are the most mature of these services, followed by EEW and RIA. The OEF service is currently in a demonstrator phase (**Table 1**).

Table 1: Status of earthquake risk-related products and services in Switzerland (as of July 2023).

Product/Service	Type	Status
Earthquake Hazard Model	product	available (SUIhaz2015)
Earthquake Risk Model	product	released (ERM-CH23)
Seismic Network	operational service	mature
Routine Seismic Data Processing	operational service	mature
ShakeMaps	operational service	mature (upgraded during RISE)
Earthquake Hazard Web-Services	operational service	mature
OE(L)F	demonstrator service	beta
EEW	demonstrator service	beta
RIA	demonstrator service	beta - operational

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SHM	demonstrator service	beta
RRE	demonstrator software	available

Earthquake hazard and risk models are important for reducing the impact of earthquakes and increasing society's resilience to disasters. The National Earthquake Risk Model of Switzerland (ERM-CH23, Wiemer *et al.*, 2023), publicly released in March 2023, is expected to increase public awareness of earthquake risk and assist authorities in updating their risk assessments and implementing mitigation measures. Further, it shall serve as a resource for the insurance and reinsurance industry as well as the scientific community. Additionally, the ERM-CH23 serves as the basis for other tools and systems being developed by the SED, such as RIA and OELF, which provide near-real-time results and vital information after earthquakes.

To harmonise risk products and workflows, the SED is focusing on user needs and interoperability of the products and services. The SED RIA system for Switzerland, for example, utilises the same ShakeMap provided in near-real-time (Section 3.3), uses the same site amplification layers derived for the national risk models (Section 1.1), and computes impact on people and buildings based on national databases of buildings and their vulnerability (Section 3.4).

The SED is further advancing its seismic observational capabilities and risk products, including double-difference earthquake catalogues, extending 3D crustal velocity models, enhancing magnitude determination, and exploring new visualisation and distribution methods (Sections 2.1 & 2.2). They aim to offer short-term earthquake probabilities and related seismic hazard and loss, provide rapid earthquake information and EEW to the Swiss public, as well as integrate the RIA system into seismic network operations for near-real-time calculations for earthquakes in and around Switzerland above magnitude 3.0.

The SED has a well-established communication network to provide rapid earthquake information over multiple channels to the public (Section 4.2). Research is ongoing to determine how best to communicate earthquake forecasts and support translation from probabilities into actions.

The SED has been investigating the use of a cost-benefit framework to evaluate earthquake dynamic risk products such as OE(L)F, EEW, RLA, SHM, and RRE. While traditional Cost-Benefit Analysis (CBA) is effective for evaluating EEW systems (e.g., Papadopoulos *et al.*, 2023) or OE(L)F based alerting systems (van Stiphout *et al.*, 2010; Hermann *et al.*, 2016), alternative methods such as Multi-Criteria Decision Analysis (MCDA) have proven useful for decision-making when non-economic factors are significant (e.g., Guarini *et al.*, 2018). The flexibility and transparency of MCDA allow for the consideration of a broader range of criteria beyond economic costs and benefits, including model bias, model uncertainty, time gain in emergency response, information gain etc., therefore providing a valuable tool for assessing the cost-effectiveness of various dynamic risk products. Ongoing research aims to evaluate the broader benefits of these dynamic risk products for earthquake risk reduction, incorporating surveys and expert opinions to facilitate a dialogue with decision-makers and the public.

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In a dynamic risk approach, the seismic activity is continually monitored by a regional seismic network, such as operated by the SED, and risk assessments are adjusted in real-time based on the latest data. Compared to a static risk approach which assumes a constant level of earthquake risk, the dynamic concept allows for more accurate and timely identification of potential seismic hazards and risks. A dynamic risk approach is thus superior for a seismic network because it provides a more accurate and up-to-date assessment of seismic risk, allowing for more effective mitigation measures and improved safety outcomes.

In the dynamic risk framework (**Figure 3**) risk is assessed in a consistent and harmonised way for the next few seconds or for the next five decades. This offers great potential for synergies, to achieve meaningful comparative risk-cost-benefit analyses underpinned by a sustainable and quantitative framework that improves with time when individual components improve. For example, in the near future, simulation-based approaches or so-called digital twin components may replace certain elements of the framework, for example, physics-based ground motion modelling. Adopting this conceptual framework of dynamic risk intrinsically implies a holistic and interdisciplinary approach to earthquake risk assessment, risk reduction and resilience. It can also be extended in a straightforward way to a multi-risk framework, providing significant added value to a range of challenges in risk reduction.

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Author contributions

We use the CRediT Contributor Roles Taxonomy to categorise author contributions. **Methodology & Investigation:** *Hazard and Risk:* LD, AP, PR, SW, PB, DF, FH, BMC, DG. *Seismic Monitoring (network & processing):* JC, TD, CC, FM, FH, DF, AF, MB, FG, LH, PJ, DJ, FL, TL, M-AM, AO, MS, LS, AS, SW, PK. *OE(L)F:* LM, SW, MH, LD, AP, PR. *EEW:* MB, FM, JC, DJ, CC. *ShakeMaps:* CC, JC, MB, PB, DF. *RIA:* LD, AP, PR, NS, SW. *SHM:* YR, EC, LB, PM, BS, NB. *RRE:* YR, EC, LB, PM, BS, NB. Communication: ID, MM, NV, LD, AP, PR. **Writing – original draft:** MB. **Writing – review & editing:** all. **Project investigators and Funding**: DG, SW.

