Deliverable

RISE-D4.6: Performance-based early warning systems in Europe

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FORWARD

This report comprises the deliverable, *D4.6 - Performance-based early warning systems in Europe*, as part of the requirements in the *EU H2020 Project, RISE-Real-time Earthquake Risk Reduction for a Resilient Europe*.

The report is presented in two parts because of the differences in their objectives, Part I emphasizes engineering applications and Part II seismological applications. The objective in the first part is to discuss an EEW (Earthquake Early Warning) approach for structures, which is based on the comparison of the predicted versus threshold response for structural safety. The objective in the second part is the early warning for earthquakes based on records from a network of ground stations. Part II also includes approaches and applications in different parts of the world.

PART I – Structure-Specific Earthquake Early Warning

Part I - Table of Contents

1. Introduction and objectives

With the rapid developments in instrumentation and communication technologies, real-time monitoring of structures is becoming an increasingly popular application in earthquake engineering. Data from monitoring systems have been used for the following purposes:

- To determine the in-situ dynamic characteristics.
- To check the design and analysis methods used.
- To improve structural design codes.
- To develop new retrofit and strengthening techniques.
- To predict behavior for future extreme loads.
- To detect and locate damage after an extreme event.
- To develop instantaneous damage distribution and loss maps.

Records from building monitoring systems can also be used for earthquake early warning. In its simplest form, the records in the building are analyzed in real-time; when a critical response parameter (e.g., base acceleration, top displacement, inter-story drift, base shear, etc.) is exceeded, some of the systems in the building can be automatically stopped, such as the elevators or gas lines. This is an early warning that does not have any lead time and should be done automatically without any human interference.

However, when there are ground stations for early warning in the area, it is possible to develop early warnings for buildings by incorporating the data from those stations. We present an EEW approach for structures by using vibration records from structures and ground motion data from EEW networks. The methodology basically involves predicting the building's base response from the recordings at early warning ground stations before seismic waves reach to building. The first step is to identify the attenuation of ground motions from each early warning station to the base of the building. Next step involves identify the base motion of the building that will cause response critical for building's safety. By knowing the critical base motion and the threshold response values of the building, we can then identify the corresponding ground motions at each early warning station. We present an application of the methodology for a tall building in Istanbul where there is a 10-station early warning seismic network.

The report includes the following sections:

- Methodology
- Istanbul EEW network
- The building used as an example
- Attenuation of ground motion parameters
- Identification of building's properties from vibration records
- Critical base motion for building's safety
- Selection of threshold ground motion values at the EEW stations

2. Methodology

To present the methodology for developing location- and structure-specific Earthquake Early Warning (EEW) algorithms, we use an instrumented tall building, the Sapphire Building, in Istanbul, where there is also a 10-station early warning seismic network. First, by using available earthquake records from the EEW stations and the building monitoring system, we develop equations for the attenuation of critical shaking parameters from the each EEW station to the building's base. We identify the critical threshold response parameters for the performance of the building and the corresponding critical foundation motions. By using the attenuation equations developed, we then identify the ground motion at each EEW stations that will cause the critical foundation motion at the building. The identified EEW values are used to issue an early warning for the building before seismic waves reach to the building. This would give about 5 to 7 seconds early warning time.

3. Istanbul Earthquake Early Warning network

The stations of Istanbul EEW network are shown in Figure I.1 below, along with the known faults in Marmara Sea. There are 15 stations, 10 on land along the shores of Marmara Sea and 5 at the bottom of the sea.

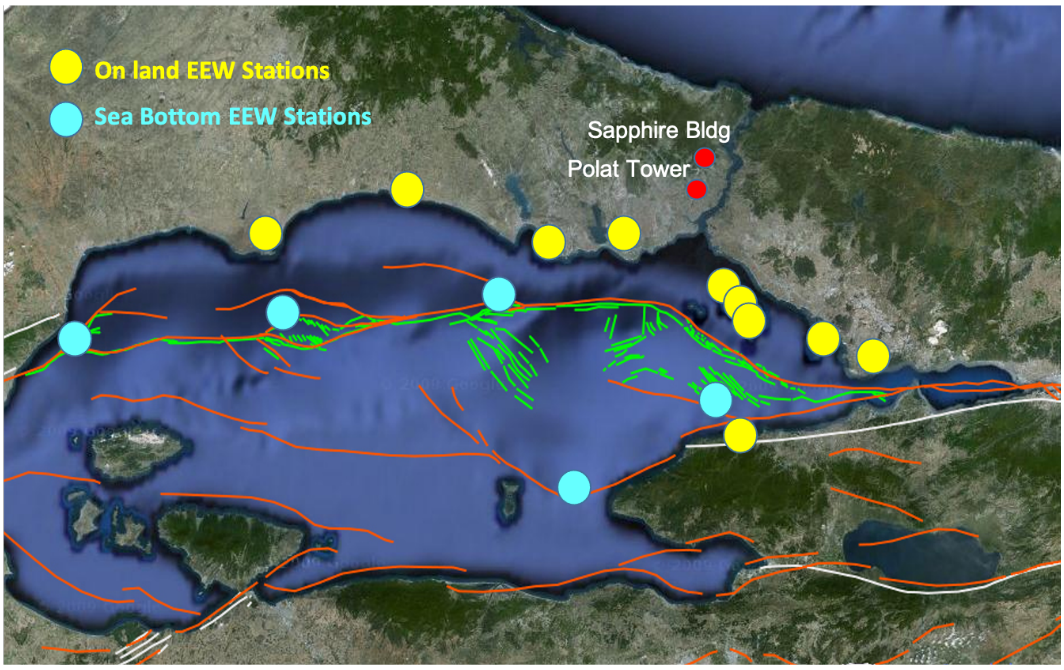

Figure I.1. Earthquake Early Warning (EEW) network in Istanbul.

Last 10-years records from the earthquakes with at M_L>4.0 at eight EEW stations and the building are compiled and processed. The locations of the EEW stations and the two buildings are shown in the figure below. Due to irregularities and breaks on the sea-bottom stations, only the data from the EEW stations on land considered in the study. The list of M_L>4.0 earthquakes considered in the study are listed in Table I.1 below.

