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 Swiss Seismological Service (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. 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. This paper may serve as a reference guide for other countries wishing to establish similar services for seismic risk reduction.

Short Summary. We are developing an interdisciplinary dynamic earthquake risk framework for advancing earthquake risk mitigation in Switzerland. It includes various earthquake risk products and services, such as Operational Earthquake Forecasting and Earthquake Early Warning. 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

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.*, 2023a).

The seismic risk to which a structure is exposed depends on its type, location, occupancy, and local site conditions; an individual's risk is also affected by her/his exact location within the structure. Seismic risk is therefore highly time-dependent (dynamic) and subject to change, because the underlying hazard, or the exposure, changes. In the short term, the risk may increase during an active seismic sequence in the vicinity. On a more immediate timescale, seismic risk is greatly increased once an event initiates and before the strong shaking begins. In the long term, seismic risk increases with rapid urbanisation and densification of the building stock. The vulnerability of certain structures may be altered by preceding events, contributing to an evolving seismic risk landscape during an ongoing seismic sequence. Compared to a static approach that assumes a constant level of hazard and risk, the dynamic risk approach allows for timely identification of changes, enabling more accurate estimates and thus more effective mitigation measures and improved safety outcomes. Here we describe the dynamic earthquake risk framework that we are implementing for Switzerland.

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.*, 2023b) serve as the basis for tools and systems which we are developing as part of a dynamic, harmonised and user-centred earthquake risk framework for Switzerland. Within our framework, earthquake risk is evaluated consistently and in a harmonised manner, whether for the immediate next few seconds or projecting ahead for the next five decades. The framework uses all available information to evaluate 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).

Harmonisation of products and workflows across different applications is crucial to ensure broad acceptance and universal recognition of products, as well as to maximise synergies and impact. The first element of our framework is the high-quality characterization of seismicity in Switzerland using the Swiss Seismic Network operated by the SED as the backbone (**Figure 1**) with reliable monitoring and recording of seismic events, reaching a completeness magnitude of ML1.0 in most Swiss regions and ML1.5 in less densely instrumented areas. Real-time waveform data and derived catalogue parameters contribute directly to EEW, ShakeMaps, and OE[L]F, and play a key role in immediate disaster response and public safety measures.

The second element of our framework involves the assessment of ground shaking hazards. Using data from the Swiss Seismic Network, we derive predictive ground motion models, which we combine with seismotectonic and seismogenic sources (again strongly informed by the seismicity catalogue described above) for a comprehensive long-term seismic hazard assessment. These assessments are used to update seismic design guidelines and regulations, and to inform seismic risk assessment.

The third element of our framework focuses on assessing the consequences of earthquakes and estimating losses at different levels of exposure, from the national scale down to individual communities. The RIA system developed at the SED provides rapid estimates of potential structural and economic losses. The SHM and RRE systems developed at the IBK are essential for post-earthquake damage assessment of structures and recovery predictions.

Finally, a carefully crafted communication strategy accompanies the entire lifecycle of our initiative, from the development of operational services and the construction of data models to the dissemination of data products. All services and tools in our framework are based on state-of-the-art research infrastructure, including powerful computational tools and databases.

A critical component of the Swiss dynamic risk framework is the standardisation into seamless products that access the same databases, workflows, and software, and are based on standard models: the Swiss EEW system (Massin *et al.*, 2021) uses the same ground-motion models as employed in the Swiss ShakeMaps (Cauzzi *et al.*, 2015; 2022); the Swiss RIA system utilises Swiss ShakeMap as input, that includes 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, RRE, 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 developed based on feedback from focus groups and discussions with stakeholders at the federal and cantonal levels, and includes new visualisations of uncertainties. The risk map was adapted to the needs of the public, which were assessed through a representative, nationwide survey.

Here we report on the main components of the Swiss dynamic earthquake risk framework, most of which have been developed within the scope of the European Union Horizon 2020 *Real-time earthquake rIsk reduction for a ReSilient Europe* (RISE; http://www.rise-eu.org/home/, last accessed November 2023) 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 advances in seismic monitoring capabilities over the last decade, which are crucial for the downstream risk mitigation products and services that we focus on in the second part of this paper. Finally, we discuss the SED strategy for implementing and communicating earthquake hazard and risk products to the public and stakeholders in Switzerland. Our paper may serve as a reference for other countries seeking to establish a similar framework.