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References

Ajo-Franklin, J., Dou, S., Lindsey, N., Monga, I., Tracy, C., Robertson, M., Rodriguez Tribaldos, V., Ulrich, C., Freifeld, B., Daley, T., and Li, X.: Distributed acoustic sensing using dark fiber for near-surface characterisation and broadband seismic event detection, Sci. Rep, 9, https://doi.org/10.1038/s41598-018-36675-8, 2019.

Al Atik, L., Abrahamson, N., Bommer, J. J., Scherbaum, F., Cotton, F., and Kuehn, N.: The Variability of Ground-Motion Prediction Models and Its Components, Seismological Research Letters, 81, 794–801, https://doi.org/10.1785/gssrl.81.5.794, 2010.

Allen, R. M., Gasparini, P., Kamigaichi, O., and Böse, M.: The status of earthquake early warning around the world: an introductory overview, Seism. Res. Lett, 80, 682-693, https://doi.org/10.1785/gssrl.80.5.682, 2009.

Armbruster, D., Mesimeri, M., Kaestli, P., Diehl, T., Massin, F., and Wiemer, S.: SCDetect: Near Real-Time Computationally Efficient Waveform Cross-Correlation Based Earthquake Detection during Intense Earthquake Sequences, EGU GA, https://doi.org/10.5194/egusphere-egu22-12443, 2022.

Bayliss, K., Naylor, M., Kamranzad, F., and Main, I.: Pseudo-prospective testing of 5-year earthquake forecasts for California using inlabru, Natural Hazards and Earth System Sciences, 22 (10), 3231–3246, 2022.

Bear, M. and Kradolfer, U.: An automatic phase picker for local and teleseismic events, Bull. Seismol Soc Am, 77, 1437–1445, 1987.

Bergamo, P., Hammer, C., and Fäh, D.: Correspondence between Site Amplification and Topographical, Geological Parameters: Collation of Data from Swiss and Japanese Stations, and Neural Networks-Based Prediction of Local Response, Bulletin of the Seismological Society of America, 112(2), 1008–1030, 2021.

Bergamo, P. et al: A site amplification model for Switzerland based on site-condition indicators and incorporating local response as measured at seismic stations, Submitted to Bulletin of Earthquake Engineering, 2023.

Blagojević, N., Hefti, F., Henken, J., Didier, M., and Stojadinović, B.: Quantifying disaster resilience of a community with interdependent civil infrastructure systems, Structure and Infrastructure Engineering, 0(0), 1–15, https://doi.org/10.1080/15732479.2022.2052912, 2022.

Bodenmann, L., Reuland, Y., and Stojadinović, B.: Dynamic post-earthquake updating of regional damage estimates using Gaussian processes, Reliability Engineering & System Safety, 234, 109201, https://doi.org/10.1016/j.ress.2023.109201, 2023.

Bogris, A., Nikas, T., Simos, C., Simos, I., Lentas, K., Melis, N. S., Fichtner, A., Bowden, D., Smolinski, K., Mesaritakis, C., and Chochliournos, I.: Sensitive seismic sensors based on microwave frequency fiber interferometry in commercially deployed cables, Sci. Rep, 12, https://doi.org/10.1038/s41598-022-18130-x, 2022.

Böse, M., Heaton, T. H., and Hauksson, E.: Real-time Finite Fault Rupture Detector (FinDer) for large earthquakes, Geophysical Journal International, 191, 803-812, https://doi.org/10.1111/j.1365-246X.2012.05657.x, 2012.

Böse, M., Papadopoulos, A. N., Danciu, L., Clinton, J. F., and Wiemer, S.: Loss-Based Performance Assessment and Seismic Network Optimization for Earthquake Early Warning, Bulletin of the Seismological Society of America, 112, 1662–1677, https://doi.org/10.1785/0120210298, 2022.

Burjánek, J., Gischig, V., Moore, J. R., and Fäh, D.: Ambient vibration characterization and monitoring of a rock slope close to collapse, Geophysical Journal International, 212(1), 297–310, 2018.

Cattania, C., Werner, M. J., Marzocchi, W., Hainzl, S., Rhoades, D., Gerstenberger, M., Liukis, M., Savran, W., Christophersen, A., and Helmstetter, A.: The forecasting skill of physics-based seismicity models during the 2010–2012 Canterbury, New Zealand, earthquake sequence, Seismological Research Letters, 89(4), 1238–1250, 2018.

Cauzzi, C. and Clinton, J.: A High- and Low-Noise Model for High-Quality Strong-Motion Accelerometer Stations, Earthquake Spectra, 29(1), 85–102, https://doi.org/10.1193/1.4000107, 2013.

Cauzzi, C., Edwards, B., Fäh, D., Clinton, J., Wiemer, S., Kästli, P., Cua, G., and Giardini, D.: New predictive equations and site amplification estimates for the next-generation Swiss ShakeMaps, Geophysical Journal International, 200(1), 421-438, https://doi.org/10.1093/gji/ggu404, 2015.

Cauzzi, C., Behr, Y., Le Guenan, T., Douglas, J., Auclair, S., Woessner, J., Clinton, J., and Wiemer, S.: Earthquake early warning and operational earthquake forecasting as real-time hazard information to mitigate seismic

https://doi.org/10.5194/egusphere-2023-1863
Preprint. Discussion started: 22 August 2023

risk at nuclear facilities, Bulletin of Earthquake Engineering, 14, 2495–2512, https://doi.org/10.1007/s10518-016-9864-0, 2016a.

Cauzzi, C., Sleeman, R., Clinton, J., Ballesta, J. D., Galanis, O., and Kästli, P.: Introducing the European Rapid Raw Strong-Motion Database, Seismological Research Letters, 87, 977–986, https://doi.org/10.1785/0220150271, 2016b.