Table I.1 – M_L>4.0 Earthquakes used in the study

No	DATE	TIME-UTC	LATITUDE	LONGITUDE	DEPTH (k	ML	LOCATION
1	20130730	05:33:08	40,3037	25,7803	9,8	5,3	GÖKÇEADA(ÇANAKKALE)
2	20131124	19:49:37	40,7843	31,8760	8,0	4,8	ULUMESCİT(BOLU)
3	20131127	03:13:37	40,8510	27,9198	9,6	4,7	MARMARA E. AÇIKLARI
4	20131127	03:21:35	40,8470	27,9120	7,4	4,0	MARMARA E. AÇIKLARI
5	20140524	09:25:01	40,3242	25,4687	23,3	6,5	EGE DENİZİ
6	20140804	22:22:44	40,6025	29,1655	10,7	4,0	TERMAL (YALOVA)
7	20141122	19:14:15	45,7420	27,2147	27,9	5,6	ROMANYA
8	20150117	00:42:34	39,8848	30,3955	5,5	4,3	KARACOBANPINARI-TEPEBASI (ESKISEHIR)
9	20150123	10:19:42	40,0647	28,5870	5,0	4,5	MUSTAFAKEMALPASA (BURSA)
10	20150202	04:41:03	40,3412	26,0567	13,4	4,1	SAROS KORFEZI (EGE DENIZI)
11	20150416	18:07:43	35,0750	26,9095	22,1	6,1	GIRIT ADASI ACIKLARI (AKDENIZ)
12	20150429	04:40:53	42,0393	29,3078	14,1	4,0	KARADENIZ AÇIKLARI
13	20151028	16:20:02	40,8205	27,7648	12,7	4,5	MARMARA DENIZI
14	20151116	14:45:43	40,8258	28,7590	7,7	4,2	MARMARA DENIZI
15	20160607	04:09:45	40,2627	29,1460	11,5	4,6	GURSU -BURSA
16	20160625	05:40:11	40,7032	29,2147	6,8	4,4	YALOVA ACIKLARI
17	20160717	08:55:41	40,7118	29,1800	7,4	4,0	YALOVA ACIKLARI
18	20161015	08:18:32	42,2063	30,7133	11,4	5,0	KARADENIZ
19	20161228	23:20:57	45,3533	26,5457	49,7	5,9	ROMANYA
20	20170206	03:51:39	39,5575	26,0197	5,5	5,5	GULPINAR ACIKLARI-ÇANAKKALE
21	20170206	10:58:00	39,5098	26,0747	6,8	5,3	BABAKALE-AYVACIK-ÇANAKKALE
22	20170207	02:24:02	39,5212	26,0873	5	5,3	GULPINAR ACIKLARI-ÇANAKKALE
23	20170212	13:48:15	39,5177	26,116	11,1	5,3	GUPINAR AYVACIK-CANAKKALE
24	20170308	20:09:58	39,9760	27,6575	7	4,1	ÇATAK-GONEN-BALIKESIR
25	20170612	12:28:38	38,8512	26,2583	20,7	6,3	EGE DENIZI
26	20170617	19:50:04	38,8542	26,4365	14,1	5,6	EGE DENIZI
27	20170622	02:48:52	38,8205	26,4593	15,3	5,0	EGE DENIZI
28	20170721	22:31:00	36,9620	27,4053	5	6,2	GOKOVA KORFEZI
29	20171231	20:12:02	40,5655	27,8653	4,3	4,3	ERDEK ACIKLARI MARMARA DENIZI
30	20180408	21:16:31	40,8615	31,6625	5,8	4,9	YESILCELE-(BOLU)
31	20190924	08:00:21	40 .8780	28 .2060	11.2	4.7	SILIVRI ACIKLARI-ISTANBUL (MARMARA DENIZI)
32	20190926	20:20:18	40 .8743	28 .2367	12.7	4.3	SILIVRI ACIKLARI-ISTANBUL (MARMARA DENIZI)
33	20191010	16:52:03	40,7008	29,2572	10,3	4,1	YALOVA ACIKLARI
34	20200111	13:37:36	40,8548	28,242	16,2	4,8	SİLİVRİ ACIKLARI
35	20200122	19:22:15	39,0575	27,8445	8,5	5,6	AKHİSAR MANİSA

4. Sapphire Building

Sapphire Building is a 261m high, 62 story tall building in Istanbul with rectangular cross-section and a flat roof. Figure I.2 shows the building and its surroundings. It has 6 stories below ground, and 56 stories above ground. The soil condition is stiff soil; the foundation type is a mat foundation. The structural system is a reinforced-concrete shear walls and frames. It was instrumented with 30 channels of acceleration sensor, operating in real-time at 200 sps. The Guralp 5TC sensors are used in the instrumentation (see: https://www.guralp.com/documents/DAS-050-0004.pdf).

More on the earthquake data recorded from the building is given in Appendix II.

Figure I.2. Sapphire Building in Istanbul.

The locations of instrument floors are shown in Figure I.3, and the layout and orientations of sensors are in Figure I.4.