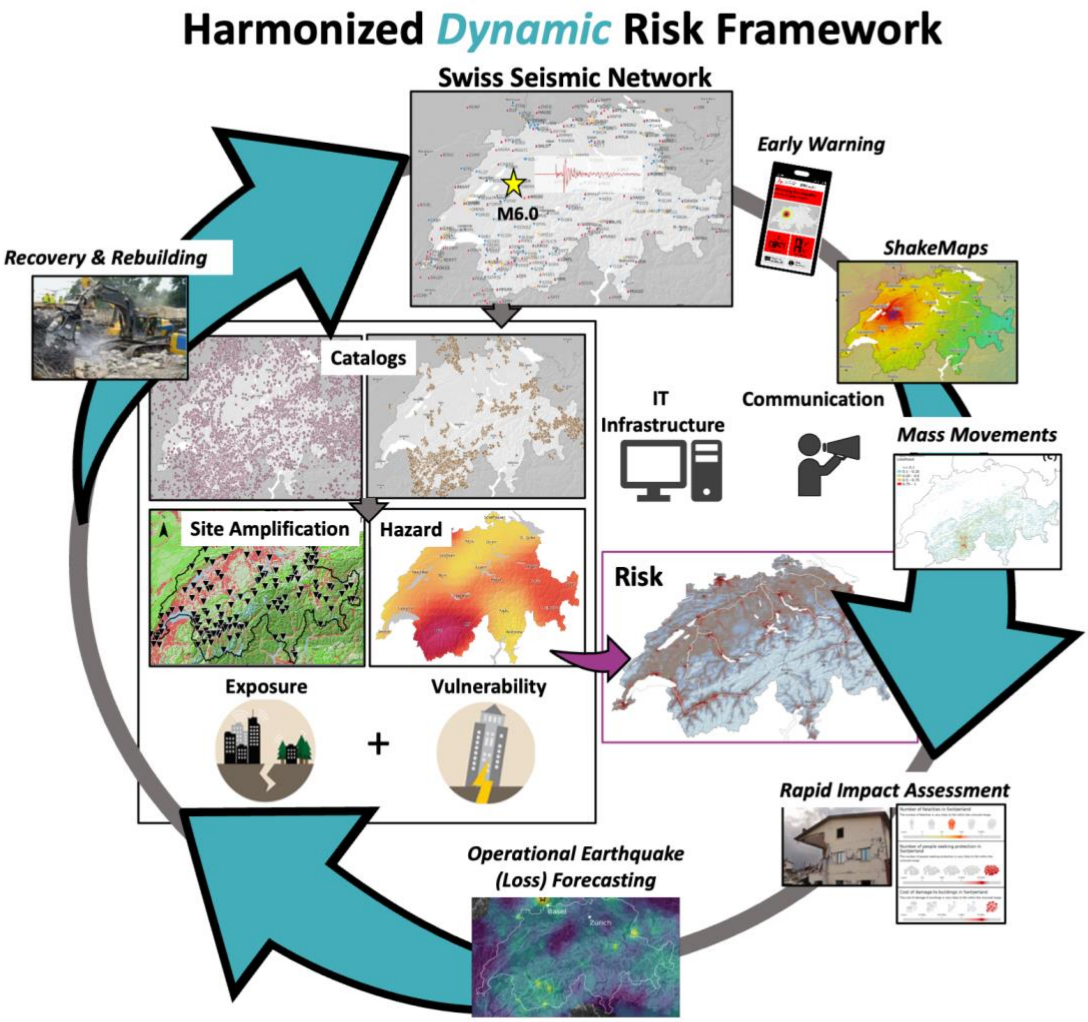

Figure 1: Schematic representation of the dynamic risk framework.

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 10 to 20 events that are felt by the population (**Figure 2**). The 2015 Swiss seismic hazard model, SUIhaz2015 (**Figure 3a**; Wiemer *et al.*, 2016), which assesses the likelihood of ground shaking, forecasts that earthquakes of magnitude 5 or greater 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.

SUIhaz2015 has been implemented in the most recent version of Swiss building code SIA 261 (2020). It 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 & Mayer-Rosa (1978) which was based on the historical catalogue available at that time, as well as on macroseismic intensity data.

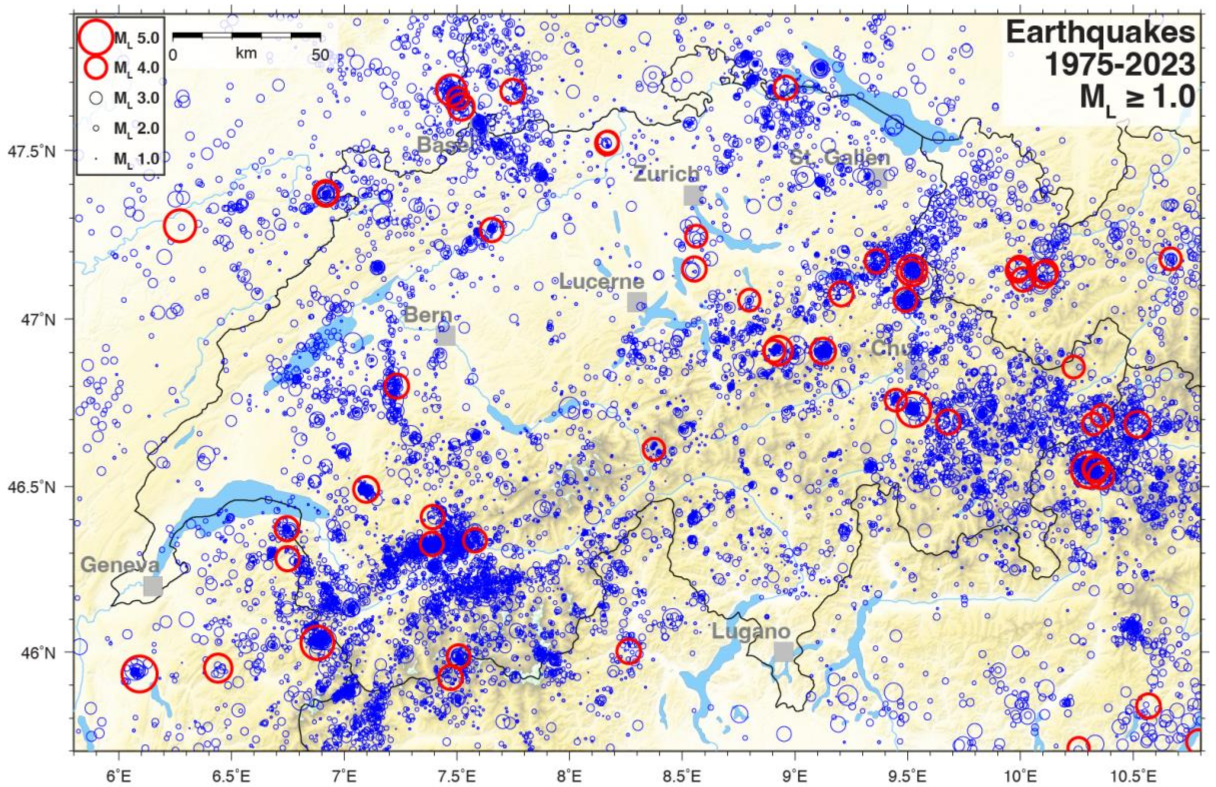

Figure 2: Map of Switzerland and the surrounding area showing all seismicity with ML ≥ 1.0 since 1975 in the SED earthquake catalogue (bulletin locations). Events with ML ≥ 4.0 are highlighted by bold red circles.