Cauzzi, C., Clinton, J., Faenza, L., Heimers, S., Koymans, M. R., Lauciani, V., Luzi, L., Michelini, A., Puglia, R., and Russo, E.: Introducing a European integrated ShakeMap system, Seismol. Res. Lett., 2018a.

Cauzzi, C., Fäh, D., Wald, D. J., Clinton, J., Losey, S., and Wiemer, S.: ShakeMap-based prediction of earthquake-induced mass movements in Switzerland calibrated on historical observations, Natural Hazards, 92(2), 1211–1235, https://doi.org/10.1007/s11069-018-3248-5, 2018b.

Cauzzi, C. V., Clinton, J., Kaestli, P., Fäh, D., Bergamo, P., Böse, M., Haslinger, F., and Wiemer, S.: Swiss Shakemap at Fifteen: Distinctive Local Features and International Outreach, in: Seismological Society of America Annual Meeting (SSA 2022), 2022.

Chiaraluce, L., Festa, G., Bernard, P., Caracausi, A., Carluccio, I., Clinton, J., Stefano, R., Elia, L., Evangelidis, C., Ergintav, S., Jianu, O., Kaviris, G., Marmureanu, A., Sebela, S., and Sokos, E.: The Near Fault Observatory community in Europe: a new resource for faulting and hazard studies, Ann. Geophys, 65, 2022.

Console, R., and Di Giovambattista, R.: Local earthquake relative location by digital records. Physics of the Earth and Planetary Interiors, 47I, 43–49. https://doi.org/10.1016/0031-9201(87)90065-3, 1987.

Clinton, J., Cauzzi, C., Fäh, D., Michel, C., Zweifel, P., Olivieri, M., Cua, G., Haslinger, F., and Giardini, D.: The current state of strong motion monitoring in Switzerland, Earthquake Data in Engineering Seismology: Predictive Models, Data Management and Networks, 219–233, 2011.

Cremen, G. and Galasso, C.: Earthquake early warning: Recent advances and perspectives, Earth-Science Reviews, 205, 103184, https://doi.org/10.1016/j.earscirev.2020.103184, 2020.

Crowley, H., Dabbeek, J., Despotaki, V., Rodrigues, D., Martins, L., Silva, V., Romão, X., Pereira, N., Weatherill, G., and Danciu, L.: European seismic risk model (ESRM20), EFEHR Technical Report, 2, https://doi.org/10.3929/ethz-b-000590388, 2021.

Cua, G. B.: Creating the Virtual Seismologist: Developments in Ground Motion Characterization and Seismic Early Warning, Dissertation (Ph.D.), California Institute of Technology, https://doi.org/10.7907/M926-J956.https://resolver.caltech.edu/CaltechETD:etd-02092005-125601, 2005.

Dahmen, N. L., Clinton, J. F., Meier, M. A., Stähler, S. C., Ceylan, S., Kim, D., Stott, A. E., and Giardini, D.: MarsQuakeNet: A more complete marsquake catalog obtained by deep learning techniques, Journal of Geophysical Research: Planets, 127(11), p.e2022JE007503, 2022.

Dallo, I., Marti, M., Clinton, J., Böse, M., Massin, F., and Zaugg, S.: Earthquake early warning in countries where damaging earthquakes only occur every 50 to 150 years – The societal perspective, International Journal of Disaster Risk Reduction, 83, 103, https://doi.org/10.1016/j.ijdrr.2022.103441, 2022a.

Dallo, I., Stauffacher, M., and Marti, M.: Actionable and understandable? Evidence-based recommendations for the design of (multi-)hazard warning messages, International Journal of Disaster Risk Reduction, 74, 102917, https://doi.org/10.1016/j.ijdrr.2022.102917, 2022b.

Danciu, L., Nandan, S., Reyes, C., Basili, R., Weatherill, G., Beauval, C., Rovida, A., Vilanova, S., Sesetyan, K., Bard, P.-Y., Cotton, F., Wiemer, S., and Giardini, D.: The 2020 update of the European Seismic Hazard Model: Model Overview, https://doi.org/10.12686/a15, 2021.

Danciu, L., Weatherill, G., Rovida, A., Basili, R., Bard, P.-Y., Beauval, C., Nandan, S., Pagani, M., Crowley, H., and Sesetyan, K.: The 2020 European seismic hazard model: milestones and lessons learned, in: European Conference on Earthquake Engineering and Seismology, 3–25, 2022a.

Danciu, L. et al.: The 2020 European Seismic Hazard Model: Milestones and Lessons Learned, in: Progresses in European Earthquake Engineering and Seismology. ECEES 2022. Springer Proceedings in Earth and Environmental Sciences, Cham, https://doi.org/10.1007/978-3-031-15104-0_1, 2022b.

Diehl, T., Husen, S., Kissling, E., and Deichmann, N.: High-resolution 3-D P-wave model of the Alpine crust, Geophys. J. Int, 179(2), 1133-1147, https://doi.org/10.1111/j.1365-246X.2009.04331.x, 2009.

Diehl, T., Kraft, T., Kissling, E., and Wiemer, S.: The induced earthquake sequence related to the St. Gallen deep geothermal project (Switzerland): Fault reactivation and fluid interactions imaged by microseismicity.

https://doi.org/10.5194/egusphere-2023-1863
Preprint. Discussion started: 22 August 2023

Journal of Geophysical Research: Solid Earth, 122(9), 7272–7290. https://doi.org/10.1002/2017JB014473, 2017.

Diehl, T., Kissling, E., Herwegh, M., and Schmid, S.: Improving Absolute Hypocenter Accuracy with 3-D Pg and Sg Body-Wave Inversion Procedures and Application to Earthquakes in the Central Alps Region, J. Geophys. Res. Solid Earth, 1–26, https://doi.org/10.1029/2021jb022155, 2021a.