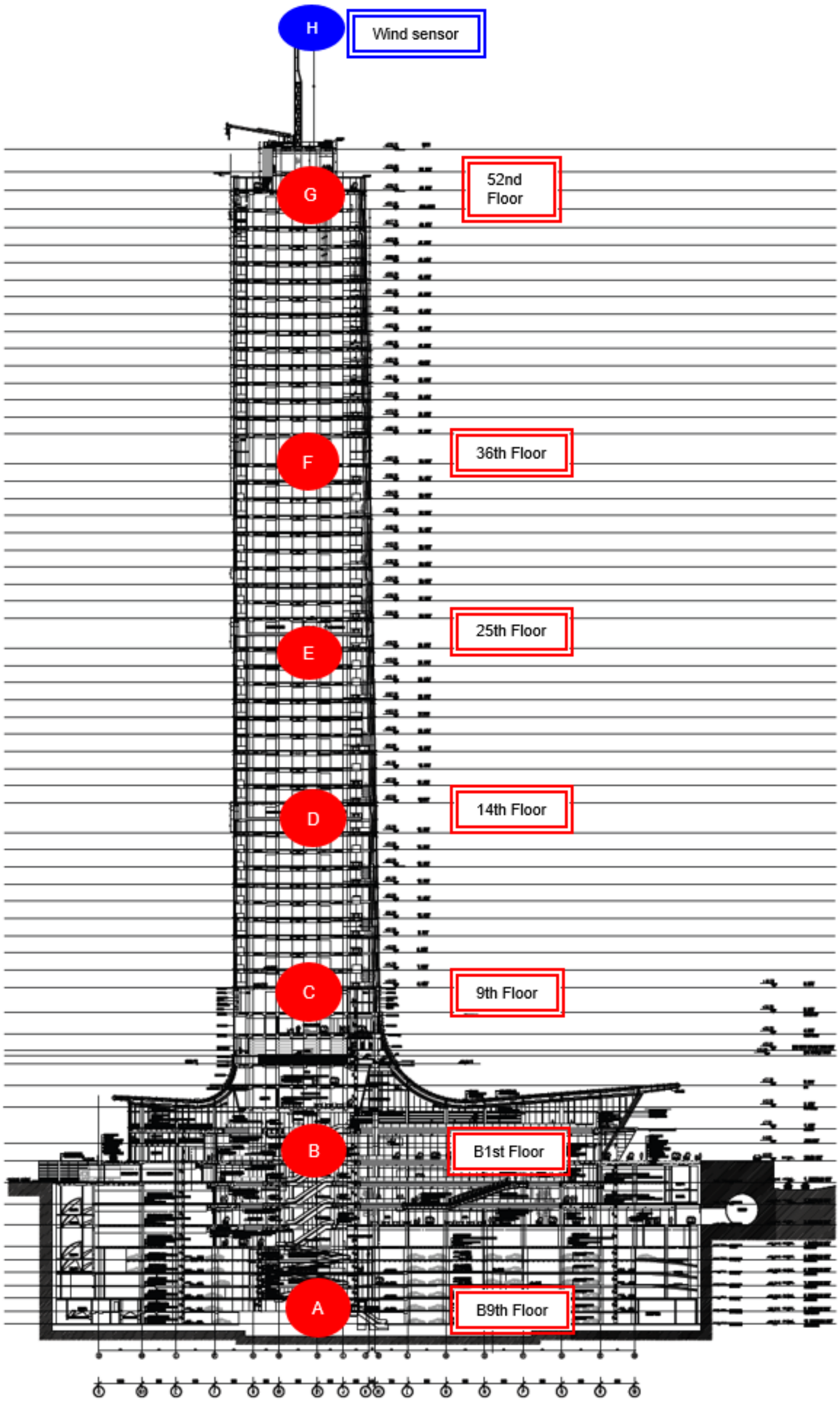

Fig. I.3. *Locations of instrumented floors in the Sapphire building in Istanbul, Turkey.*

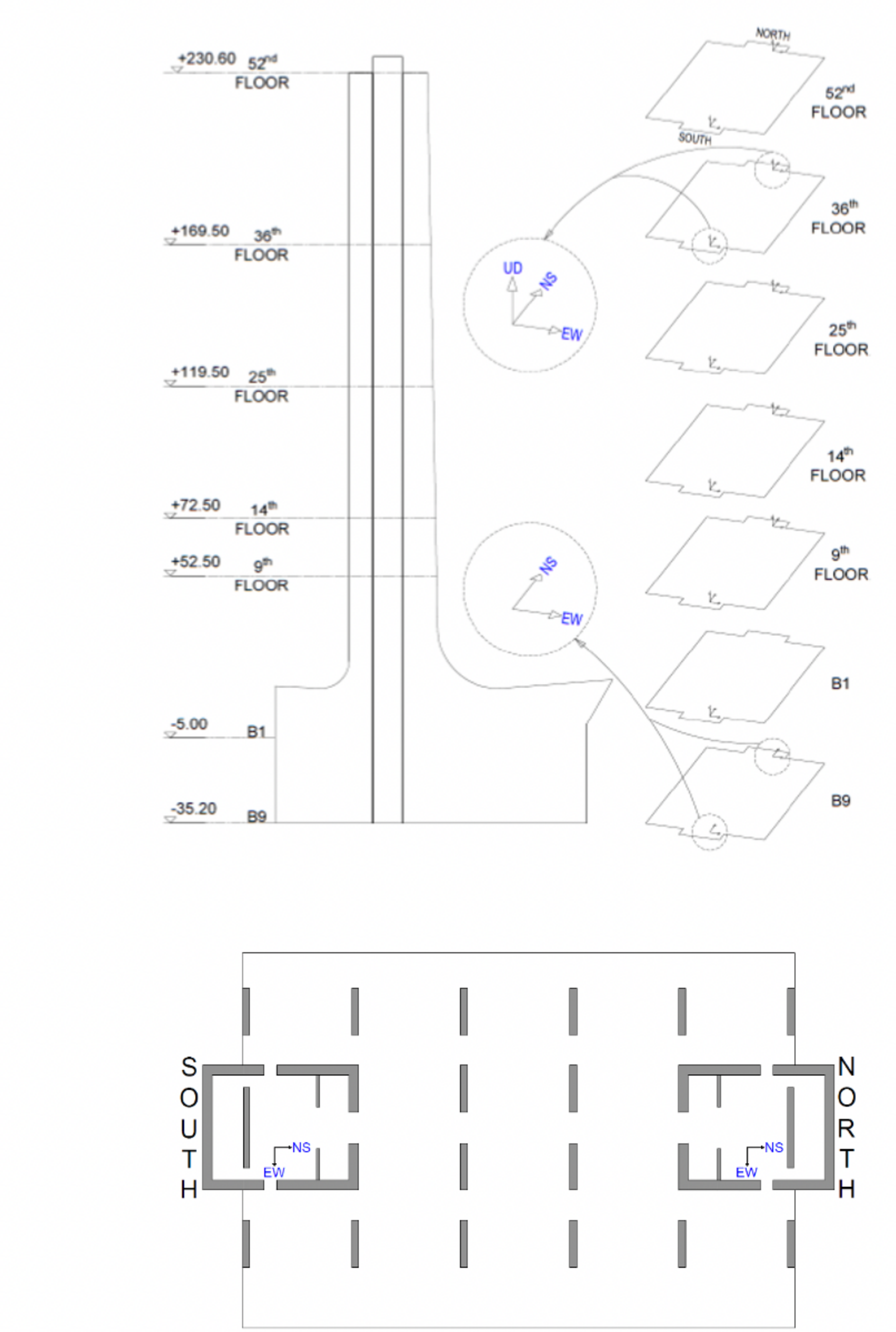

Fig. I.4 Location and orientations of the sensors in the Sapphire building (vertical elevation and plan view).

5. Attenuation of shaking parameters

We have used the records from the land stations only of the EEW network in Istanbul to calculate the attenuation of various shaking parameters from each EEW station to Sapphire Building. The map in Figure I.5 shows the on-land EEW stations and the building location.