Methods for estimating site-specific amplification and local seismic hazard were developed at the 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 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; Janusz *et al.*, 2023). Findings from these studies have been incorporated into rapid estimates of earthquake-induced mass movements and liquefaction probabilities via the SED ShakeMap application (Cauzzi *et al.*, 2018a; Section 3.3).

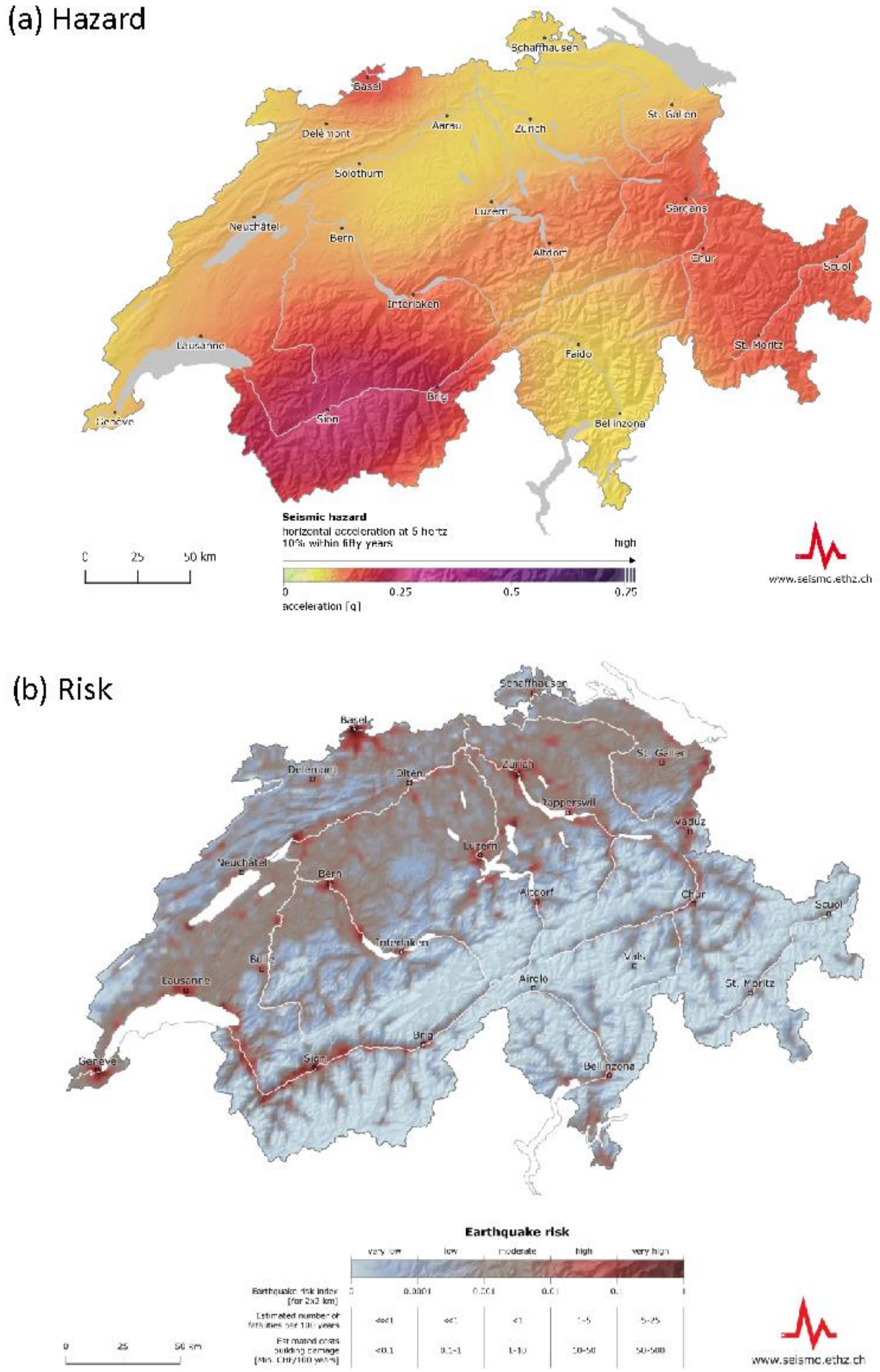

Figure 3: (a) Swiss Hazard Map (SUIhaz2015; @Swiss Seismological Service) showing the horizontal acceleration at 5 Hz; the probability of a building constructed on rock-like ground type experiencing this is 10% within 50 years (i.e., mean return period of 475 years). On average, 5 Hz represents the natural 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 of Switzerland (ERM-CH23; @Swiss Seismological Service). The color scale refers to a composite index based on

equally-weighted, normalized average structural/nonstructural loss and fatalities during 100 years. Values are provided in a 2 x 2 km grid. Comparatively high seismic risk is shown in dark red, lower risk is pale blue.

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 and high-resolution data.

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 at 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 peak ground velocity, PGV, and 5%-damped pseudo-spectral acceleration, PSA, at periods of 1.0 s, 0.6 s, and 0.3 s (e.g., **Figure 4b**), each with associated maps of epistemic and aleatory variability following the definition in Al Atik *et al.* (2010). The amplification maps for PGV and PSA were also converted into layers of aggravation or reduction of macroseismic intensity by means of the relations of Faenza & Michelini (2010, 2011).

The exposure model represents the results of a national effort to obtain an extensive geo-referenced database of all building objects in Switzerland. ERM-CH23 makes use of over 2.25 million building entries in the database, after excluding close to 900’000 too small or unclassified objects. Among others, the building database contains for each object information such as the period of construction, building function, footprint area, volume, height or reconstruction cost (determined for each building individually and validated with data from the cantonal building insurance companies). Together with ground surveys to assess the frequency of different building materials in several cities, they underpin the ERM-CH23 exposure model. The number of occupants in each building is defined through de-aggregation of geo-referenced housing and employment statistics (Papadopoulos *et al.*, 2023b).