Diehl, T., Clinton, J., Cauzzi, C., Kraft, T., Kaestli, P., Deichmann, N., Massin, F., Grigoli, F., Molinari, I., and Böse, M.: Earthquakes in Switzerland and surrounding regions during 2017 and 2018, Swiss J. Geosci, 106(3), 543-558, https://doi.org/10.1007/s00015-013-0154-4, 2021b.

Diehl, T., Madritsch, H., Schnellmann, M., Spillmann, T., Brockmann, E., & Wiemer, S.: Seismotectonic evidence for present-day transtensional reactivation of the slowly deforming Hegau-Bodensee Graben in the northern foreland of the Central Alps, Tectonophysics, 846, 229659, 2023.

Dryhurst, S., Mulder, F., Dallo, I., Kerr, J. R., McBride, S. K., Fallou, L., and Becker, J. S.: Fighting misinformation in seismology: Expert opinion on earthquake facts vs. fiction, Frontiers in Earth Science, 10, https://www.frontiersin.org/articles/10.3389/feart.2022.937055, 2022.

Edwards, B., Allmann, B., Fäh, D., and Clinton, J.: Automatic computation of moment magnitudes for small earthquakes and the scaling of local to moment magnitude, Geophysical Journal International, 183(1), 407-420, https://doi.org/10.1111/j.1365-246X.2010.04743.x, 2010.

Edwards, B., Michel, C., Poggi, V., and Fäh, D.: Determination of Site Amplification from Regional Seismicity: Application to the Swiss National Seismic Networks, Seismological Research Letters, 84, 611–621, 2013.

Edwards, B., Kraft, T., Cauzzi, C., Kastli, P., and Wiemer, S.: Seismic monitoring and analysis of deep geothermal projects in St Gallen and Basel, Switzerland, Geophysical Journal International, 201, 1022-1039, https://doi.org/10.1093/gji/ggv059, 2015.

ETH Zurich, S. S. S.: National Seismic Networks of Switzerland; ETH Zürich, Other/Seismic Network, https://doi.org/10.12686/SED/NETWORKS/CH, 1983.

ETH Zurich, S. S. S.: The Site Characterization Database for Seismic Stations in Switzerland, https://doi.org/10.12686/sed-stationcharacterizationdb, 2015.

Faenza, L. and Michelini, A.: Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap, Geophys. J. Int, 180, 1138–1152, 2010.

Faenza, L. and Michelini, A.: Regression analysis of MCS intensity and ground motion spectral accelerations (SAs) in Italy, Geophys. J. Int, 186, 1415–1430, 2011.

Fäh, D., and Huggenberger, P.: INTERREG III Projekt: Erdbebenmikrozonierung am südlichen Oberrhein. Zusammenfassung, doi:10.3929/ethz-a-006412199, 2006.

Fäh, D., Giardini, D., Kästli, P., Deichmann, N., Gisler, M., Schwarz-Zanetti, G., Alvarez-Rubio, S., Sellami, S., Edwards, B., Allmann, B., Bethmann, F., Wössner, J., Gassner-Stamm, G., Fritsche, S., and Eberhard, D.: ECOS-09 Earthquake Catalogue of Switzerland Release 2011 Report and Database, Public catalogue, 17, 4, 2011.

Fäh, D., Moore, J. R., Burjanek, J., Iosifescu, I., Dalguer, L., Dupray, F., Michel, C., Woessner, J., Villiger, A., and Laue, J.: Coupled seismogenic geohazards in Alpine regions., Bollettino di geofisica teorica ed applicata, 53, 2012.

Fritsche, S., Fäh, D., and Schwarz-Zanetti, G.: Historical intensity VIII earthquakes along the Rhone valley (Valais, Switzerland): primary and secondary effects, Swiss Journal of Geosciences, 105, 1–18, 2012.

Giardini, D., Wiemer, S., Fäh, D., and Deichmann, N.: Seismic hazard assessment of Switzerland, 2004. Publication Series of the Swiss Seismological Service, ETH Zürich, 91 pages, 2004.

Giardini, D.: The global seismic hazard assessment program (GSHAP)—1992/1999, Ann Geophys, 42(6), 1999.

Giardini, D., Danciu, L., Erdik, M., Sesetyan, K., Demircioglu, M., Akkar, S., Gülen, L., and Zare, M.: Seismic Hazard Map of the Middle East, https://doi.org/10.12686/a1, 2017.

Glueer, F., Häusler, M., Gischig, V., and Fäh, D.: Coseismic Stability Assessment of a Damaged Underground Ammunition Storage Chamber Through Ambient Vibration Recordings and Numerical Modelling, Frontiers in Earth Science, 9, 773155, 2021.

Grigoli, F., Scarabello, L., Böse, M., Weber, B., Wiemer, S., Stefan, and Clinton, J. F.: Pick- and waveform-based techniques for real-time detection of induced seismicity, Geophysical Journal International, 213(2), 868-884, https://doi.org/10.1093/gji/ggy019, 2018.

Guarini, M. R., Battisti, F., and Chiovitti, A.: A Methodology for the Selection of Multi-Criteria Decision Analysis Methods in Real Estate and Land Management Processes, Sustainability, 10, 507, https://doi.org/10.3390/su10020507, 2018.

Hammer, C., Ohrnberger, M., and Fäh, D.: Classifying seismic waveforms from scratch: a case study in the alpine environment, Geophysical Journal International, https://doi.org/10.1093/gji/ggs036, 2013.