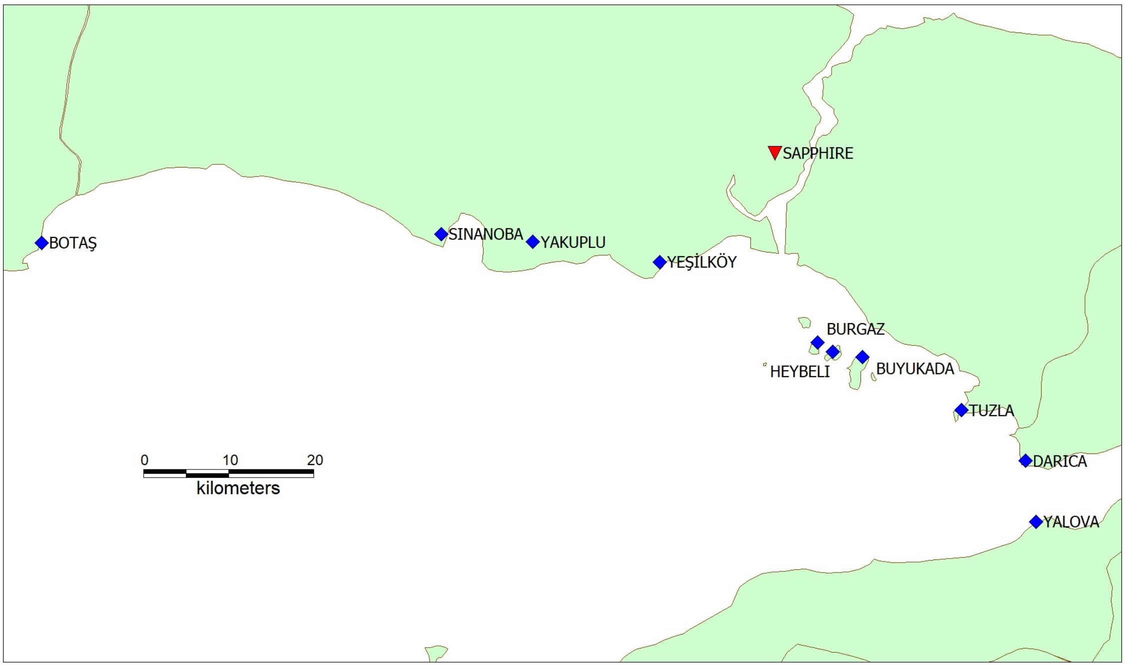

Figure I.5. *On-land EEW stations and the location of Sapphire Building.*

The following shaking parameters, which are commonly assumed to control damage in structures, are used for the attenuations:

- PGA - Peak Ground Acceleration
- PGV- Peak Ground Velocity
- SA02 – Spectral Acceleration at 0.2 second period.
- SA1– Spectral Acceleration at 1.0 second period.
- CAV – Cumulative Absolute Velocity
- Ia – Arias's Intensity
- SI _ Spectral (i.e., Housner's) Intensity

We have calculated the attenuation of each shaking parameter from each EEW station to Sapphire Building for the 35 earthquakes with M_L>4.0. As an example, we show the attenuations of PGA and PGV from Burgaz EEW to Sapphire Building in Figure I.6 below. The blue circles correspond to the earthquakes who's the epicentral distance to the building is smaller than the epicentral distance to the EEW station, and the blue circles represent the opposite. The results for the remaining ground motion parameters and the EEW stations are presented in Appendix I.

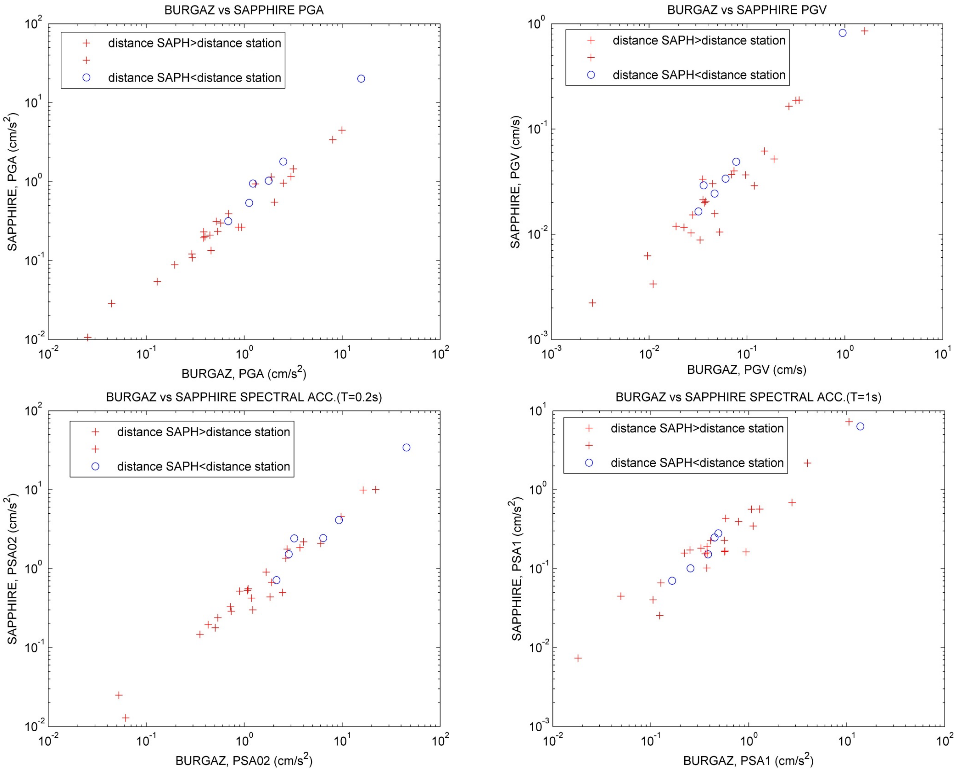

Figure I.6. Attenuation from Burgaz EEW station to Sapphire Bldg. for PGA, PGV, SA(0.2) and SA(1.0)

6. System Identification of Sapphire Building from the recorded response

We were not able to obtain the structural design drawings and calculations from the building's owner due to the confidentiality of the information. Therefore, we were forced to use the monitoring data from five different earthquakes to identify the structural properties of Sapphire Building. We have used advanced tools and techniques for the identification.

Since some of the techniques required that we have the records of every floor, we first had to estimate the accelerations at the non-instrumented floors from those of the instrumented floors. For this, we have used a modified version of the MSBE (Mode-Shape Based Estimation) approach introduced by Kaya, et. al. (2015). The modified approach, abbreviated as MMSBE, is based on the Timoshenko and Bernoulli-Euler beam theories, and approximates the response not only at modal frequencies but at all the frequencies (Çağlar and Şafak, 2022). The tests and confirmation of the MMSBE method, and the estimated records at non-instrumented floors are presented in Appendix II.

For system identification, we use the transfer matrix formulation of the response, introduced in Cetin and Safak (2021). In this approach, a multi-story building is modeled as a superposition of one-story structures, one put on top of the other. System identification involves finding the natural frequencies and damping of each story, as it were a single-story building. Moreover, the shear wave and phase velocities of each story are also identified.
Figure 7 shows the variation of story frequencies calculated from the for the E-W and N-S direction records in the building. Note that there are two sensors in each direction (Fig. I.4). Also note that the stories with a sharp drop in the story frequency correspond to commercial floors

near the ground with shopping mall, pool, and restaurants, or mechanical floors where the story heights are twice the normal story height. It should be mentioned here that such variations in the story stiffness cannot be identified by using standard modal identification techniques.

Knowing such properties of each story, we can reconstruct a much more accurate analytical model of the building than a standard model identification would permit. Comparisons of the measured responses from five earthquakes with those calculated using the analytical model gives a very good match. The details of the system identification, the analytical model devel-opement, and the confirmation of the model accuracy are all presented in Appendix II.