Relying on the aforementioned surveys and past experience the building taxonomy proposed in Lagomarsino & Giovinazzi (2006) was found to be suitable and applicable to Switzerland, with minor modifications. Two sets of fragility curves were derived, one in terms of macroseismic intensity for the relevant part of the logic tree of the overall model and one in terms of spectral acceleration (at 0.3s or 0.6s) for the other part (Wiemer *et al.*, 2023). The former relies on the methodology described in Lagomarsino & Giovinazzi (2006) and Lagomarsino *et al.* (2021), together with engineering judgement about Swiss practice. For the development of the latter, a statistical investigation of building blueprints was first performed to identify average geometric characteristics of various building types. Capacity curves, idealised in bilinear form, were obtained from numerical models (Lestuzzi *et al.*, 2017).

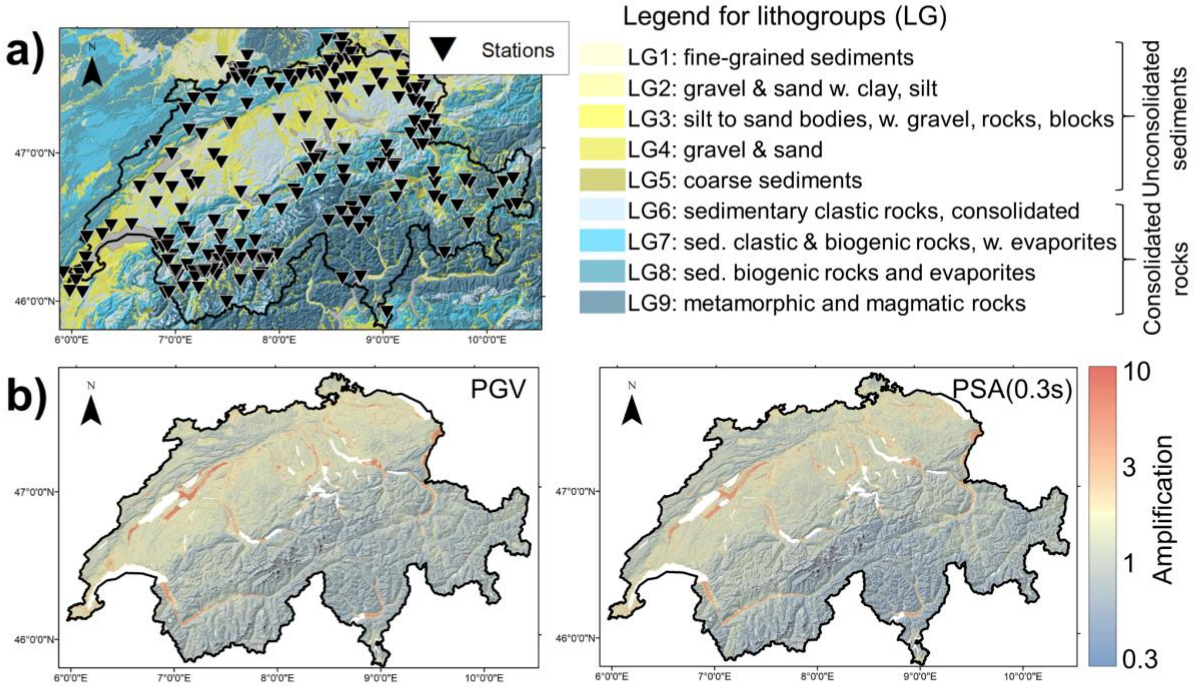

Figure 4: (a) Geographical locations of the 243 (urban) free-field stations having recorded at least 5 earthquakes with signal-to-noise ratios > 3 in the period 2000 – 2021, superimposed on the lithological classification of Switzerland employed to derive the national soil response model. (b) PGV (left) 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 (SED) at ETH Zurich, 1983) with the aim of monitoring the seismic activity in Switzerland, supporting scientific research, and assessing seismic hazard and 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 (broadband 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 Swiss Seismic Network operates another ~70 temporary stations, which were installed for a variety of reasons, including the monitoring of geothermal exploration (Swiss Seismological Service (SED) at ETH Zurich, 2006); aftershocks and seismic sequences (Swiss Seismological Service (SED) at ETH Zurich, 2005), mass movements (Swiss Seismological Service (SED) at ETH Zurich, 2012), glaciers (Swiss Seismological Service (SED) at ETH Zurich, 1985), underground rock physics laboratories (Swiss Seismological Service (SED) at ETH Zurich, 2018a); as well as for risk studies (Swiss Seismological Service (SED) at ETH Zurich, 2018b). 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). Around 50 stations operated by seismic agencies in neighbouring countries are also included in the real-time monitoring, which are crucial for accurate event locations and lowering the magnitude of completeness in and around the border regions.

The majority of broadband sensors in the Swiss Seismic Network are Streckeisen STS-2 and STS-2.5 and Nanometrics T240 or T120; the Kinemetrics EpiSensor is deployed for strong-motion stations. 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. GNSS datasets are currently not collected, processed, or integrated by the SED.