Harte, D. S.: Evaluation of earthquake stochastic models based on their real-time forecasts: a case study of Kaikoura 2016, Geophysical Journal International, 217(3), 1894–1914, 2019.

Haslinger, F., Basili, R., Bossu, R., Cauzzi, C., Cotton, F., Crowley, H., Custodio, S., Danciu, L., Locati, M., Michelini, A., Molinari, I., Ottemöller, L., and Parolai, S.: Coordinated and interoperable seismological data and product services in Europe: the EPOS thematic core service for seismology, Annals of Geophysics, 65(2), 213, https://doi.org/10.4401/ag-8767, 2022.

Häusler, M., Gischig, V., Thöny, R., Glueer, F., and Donat, F.: Monitoring the changing seismic site response of a fast-moving rockslide (Brienz/Brinzauls, Switzerland), Geophysical Journal International, 229, 299–310, 2022.

Hengl, T., Heuvelink, G. B. M., and Rossiter, D. G.: About regression-kriging: From equations to case studies, Computers & Geosciences, 33(10), 1301–1315, 2007.

Hermann, M., Zechar, J. D., and Wiemer, S.: Communicating time-varying seismic risk during an earthquake sequence, Seismological Research Letters, 87, 301–312, https://doi.org/10.1785/0220150168, 2016.

Hetényi, G., Molinari, I., Clinton, J., Bokelmann, G., Bondár, I., Crawford, W. C., Dessa, J.-X., Doubre, C., Friederich, W., and Fuchs, F.: The AlpArray seismic network: a large-scale European experiment to image the Alpine Orogen, Surveys in Geophysics, 39, 1009–1033, doi:10.1007/s10712-018-9472-4, 2018.

Hillers, G., Husen, S., Obermann, A., Planès, T., Larose, E., and Campillo, M.: Noise-based monitoring and imaging of aseismic transient deformation induced by the 2006 Basel reservoir stimulation, Geophysics, 80(4), KS51–KS68, 2015.

Hobiger, M., Bergamo, P., Imperatori, W., Panzera, F., Lontsi, A. M., Perron, V., C., M., J., B., and Fäh, D.: Site Characterization of Swiss Strong-Motion Stations: The Benefit of Advanced Processing Algorithms, Bulletin of the Seismological Society of America, 111(4), 1713–1739, 2021.

Husen, S., Kissling, E., Deichmann, N., Wiemer, S., Giardini, D., and Baer, M.: Probabilistic earthquake location in complex three-dimensional velocity models: Application to Switzerland, Journal of Geophysical Research-Solid Earth, 108(B2), 2003.

Janusz, P., Bonilla, L. F., and Fäh, D.: URBASIS Deliverable: A case study on non-linear soil response in urban areas, https://doi.org/10.3929/ethz-b-000575536, 2022.

Jousset, P., Currenti, G., Schwarz, B., Chalari, A., Tilmann, F., Reinsch, T., Zuccarello, L., Privitera, E., and Krawczyk, C. M.: Fibre optic distributed acoustic sensing of volcanic events, Nature communications, 13, 1753, 2022.

Jozinović, D., Massin, F., Böse, M., and Clinton, J.: Combining earthquake early warning solutions from different algorithms: application to Switzerland, SSA sbstract, 2023.

Klaasen, S., Paitz, P., Lindner, N., Dettmer, J., and Fichtner, A.: Distributed Acoustic Sensing in volcano-glacial environments — Mount Meager, British Columbia, J. Geophys. Res, 159, https://doi.org/10.1029/2021JB022358., 2021.

Kleinbrod, U., Burjánek, J., and Fäh, D.: Ambient vibration classification of unstable rock slopes: A systematic approach, Engineering Geology, 249, 198–217, 2019.

Kremer, K., Fabbri, S. C., Evers, F. M., Schweizer, N., and Wirth, S. B.: Traces of a prehistoric and potentially tsunamigenic mass movement in the sediments of Lake Thun (Switzerland), Swiss journal of geosciences, 115, 1–20, 2022.

Lanza, F., Diehl, T., Deichmann, N., Kraft, T., Nussbaum, C., Schefer, S., and Wiemer, S.: The Saint-Ursanne earthquakes of 2000 revisited: evidence for active shallow thrust-faulting in the Jura fold-and-thrust belt, Swiss Journal of Geosciences, 115, 2, doi: 10.1186/s00015-021-00400-x, 2022.

Lee, T., Diehl, T., Kissling, E., and Wiemer, S.: New insights into the Rhône–Simplon fault system (Swiss Alps) from a consistent earthquake catalogue covering 35 yr, Geophysical Journal International, 232(3), 1568-1589, https://doi.org/10.1093/gji/ggac407, 2023.

Lee, T.: The transition between Western and Central Alps: New seismotectonic insights from high-resolution earthquake catalogs and tomography, Ph.D. Thesis, ETH Zurich, Diss No.: 29073. doi: 10.3929/ethz-b-000613262, 2023.

Lindsey, N., Rademacher, H., and Ajo-Franklin, J.: On the broadband instrument response of fiber-optic (DAS) arrays, J. Geophys. Res, 125, https://doi.org/10.1029/2019JB018145, 2020.

Lomax, A., Virieux, J., Volant, P., and Berge, C.: Probabilistic earthquake location in 3D and layered models: Introduction of a Metropolis-Gibbs method and comparison with linear locations, in: Advances in Seismic Event Location, Thurber, C.H and N. Rabinowitz (eds.), Kluwer, Amsterdam, 101-134, 2000.

Maranò, S., Reller, C., Loeliger, H.-A., and Fäh, D.: Seismic waves estimation and wave field decomposition: Application to ambient vibrations, Geophys. J. Int, 191, 175–188, 2012.