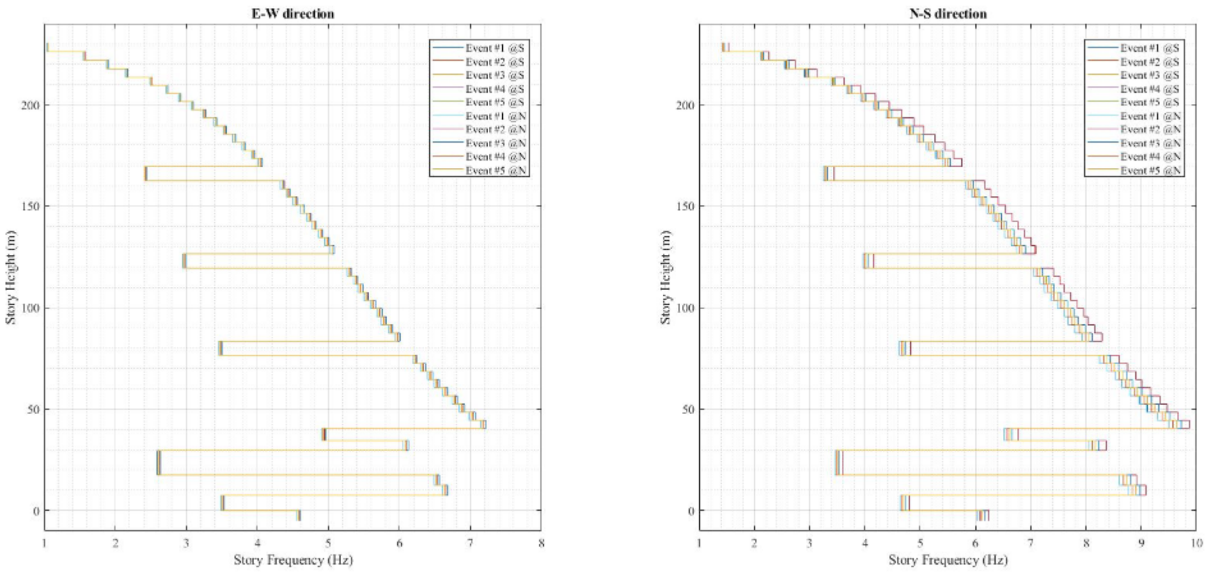

Figure I.7. Variation of E-W and N-S story frequencies along the height of the building.

7. Critical response parameters and base motions for safety

After developing a calibrated analytical model of the building from five earthquakes, we identified the parameters of the base accelerations that will cause response components critical for the building's safety. For the base ground motions, we used the parameters PGA (Peak Ground Ac-celeration) and PGV (Peak Ground Velocity), and the values of Spectral Acceleration (PSA), Spectral Velocity (PSV), and Spectral Displacement (SV) at the first modal frequency of the build-ing. For the critical response parameters, we used the allowed top-story displacement and inter-story drift values as specified in the latest Turkish seismic design code.

The code considers four different levels of earthquakes:

- DD1: 2% probability of exceeding in 50 years, corresponding to a return period of 2475 years.
- DD2: 10% probability of exceeding in 50 years, corresponding to a return period of 475 years.
- DD3: 50% probability of exceeding in 50 years, corresponding to a return period of 72 years.
- DD4: 50% probability of exceeding in 30 years, corresponding to a return period of 43 years.

The design spectra, in terms of PSA, for each earthquake level is generated based on the following figure (Fig. I.8) and the table, Table I.2:

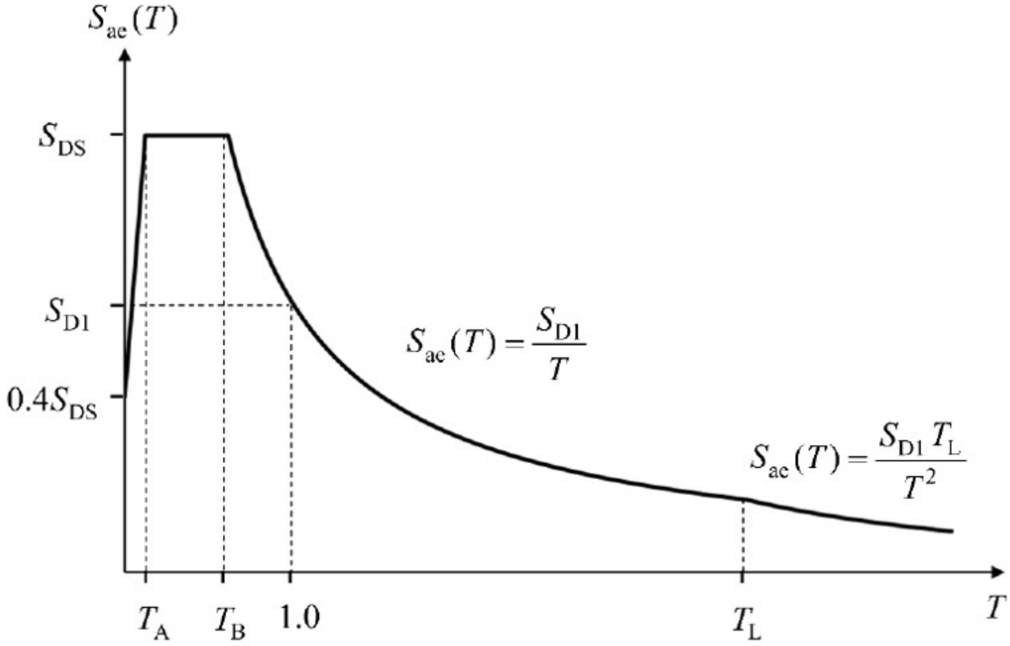

Figure I.8. Design spectra as specified in Turkish

Table I.2. Parameters of design spectra for four different levels of earthquake.

	S_S	**S_1**	**S_{DS}**	**S_{D1}**	**PGA**	**PGV**
DD1	1.335	0.372	1.602	0.558	0.543	33.360
DD2	0.752	0.216	0.902	0.324	0.312	19.517
DD3	0.296	0.089	0.385	0.134	0.129	8.248
DD4	0.193	0.058	0.251	0.087	0.084	5.439

Based on the above parameters, the design spectra for four different earthquake levels are presented in Figure I.9.