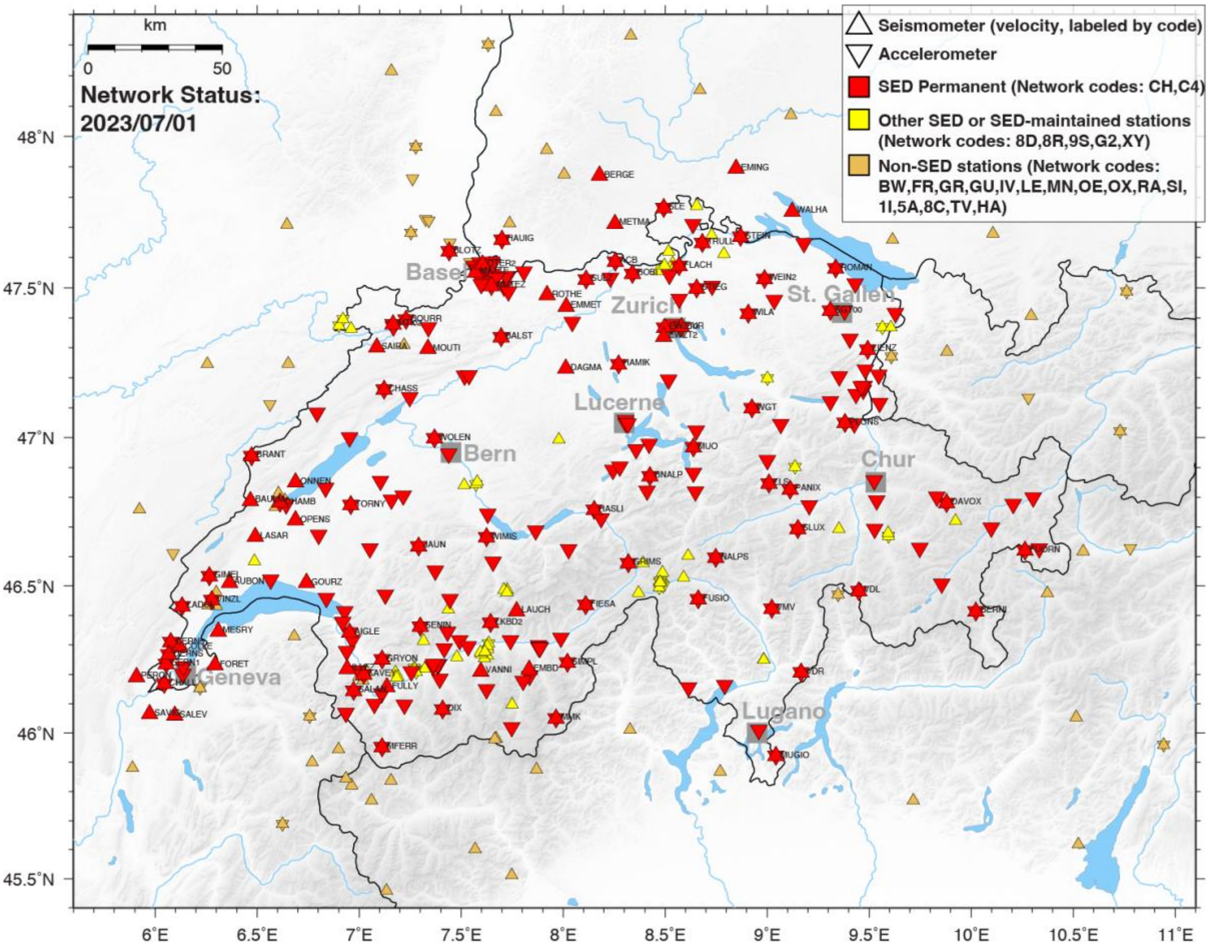

Figure 5: Map of Switzerland and the surrounding area showing broadband seismometers and strong-motion accelerometers monitored by the Swiss Seismic Network as of July 2023. The map shows permanent and temporary stations operated by the SED, as well as stations operated by external partners in and outside 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 SED 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 (**Table 1**).

Since 2012, the Swiss Seismic Network has been utilising SeisComP (https://www.seiscomp.de/, last accessed November 2023), a software developed by the German Research Centre for Geosciences (GFZ) Potsdam and gempa GmbH (https://www.gempa.de/, last accessed November 2023), 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 (Diehl *et al.*, 2021a; 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).

Source Characterization: Over the last couple of 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). In this article we use the generic "ML" notation for local magnitudes at the SED. 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 preferred origin is selected using a SED developed origin score that considers the number of picks, pick residuals, and azimuthal gap. For earthquakes larger than ML2.5, alerts are automatically sent to federal and cantonal authorities (Section 4.2), a ShakeMap is created (Section 3.3), and the strong-motion portal (http://strongmotionportal.seismo.ethz.ch/home/, last accessed November 2023) is populated. Manual review is performed using the SeisComP *scolv* GUI. For large events with ML >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 intensity measures and input to ShakeMap (Cauzzi *et al.*, 2016);
- *sceeewenv*, *scvsmag*, *scfinder,* and *sceewlog* 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. The spatio-temporal evolution of seismicity can also provide information about fluid-flow processes and hydraulic properties, including the possible existence of 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 (Scarabello & Diehl, 2021), 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 are proxies for aseismic stress changes in the subsurface that could indicate weakening, stress build-up or imminent failure. At geothermal project sites coda wave interferometry has already proven its potential 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) and as such could become a valuable contributor to our earthquake risk framework in the future.

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 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. At the current stage, fibre-optic seismology is still in exploratory mode, and the identification of clear applications where it would be beneficial within an earthquake risk framework is work in progress. Specific next steps include the routine incorporation of DAS data in near-real-time earthquake detections and locations, as well as the detection of secondary effects, such as landslides and avalanches using existing telecom infrastructure.

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 (such as seismicity catalogues) of high quality that match or even exceed the reliability and fidelity of those made by human data 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 signal denoising, phase detection and 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 these 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.*, 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 earthquake. 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 (Ogata, 1988) for Switzerland that describes the temporal fluctuations of earthquake probabilities. ETAS models are well suited for this task: they are being used for OEF by agencies worldwide (Marzocchi *et al.*, 2014; Harte, 2019; van der Elst *et al.*, 2022) and are the most extensively tested time-dependent models available (Woessner et al., 2011; Ogata et al., 2013; Strader et al., 2017; Savran *et al.*, 2020). Furthermore, an expert elicitation conducted within the RISE project showed wide consensus among experts that the ETAS model shall be used as a default model for earthquake forecasting (Mizrahi *et al.*, 2023). In ETAS, earthquakes are partitioned into background seismicity and aftershock clusters. 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, 2022), 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).