Marra, G., Clivati, C., Luckett, R., Tampellini, A., Kronjäger, J., Wright, L., Mura, A., Levi, F., Robinson, S., Xuereb, A., Baptie, B., and Calonico, D.: Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables, Science, 361, 486–490, 2018.

Martakis, P., Movsessian, A., Reuland, Y., Pai, S. G., Quqa, S., Garcia Cava, D., Tcherniak, D., and Chatzi, E.: A semi-supervised interpretable machine learning framework for sensor fault detection, Smart Struct. Syst. Int. J, 29, 251–266, 2022a.

Martakis, P., Movsessian, A., Reuland, Y., Pai, S. G., Quqa, S., Garcia Cava, D., Tcherniak, D., and Chatzi, E.: A semi-supervised interpretable machine learning framework for sensor fault detection, Smart Struct. Syst. Int. J, 29, 251–266, 2022b.

Marti, M., Stauffacher, M., and Wiemer, S.: Anecdotal evidence is an insufficient basis for designing earthquake preparedness campaigns, Seismological Research Letters, 91, 4, https://doi.org/10.1785/0220200010, 2020.

Marti, M., Dallo, I., Roth, P., Papadopoulos, A. N., and Zaugg, S.: Illustrating the impact of earthquakes: Evidence-based and user-centered recommendations on how to design earthquake scenarios and rapid impact assessments, International Journal of Disaster Risk Reduction, 103674, https://doi.org/10.1016/j.ijdrr.2023.103674, 2023.

Marzocchi, W., Lombardi, A. M., and Casarotti, E.: The establishment of an operational earthquake forecasting system in Italy, Seismological Research Letters, 85(5), 961–969, 2014.

Massin, F., Clinton, J., and Böse, M.: Status of Earthquake Early Warning in Switzerland, Front, Earth Sci, 9, https://doi.org/10.3389/feart.2021.707654, 2021.

Meier, M.-A., Ross, Z. E., Ramachandran, A., Balakrishna, A., Nair, S., Kundzicz, P., Li, Z., Andrews, J., Hauksson, E., and Yue, Y.: Reliable real-time seismic signal/noise discrimination with machine learning, Journal of Geophysical Research: Solid Earth, 124, 788–800, https://doi.org/10.1029/2018JB016661, 2019.

Mesimeri, M., Armbruster, D., Kaestli, P., Scarabello, L., Diehl, T., Clinton, J., and Wiemer, S.: SCDetect: Real-time computationally efficient waveform cross-correlation based earthquake detection, To be submitted to SRL, 2023.

Michel, C., Edwards, B., Poggi, V., Burjánek, J., and Fäh, D.: Assessment of Site Effects in Alpine Regions through Systematic Site Characterization of Seismic Stations, Bulletin of the Seismological Society of America, 104(6), 2809–2826, 2014.

Michel, C., Fäh, D., Edwards, B., and Cauzzi, C. V.: Site amplification at the city scale in Basel (Switzerland) from geophysical site characterization and spectral modelling of recorded earthquakes, Physics and Chemistry of the Earth, 98, 27–40, 2017.

Mitchell-Wallace, K., Jones, M., Hillier, J., and Foote, M.: Natural catastrophe risk management and modelling. Natural catastrophe risk management and modelling: A practitioner's Guide, 1st ed., John Wiley & Sons, Hoboken, NJ, https://doi.org/10.1002/9781118906057., 2017.

Mizrahi, L., Nandan, S., and Wiemer, S.: Developing and Testing ETAS-Based Earthquake Forecasting Models for Switzerland, In preparation.

Molinari, I., Obermann, A., Kissling, E., Hetényi, G., Boschi, L., and AlpArray-Easi Working, G.: 3D crustal structure of the Eastern Alpine region from ambient noise tomography, in: Results in Geophysical Sciences, 1–4, https://doi.org/10.1016/j.ringps.2020.100006, 2020.

Mousavi, S. M. and Beroza, G. C.: Deep-learning seismology, Science, 377, https://doi.org/10.1126/science.abm4470, 2022.

Nakata, N., Gualtieri, L., and Fichtner, A. (Eds.): Seismic ambient noise, Cambridge University Press, 2019.

Nandan, S., Kamer, Y., Ouillon, G., Hiemer, S., and Sornette, D.: Global models for short-term earthquake forecasting and predictive skill assessment, The European Physical Journal Special Topics, 230, 425–449, 2021.

Nievas, C. et al.: RISE deliverable 6.1: Integration of RISE Innovations in the Fields of OELF, RLA and SHM, in prep., 2023.

Obermann, A., Planès, T., Larose, E., and Campillo, M.: Imaging preeruptive and coeruptive structural and mechanical changes of a volcano with ambient seismic noise, Journal of Geophysical Research: Solid Earth, 118, 6285–6294, 2013.

Obermann, A., Froment, B., Campillo, M., Larose, E., Planès, T., Valette, B., Chen, J. H., and Liu, Q. Y.: Seismic noise correlations to image structural and mechanical changes associated with the Mw 7.9 2008 Wenchuan earthquake, Journal of Geophysical Research: Solid Earth, 119, 3155–3168, 2014.

Obermann Kraft, T., Larose, E., and Wiemer, S.: Potential of ambient seismic noise techniques to monitor the St, Gallen geothermal site (Switzerland). Journal of Geophysical Research: Solid Earth, 120, 4301–4316, 2015.

Obermann, A., Lupi, M., Mordret, A., Jakobsdo ́ttir, S.S., Miller, S.A., 2016. 3D-ambient noise Rayleigh wave tomography of Snæfellsjo ̈kull volcano, Iceland. J. Vol. Geotherm. Res. 317, 42–52. https://doi.org/10.1016/j.jvolgeores.2016.02.013.