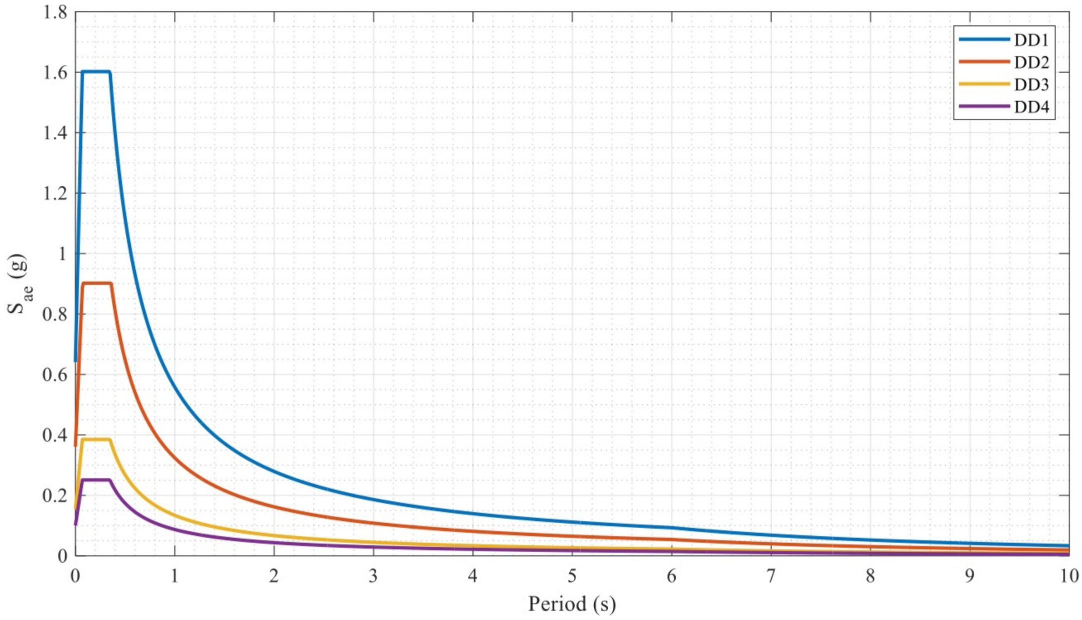

Figure I.9. Design spectra for four different levels of

To evaluate the performance of the building, and using the analytical model developed, the probability of exceeding the code-specified 2% Spectral Acceleration, Spectral Velocity, and Spectral Displacement associated with the first modal frequency and 5% damping is calculated based on the drift at the top of the building. Since five earthquakes are not enough to develop the probability curves, we selected 178 more earthquakes from the PEER Ground Motion Database (https://ngawest2.berkeley.edu/users/sign_in?unauthenticated=true). The selection is based on the magnitudes (M>5) and the similarity of the fault rupture mechanisms for Istanbul (strike-slip). The list of earthquakes selected is given in Appendix II. As an example, Figure I.10 shows below the probability of exceedance curve of the code drift limit with PSA in the E-W direction. The probability of exceedance curves for the other ground motion parameters (PSA, PSV, SA, SV, SD) at first modal frequency in the E-W and N-S directions are presented in Appendix II.

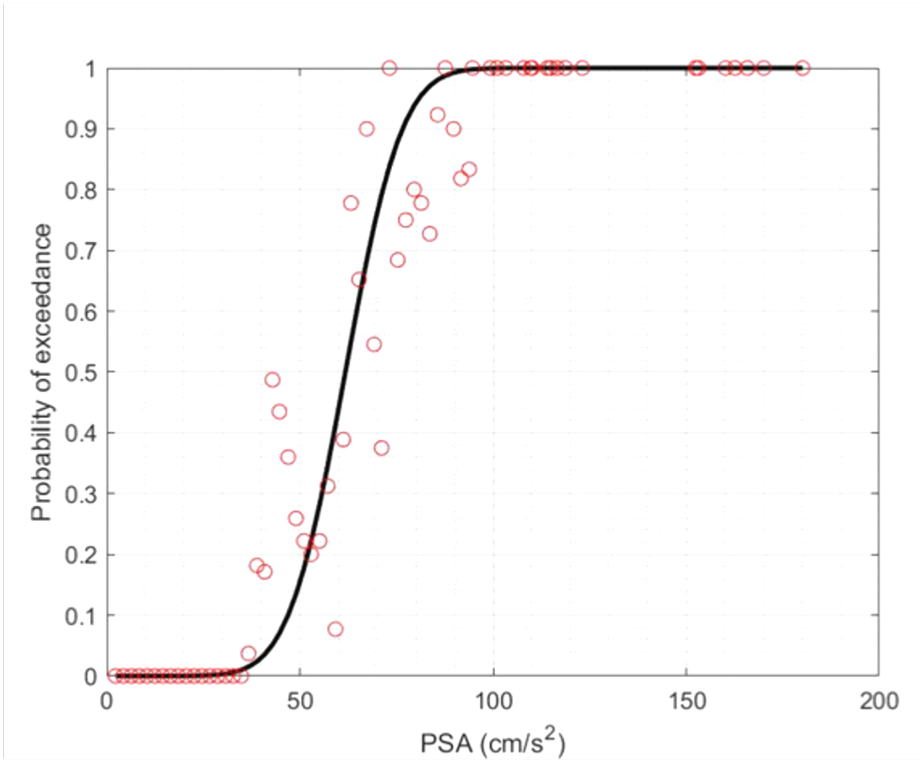

Figure I.10. Probability of exceedance of 2% code drift limit with PSA at the first modal frequency in the E-W direction.

8. Selection of threshold ground motion values at the EEW stations

The selection of threshold ground motion values at the EEW stations requires the following steps:

1. Select the design earthquake that will be considered for the building's safety (e.g., D1,D2,D3,or D4 level earthquake). This selection is based on the performance criteria (i.e., acceptable damage level for a specified return period of earthquake, importance of the building, etc.), and decided by the design engineer.
2. By using the attenuation of ground motions from the EEW stations and the building, select the ground motion parameter for each EEW station that gives the best correlation between the corresponding values at EEW stations and the building's base (note that the best correlating parameter may be different for different EEW stations).
3. Select the acceptable probability of exceedance levels for the selected parameters. This is also decided by the design engineer depending on the importance of the building, acceptable damage level, and the selected return period of the earthquake.
4. Read the corresponding ground motion values from the probability curves for each parameter.
5. Read the values of the corresponding parameters at EEW stations from the attenuation plots.