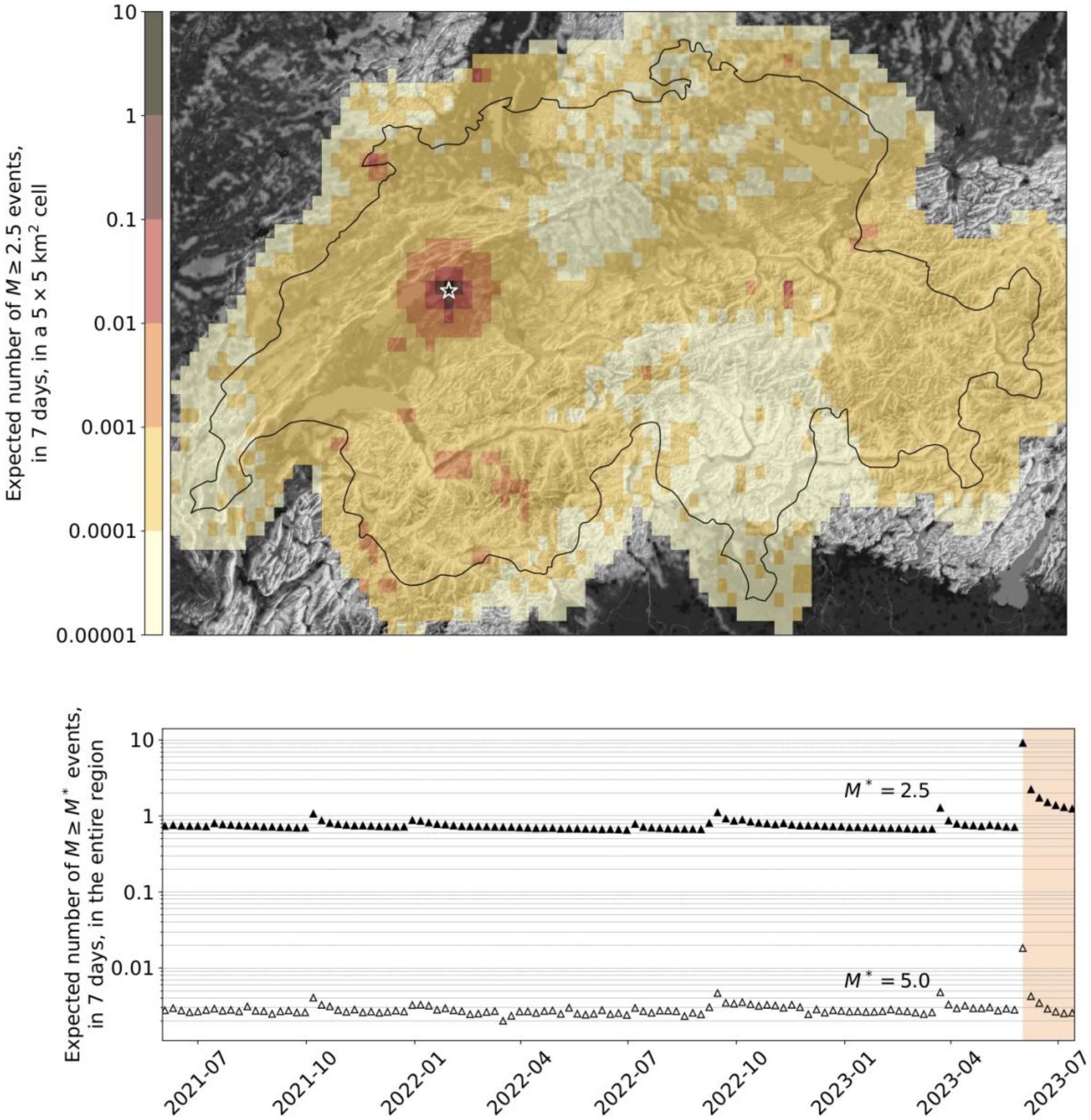

Figure 6: Time-dependent earthquake forecast for Switzerland after a hypothetical Mw 6.0 earthquake near Bern, Switzerland, at midnight on June 1, 2023 (white star in top panel). Top: Spatial distribution of the expected number of felt earthquakes (ML ≥ 2.5) in the first 7 days following the event, per 0.05°x0.05° grid cell (roughly 5x5 km^2). 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.*, 2023a).

For around one decade, the SED has been developing open-source software and methods for EEW using a set of SeisComP modules (such as *sceewenv*, *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.*, 2023).

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 minimum number of stations required by the algorithms. 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 *Alertswiss* and *MeteoSwiss* multi-hazard 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 (Cauzzi *et al.*, 2022) 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; Michelini *et al.*, 2023). ShakeMap rapidly maps seismic shaking information based on recorded and predicted intensity measures, such as peak ground acceleration (PGA), PGV, PSA, and macroseismic intensity levels, including amplification due to local site effects.

The SED ShakeMap framework is updated regularly and employs Swiss-specific ground-motion models, 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 PGA (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).