Ogata, Y.: Statistical models for earthquake occurrences and residual analysis for point processes, Journal of the American Statistical association, 83, 9–27, https://doi.org/10.1080/01621459.1988.10478560v, 1988.

Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, L., Nastasi, M., and Panzeri, L.: OpenQuake engine: An open hazard (and risk) software for the global earthquake model, Seismological Research Letters, 85, 692–702, 10.1785/0220130087, 2014.

Paitz, P., Edme, P., Gräff, D., Walter, F., Doetsch, J., Chalari, A., Schmelzbach, C., and Fichtner, A.: Empirical investigations of the instrument response for distributed acoustic sensing (DAS) across 17 octaves, Bulletin of the Seismological Society of America, 111, 1–10, 2021.

Paitz, P., Lindner, N., Edme, P., Huguenin, P., Hohl, M., Sovilla, B., Walter, F., and Fichtner, A.: Phenomenology of avalanche recordings from distributed acoustic sensing, J. Geophys. Res, 128, https://doi.org/10.1029/2022JF007011, 2023.

Panzera, F., Bergamo, P., and Fäh, D.: Canonical Correlation Analysis Based on Site- Response Proxies to Predict Site- Specific Amplification Functions in Switzerland. Bulletin of the Seismological Society of America 111(4):1905–1920, 2021.

Panzera, F., Alber, J., Imperatori, W., Bergamo, P., and Fäh D.: Reconstructing a 3D model from geophysical data for local amplification modelling: The study case of the upper Rhone valley, Switzerland. Soil Dynamics and Earthquake Engineering 155:107163, 2022.

Papadopoulos, A. N., Böse, M., Danciu, L., Clinton, J., and Wiemer, S.: A framework to quantify the effectiveness of earthquake early warning in mitigating seismic risk, Earthquake Spectra, 39, 938–961, 10.1177/87552930231153424, 2023.

Papadopoulos, A. N., Roth, P., Danciu, L., Bergamo, P., Panzera, F., Fäh, D., Cauzzi, C., Duvernay, B., Khodaverdian, A., P., L., O., O., Fagà, E., Bazzurro, P., Marti, M., Valenzuela, N., Dallo, I., Schmid, N., Kästli, P., Haslinger, F., and Wiemer, S.: in: The Earthquake Risk Model of Switzerland ERM-CH23, submitted to Nat. Hazards Earth Syst. Sci, subm.

Perron, V., Bergamo, P., and Fäh D.: Site Amplification at High Spatial Resolution from Combined Ambient Noise and Earthquake Recordings in Sion, Switzerland. Seismological Research Letters, 93(4):2281–2298, 2022.

Poggi, V., Edward, B., and Fäh, D.: A comparative analysis of site-specific response spectral amplification models. Physics and Chemistry of the Earth 98, 16-26. http://dx.doi.org/10.1016/j.pce.2016.09.001, 2017.

Racine, R., Cauzzi, C., Clinton, J. et al.: Updated determination of earthquake magnitudes at the Swiss Seismological Service, EGU2020-8273, 2020.

https://doi.org/10.5194/egusphere-2023-1863
Preprint. Discussion started: 22 August 2023

Reuland, Y., Martakis, P., and Chatzi, E.: Damage-sensitive features for rapid damage assessment in a seismic context, in: Proc. of the International Conference on Structural Health Monitoring of Intelligent Infrastructure, 613–619, 2021.

Reuland, Y., Martakis, P., and Chatzi, E.: A comparative study of damage-sensitive features for rapid data-driven seismic structural-health monitoring, Applied Sciences. Under Review, 2023a.

Reuland, Y., Khodaverdian, A., Crowley, H., Nievas, H., Martakis, P., and Chatzi, E.: Monitoring-driven post-earthquake building damage tagging, in: 10th International Conference on Experimental Vibration Analysis for Civil Engineering Structures, Milano, Italy, 2023b.

Roten, D., Fäh, D., and Bonilla, L. F.: Quantification of cyclic mobility parameters in liquefiable soils from inversion of vertical array records, Bulletin of the Seismological Society of America, 104, 3115–3138, 2014.

Sägesser, R. und Mayer-Rosa, D: Erdbebengefährdung in der Schweiz. Schweizerische Bauzeitung Heft 7, 1978.

Sánchez-Pastor, P., Obermann, A., Schimmel, M., Weemstra, C., Verdel, A., and Jousset, P.: Short-and long-term variations in the Reykjanes geothermal reservoir from seismic noise interferometry, Geophysical Research Letters, 46, 5788–5798, doi:10.1029/2019GL082352, 2019.

Scarabello, L., Diehl, T., Kästli, P., Clinton, J., and Wiemer, S.: Towards Real-Time Double-Difference Hypocenter Relocation of Natural and Induced Seismicity, in: EGU General Assembly Conference Abstracts, https://doi.org/10.5194/egusphere-egu2020-13058, 2020.

Schorlemmer, D., Euchner, F., Kästli, P., Saul, J., and Group, Q. W.: QuakeML: status of the XML-based seismological data exchange format, Annals of Geophysics, 54, doi: 10.4401/ag-4874, 2011.

Shynkarenko, A., Kremer, K., Stegmann, S., Bergamo, P., Lontsi, A. M., Roesner, A., Hammerschmidt, S., Kopf, A., and Fäh, D.: Geotechnical characterization and stability analysis of subaqueous slopes in Lake Lucerne (Switzerland), Natural Hazards, 113, 475–505, 2022.