References

1. Şafak,E.(1995).Detection and identification of soil-structure interaction in buildings from vibration recordings, *Journal of Structural Engineering*, ASCE, Vol.121, No.5, May 1995, pp.899-906.
2. Safak, E. (1999). Wave propagation formulation of seismic response of multi-storybuildings, *Journal of Structural Engineering*, ASCE, Vol. 125, No. 4, pp.426-437.
3. Kaya, Y ., S. Kocakaplan, and E. Şafak (2015). System identification and model calibration of multi-story buildings through estimation of vibration time histories at non- instrumented floors. *Bulletin of Earthquake Engineering 13(11)*, 3301–3323.
4. Cetin M, and E. Safak (2021) . An algorithm to calibrate analytical models of multi-story buildings from vibration records, *Earthquake Spectra, 1–17, DOI: 10.1177/87552930211046969.*
5. Caglar, N.M. and Safak, E. (2021). Predicting Seismic Response of a Tall Building to a Large Earthquake Using Recorded Waveforms from Small Earthquakes, accepted for presentation and will appear in the proccedings of the *European Safety and Reliability Conference,* 19-23 September 2021, Angers, France
6. Caglar, N.M. and E. Safak (2022). Estimation of the response of non-instrumented floors using the Timoshenko and Bernoulli-Euler Beam Theories, *Earthquake Engineering & Structural Dynamics*, 2022, Vol.1, No.3, DOI: 10.1002/eqe.3636

Appendices

I – Attenuation of ground motion parameters from the EEW stations to Sapphire Building

II – System identification and modeling of Sapphire Building

Part II – EEW efforts and initiatives at the Swiss Seismological Service

Part II - Table of Contents

1. EEW performance – benchmarked in Switzerland

The Swiss Seismological Service (SED) at ETH has been developing methods and open-source software for Earthquake Early Warning (EEW) for more than a decade and has been using SeisComP for earthquake monitoring since 2012. The SED has built a comprehensive set of SeisComP modules that can provide EEW solutions in a quick and transparent manner by any seismic service operating SeisComP (Fig. II.1). To date, implementations of the Virtual Seismologist (VS) and Finite-Fault Rupture Detector (FinDer) EEW algorithms are available. VS provides rapid EEW magnitudes building on existing SeisComP detection and location modules for point-source origins. FinDer matches growing patterns of observed high-frequency seismic acceleration amplitudes with modeled templates to identify rupture extent, and hence can infer on-going finite-fault rupture in real-time. Together these methods can increase the tolerance to failures of a single algorithm, while providing EEW for all event dimensions from moderate to great, if a high quality, EEW-ready, seismic network is available.

The performance is benchmarked in Massin et al, 2021 and sample performance is seen in Fig. II.2. In Switzerland, both algorithms are observed to be similarly fast, and can often produce first EEW alerts within 4–6 s of origin time. The pick-based VS method provides fast locations and magnitudes for any event that triggers the national network. Since 2014, the median delay for the first VS alert is 8.7 s after origin time (56 earthquakes since 2014, from M2.7 to M4.6). FinDer relies on recognition of peak amplitudes exceeding a certain threshold (here 2 cm/s2), so is only activated for larger events (M > 3.5), but events as small as M2.7 have been detected. Since 2017, the median delay for the first FinDer alert is 7 s (10 earthquakes since 2017, from M2.7 to M4.3). Playbacks of the largest 100 events, with M ≥ 2.7, over the last 10 years using the current configuration indicate median delays of 7.3 and 5.8 s for VS and FinDer, respectively–though FinDer only provides a solution for 37 of these events. The median value for the travel time of the P waves from event origin to the fourth station accounts for 3.5 s of delay; with an additional 1.4 s for data sample delays in real-time testing.

The Swiss Seismic Network continues to be optimised for EEW. Today over 175 permanent stations include strong motion stations, and the majority of stations have been upgraded to include low-latency streaming. Station uptime is high. With the EEW methodologies integrated in SeisComP, and the quality of the monitoring infrastructure, the ESE system in Switzerland is achieving a performance in terms of speed that is similar to the US ShakeAlert EEW system.

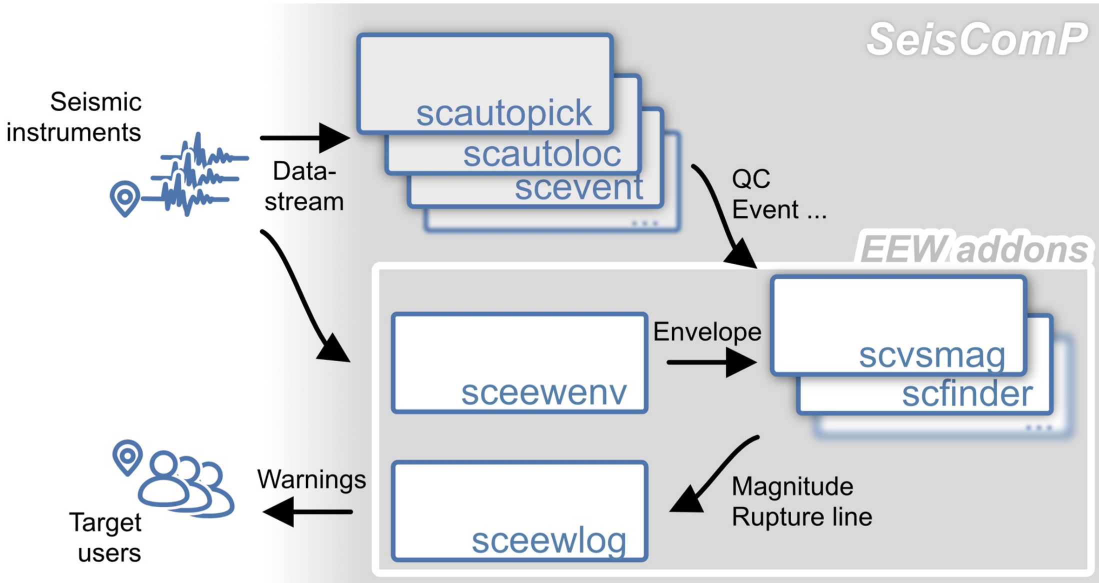

Figure II.1 (from Massin et al., 2021). Schematic workflow of the SED-ETHZ SeisComP EEW system (ESE). The main SeisComP framework includes automatic picking and location modules (scautopick and scautoloc) which can be tuned for event detection with P-wave arrival detection at four stations. The VS algorithm is implemented in the scvsmag module. FinDer is a stand-alone library that is integrated in the scfinder wrapper module. SeisComP event detections are fed into VS together with acceleration and displacement envelope amplitudes (provided by the sceewenv module), while FinDer only relies on envelopes for detecting intermediate events with co-seismic ground motion detection at three stations. Both can provide EEW to target users via the sceewlog module using multiple real-time dissemination interfaces. It allows the EEWD open-source client software to display end-user EEW information (Cauzzi et al., 2016).