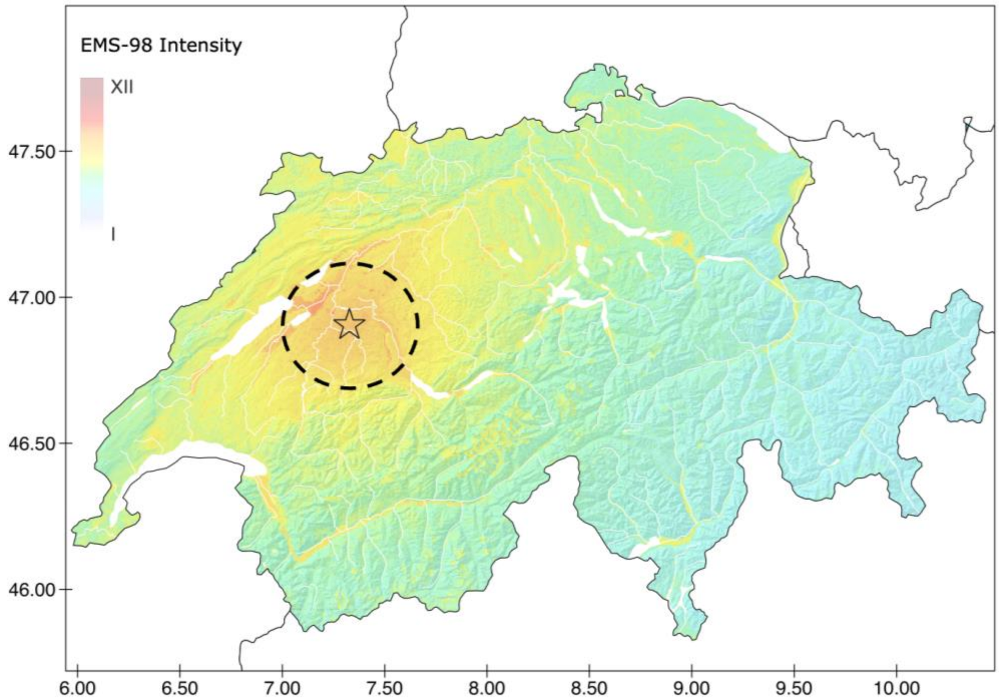

Figure 7: Swiss ShakeMap for a hypothetical Mw 6.0 earthquake near Bern. Dashed circle shows the 30-km-large no-alert-zone centred on the epicentre where EEW could probably not be provided before strong shaking initiates.

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.

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 (see example in **Figure 8**). 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 are shared internally at the SED for verification, but will soon be made available to the public.

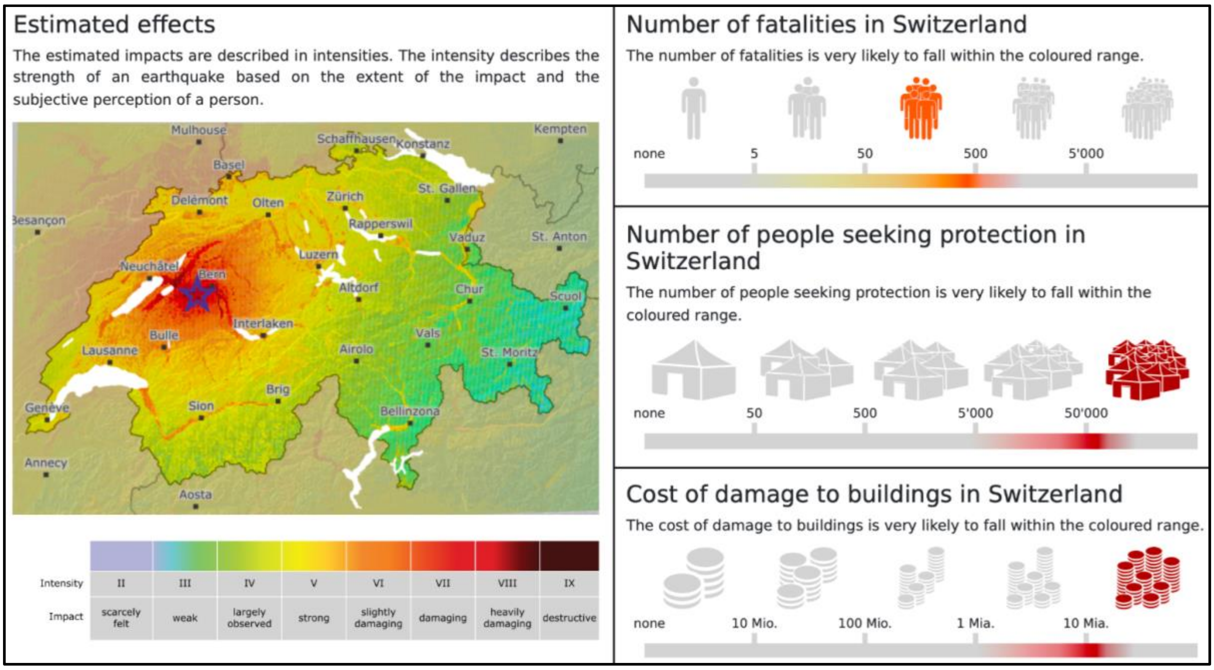

Figure 8: Exemplary Rapid Impact Assessment (RIA; @Swiss Seismological Service) output (here national level estimate) for a hypothetical Mw 6.0 earthquake near Bern. See http://www.seismo.ethz.ch/static/ERM-CH23/scenario/Bern_M6_0_en.pdf for full report.

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, 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 IBK: (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 malfunctioning 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 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 in the future.

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 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 affecting 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 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

Earthquake hazard and risk are often assumed to be constant over time. However, because seismicity is spatially and temporally clustered, and because individual exposure can change rapidly, both hazard and risk are often strongly time-dependent on different time scales. In the dynamic-risk framework outlined in this paper, seismic activity is continuously monitored by a regional seismic network, such as the one operated by the SED, and risk assessments are dynamically adapted in response to the latest data. We believe that this dynamic concept provides a more accurate and timely means of identifying potential seismic hazards and assessing risks, thereby enabling more efficient mitigation strategies and improving overall safety outcomes.

As described in this paper, we have developed key operational services of a dynamic earthquake risk framework for Switzerland. These include earthquake monitoring, ShakeMaps, EEW, OEF, RIA, and computational infrastructure. The seismic network and the ShakeMap system are currently the most mature of these services in Switzerland, followed by EEW and RIA; the OEF service is currently in a demonstration phase (**Table 1**). Furthermore, the SED has a well-established communication network to provide rapid earthquake information to the public over multiple channels.

Integration and interoperability are important aspects of our dynamic risk framework. Integration means that the framework must be able to accommodate different components while also remaining adaptable enough to function even when specific components are not connected. For example, some countries interested in establishing similar services may prioritise ShakeMaps and RIA while opting not to invest in EEW. Interoperability, on the other hand, entails that the various products and services within the framework should share common models and databases, thus eliminating redundancy in processing and ensuring efficient utilisation of resources. For example, the Swiss EEW system uses the same ground-motion models as ShakeMaps, and the Swiss RIA system uses the same ShakeMaps and the same site amplification layers derived for the national risk models, and calculates impacts on people and buildings based on national databases of buildings and their vulnerability.