SIA 261: Norm 261, Einwirkungen auf Tragwerke. Schweizerischer Ingenieur- und Architektenverein (SIA), Zürich, 2020.

Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., Martins, L., Pagani, M., Rao, A., and Simionato, M.: Development of a global seismic risk model, Earthquake Spectra, 36, 372–394, 2020.

Spica, Z., Perton, M., Martin, E., Beroza, G., and Biondi, B.: Urban seismic site characterization by fiber-optic seismology, J. Geophys. Res, 125, https://doi.org/10.1029/2019JB018656, 2020.

Spica, Z. J., Castellanos, J. C., Viens, L., Nishida, K., Akuhara, T., Shinohara, M., and Yamada, T.: Subsurface imaging with ocean-bottom distributed acoustic sensing and water phases reverberations, Geophysical Research Letters, 49, e2021GL095287, 2022.

Strollo, A., Cambaz, D., Clinton, J., Danecek, P., Evangelidis, C. P., Marmureanu, A., Ottemöller, L., Pedersen, H., Sleeman, R., and Stammler, K.: EIDA: The European integrated data archive and service infrastructure within ORFEUS, Seismological Society of America, 92, 1788–1795, 2021.

Strupler, M., Hilbe, M., Kremer, K., Danciu, L., Anselmetti, F. S., Strasser, M., and Wiemer, S.: Subaqueous landslide-triggered tsunami hazard for Lake Zurich, Switzerland, Swiss journal of geosciences, 111, 353–371, 2018.

Swiss Seismological Service (SED) at ETH Zurich (1983): National Seismic Networks of Switzerland; ETH Zürich. Other/Seismic Network. https://doi.org/10.12686/SED/NETWORKS/CH DataCite metadata:HTML JSON XML

Swiss Seismological Service (SED) at ETH Zurich (2015). The Site Characterization Database for Seismic Stations in Switzerland. Zurich: Federal Institute of Technology. doi: 10.12686/sed-stationcharacterizationdb

Toledo, T., Obermann, A., Verdel, A., Martins, J. E., Jousset, P., Mortensen, A. K., Erbas, K., and Krawczyk, C. M.: Ambient seismic noise monitoring and imaging at the Theistareykir geothermal field (Iceland), Journal of Volcanology and Geothermal Research, 429, 107590,10.1016/j.jvolgeores.2022.107590, 2022.

Valenzuela Rodríguez, N.: Die aktuelle Erdbebensituation der Schweiz visualisieren—Eine Analyse der Erdbebenkarte der MeteoSchweiz-App hinsichtlich ihrer Verständlichkeit und ihres Verbesserungspotenzials, [Master Thesis, Zurich University of Applied Sciences (ZHAW)]. https://www.polybox.ethz.ch/index.php/s/vaBmjfUr0AgaVtS, 2021.

https://doi.org/10.5194/egusphere-2023-1863
Preprint. Discussion started: 22 August 2023

Van der Elst, N. J., Hardebeck, J. L., Michael, A. J., McBride, S. K., and Vanacore, E.: Prospective and retrospective evaluation of the US Geological Survey Public aftershock forecast for the 2019–2021 Southwest Puerto Rico Earthquake and aftershocks, Seismological Society of America, 93, 620–640, 2022.

Van Stiphout, T., Wiemer, S., and Marzocchi, W.: Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake, Geophys, Res. Lett, 37, 1-5, https://doi.org/10.1029/2009GL042352, 2010.

Waldhauser, F. and Ellsworth, W.: A Double-Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California, Bulletin of the Seismological Society of America, 90, 1353–1368, https://doi.org/10.1785/0120000006, 2000.

Waldhauser, F.: Near-real-time double-difference event location using long-term seismic archives, with application to Northern California, Bull. Seismol. Soc. Am., 99(5), 2736–2748, doi:10.1785/0120080294, 2009.

Walter, F., Gräff, D., Lindner, N., Paitz, P., Köpfli, M., Chmiel, M., and Fichtner, A.: Distributed Acoustic Sensing of microseismic sources and wave propagation in glaciated terrain, Nat. Comm, 11, https://doi.org/10.1038/s41467-020-15824, 2020.

Wiemer, S., Danciu, L., Edwards, B., et al.: Seismic Hazard Model 2015 for Switzerland (SUIhaz2015), https://doi.org/10.12686/a2, 2016.

Wiemer, S., Papadopoulos, A., Roth, P., Danciu, L., Bergamo, P., Fäh, D., Duvernay, B., Khodaverdian, A., Lestuzzi, P., Odabaşi, Ö., Fagà, E., Bazzuro, P., Cauzzi, C., Hammer, C., Panzera, F., Perron, V., Marti, M., N., V., Dallo, I., Zaugg, S., Fulda, D., Kästli, P., Schmid, N., and Haslinger, F.: Earthquake Risk Model of Switzerland (ERM-CH23), Swiss Seismological Service, ETH Zurich, https://doi.org/10.12686/a20, 2023.

Woessner, J., Danciu, L., Giardini, D., Crowley, H., Cotton, F., Grünthal, G., Valensise, G., Arvidsson, R., Basili, R., Demircioglu, M. B., Hiemer, S., Meletti, C., Musson, R. W., Rovida, A., Sesetyan, K., and Stucchi, M.: The 2013 European Seismic Hazard Model: key components and results, Bulletin of Earthquake Engineering, 13(12), 3553–3596, https://doi.org/10.1007/s10518-015-9795-1, 2015.

Worden, C. B., Thompson, E. M., Hearne, M., and Wald, D. J.: ShakeMap Manual Online: technical manual, user's guide, and software guide, U. S. Geological Survey, https://doi.org/10.5066/F7D21VPQ, 2020.