During the development of our framework, we came across several key findings. First, the foundation of this framework is highly dependent on the existence of a robust seismic monitoring network and a high-quality data processing system and infrastructure. These components play a key role as they serve as the primary data sources for various downstream risk-related products. Secondly, the quality and effectiveness of the underlying models and methodologies are critically dependent on the incorporation of the latest scientific advances and the availability of computational infrastructure. Ensuring that the framework is kept up to date with the latest research is of paramount importance and may even be the greatest challenge in the long term. Thirdly, it is essential to involve stakeholders and target audiences at an early stage of development to ensure that products and services meet their expectations and understanding.

In the dynamic risk context, earthquake risk is assessed in a consistent and harmonised way for the next few seconds or for the next five decades. This not only offers great potential for synergy, but also means for comparative Cost-Benefit Analysis (CBA). While traditional CBA is useful for evaluating EEW systems (e.g., Papadopoulos *et al.*, 2023a) 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 important (e.g., Guarini *et al.*, 2018). The flexibility and transparency of MCDA allows for the consideration of a wider range of criteria beyond economic costs and benefits, including model bias, model uncertainty, time gain in emergency response, information gain etc., making it a valuable tool for assessing the cost-effectiveness of different dynamic risk products. Ongoing research aims to assess the wider benefits of these dynamic risk products for earthquake risk reduction, incorporating surveys and expert opinion to facilitate a dialogue with decision-makers and the public.

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

Product/Service	**Type**	**Status & Availability**
Earthquake Hazard and Risk Model	product	available (SUIhaz2015 and ERM-CH23) SED OpenQuake (engine *sed-oq-engine*): https://github.com/swiss-seismological-service/sed-oq-engine
Seismic Network	operational service	mature seismic stations: https://networks.seismo.ethz.ch/en/networks/ch/ http://eida.ethz.ch/fdsnws/station/1/ waveform data: http://eida.ethz.ch/fdsnws/dataselect/1/ earthquake catalogue: http://www.seismo.ethz.ch/en/earthquakes/ http://eida.ethz.ch/fdsnws/event/1/
Routine Seismic Data Processing	operational service	mature *scdetect:* earthquake detection using template matching https://scdetect.readthedocs.io *scrtDD:* real-time double difference relocation https://docs.gempa.de/scrtdd/current/ *scwfparam:* provides engineering parameters and input to ShakeMap https://www.seiscomp.de/doc/apps/scwfparam.html

Product/Service	Type	Status & Availability
		sceewenv, *scvsmag*, *scfinder*, *sceewlog*: EEW modules https://docs.gempa.de/sed-eew/current
ShakeMaps	operational service	mature https://github.com/DOI-USGS/ghsc-esi-shakemap
Earthquake Hazard Web-Services	operational service	mature European Facilities of the Earthquake Hazard and Risk (*EFEHR*): http://hazard.efehr.org *EPOS* ICS-C platform: https://www.epos-eu.org/integrated-core-services
Earthquake [Loss] Forecasting (OE[L]F)	demonstration service	beta RAMSIS core: (https://gitlab.seismo.ethz.ch/indu/rt-ramsis, dependencies described there) ETAS model wrapper: https://gitlab.seismo.ethz.ch/indu/ramsis-nsfm wrapped ETAS: https://github.com/swiss-seismological-service/etas/
Earthquake Early Warning (EEW)	demonstration service	beta https://docs.gempa.de/sed-eew/current
Rapid Impact Assessment (RIA)	demonstration service	beta - operational https://github.com/swiss-seismological-service/REIA
Structural Health Monitoring (SHM)	demonstration service	beta (codes not publicly available)
Recovery and Rebuilding Efforts (RRE)	demonstration software	available *pyrecodes*: open-source python library for post-disaster recovery simulation and resilience assessment (Blagojević and Stojadinović, 2023): https://nikolablagojevic.github.io/pyrecodes/html/usage/what_is_pyrecodes.html

The SED continues to advance 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. They aim to provide short-term earthquake probabilities and associated seismic hazards and losses, to provide rapid earthquake information and EEW to the Swiss public, and to integrate the RIA system into the seismic network operations for near-real-time calculations for earthquakes in and around Switzerland above magnitude 3.0. In addition, research is ongoing to determine how best to communicate earthquake forecasts and support the translation of probabilities into actions.

We expect our framework to improve over time as individual components are improved. For example, in the near future, simulation-based approaches, such as physics-based ground motion modelling, or so-called digital twin components may replace certain elements of the framework. Embracing the conceptual framework of dynamic risk inherently signifies a comprehensive and interdisciplinary approach to the assessment, reduction, and resilience of earthquake risks. Furthermore, this framework can be easily extended to a multi-risk framework, which offers significant advantages in addressing a variety of risk reduction challenges.

Future work on our framework could include (i) transitioning demonstration services to become operational; (ii) continuing the development and testing of the proposed services and risk framework in a wider range of countries, both in Europe and globally, as well as exploring collaborations with interested stakeholders; (iv) advancing the implementation of European-level services within the European Plate Observing System (EPOS); (v) widening the scope of the proposed exposure and loss models to encompass not only buildings but also critical infrastructures, such as for transportation, water, or energy, as well as high-risk industries, which play an important role in disaster risk management and emergency response efforts; and (vi) continuing and expanding the use of promising techniques like AI and DAS.

We would like to emphasise that while we believe that the dynamic and user-centric risk framework outlined here is valuable and can contribute to earthquake risk reduction, it should not detract from a strong focus on earthquake engineering efforts. Building to modern seismic standards has proven to be the most valuable means of reducing financial and human losses in future earthquake disasters and must remain a priority.

As data, models, and computing resources increase, dynamic and operational earthquake-related services will become increasingly available and important for earthquake risk assessment and mitigation. This paper may serve as a reference guide for countries wishing to establish similar tools and services in the context of dynamic risk. Links to publicly available components of our framework are provided in **Table 1**.

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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. Operations and Communication: JC, LD, PK, ID, MM, NV, LD, AP, PR. **Writing – original draft:** MB. **Writing – review & editing:** all. **Project investigators and Funding**: DG, SW.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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