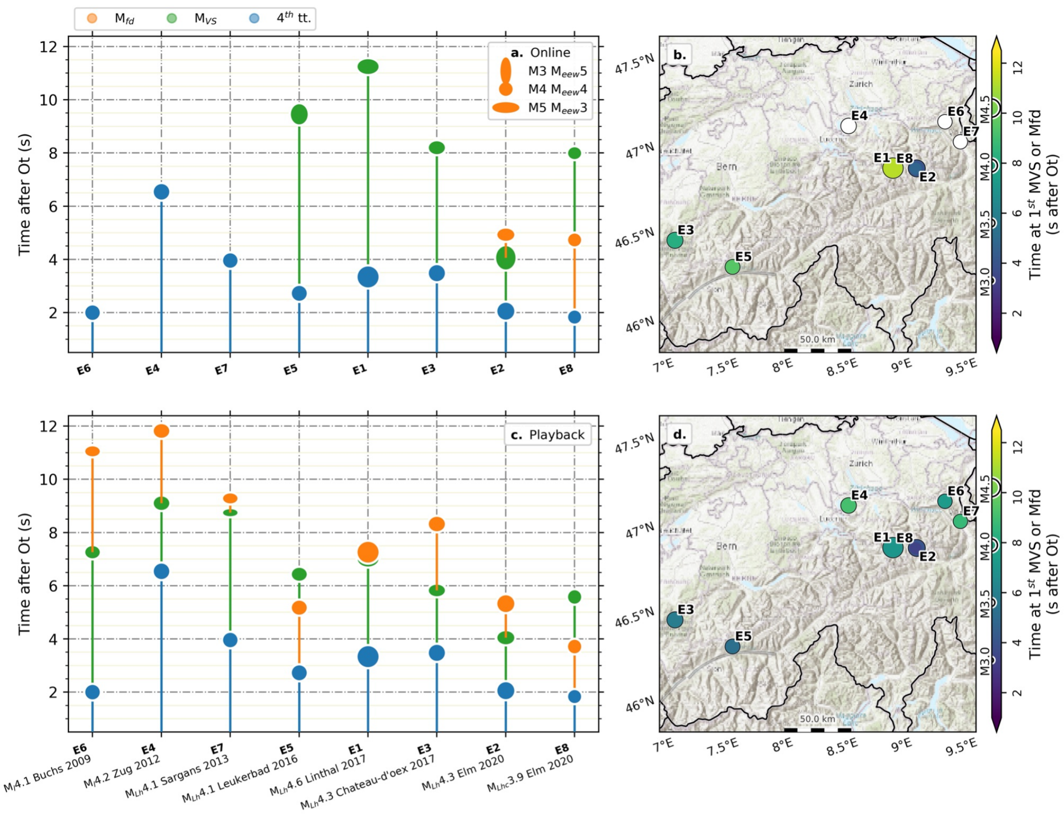

Figure II.2 (from Massin et al., 2021). Temporal (A,C) and geographical (B,D) overview of the VS (green), and FinDer (orange) performance for the eight largest earthquakes over magnitude 3.9 in Switzerland since 2009. (A,B) Online (real-time) results, provided by the real-time ESE system. The online ESE database includes VS results since late-2014, and FinDer results since mid-2017. The VS primary location method has been configured for using four stations since mid-2017. (C,D) Playback results, obtained with the ESE playback system. The EEW methods in the playback system are configured in a similar way to the post-2019 online system with the exception of one parameter in one of the VS location methods, adjusted for not aggregating triggers more than 7 s apart.

References:

C. Cauzzi, Y. Behr, J. Clinton, P. Kästli, L. Elia, A. Zollo, An Open-Source Earthquake Early Warning Display. Seismological Research Letters. 87 (2016), pp. 737–742

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

2. Contributions to operational and emerging EEW systems across the world

2.1 US West Coast ShakeAlert System

Recently, the U.S. Geological Survey (USGS) began the testing of the ShakeAlert EEW system for public notification in California (2019) and Oregon (2021) and Washington (2021) through the Wireless Emergency Alert system (WEA) and cell phone apps. The alert thresholds depend on the means of delivery and currently range from Modified Mercalli Intensity (MMI) III (weak or larger shaking) to MMI V (moderate or larger shaking) and magnitude estimates of 4.5 or 5.0.

The system consists of 2 independent seismic EEW algorithms, the EPIC point-source algorithm (Chung *et al.*, 2019) and the FinDer finite-source algorithm (Fig. II.3). The ETH team manages the scientific development of FinDer. Recent improvements as implemented in FinDer v3 (Böse et al., under review) include the handling of latent seismic data, robust event detection in regions with sparse instrumentation, enabling faster magnitude convergence in large earthquakes, use of fault- and scenario-specific earthquakes (e.g. along the Cascadia subduction zone or San Andreas Fault), as well as increased robustness in complex earthquake sequences.

Due to its superior performance in recent large earthquakes (e.g. 2021 M6.2 Petrolia, 2021 M6.0 Antelope Valley, 2019 M7.1 Ridgecrest) as well as in real and simulated earthquake sequences (Böse et al., 2022a), in which EPIC struggled for various reasons, FinDer is now allowed to issue alerts for M6+ earthquakes without requiring an additional EPIC detection.

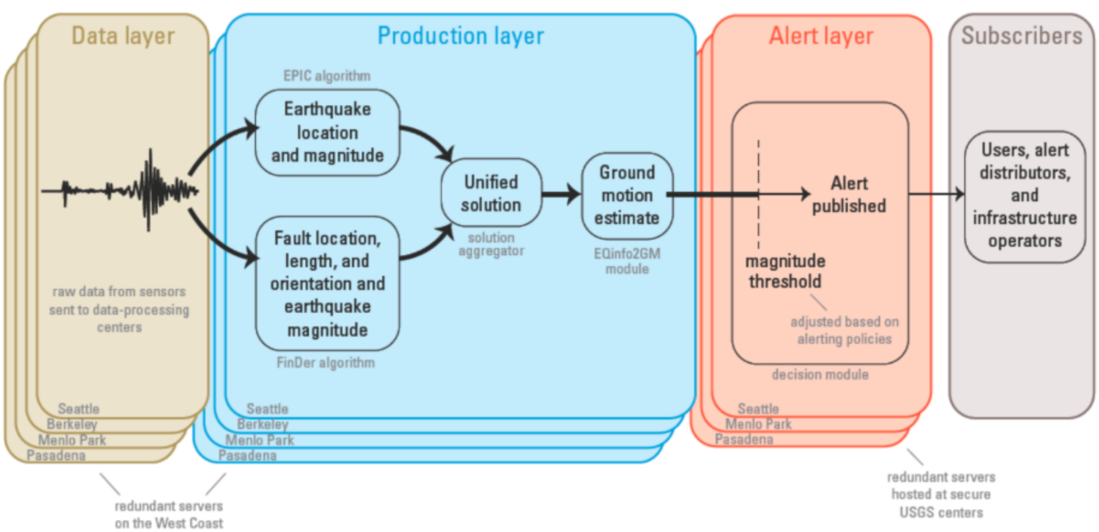

Figure II.3. From Revised Technical Implementation Plan for the ShakeAlert System (Open-File Report 2018-1155)

References:

Böse, M., J. Andrews, C. O'Rourke, D. Kilb, A. Chung, J. Bunn, and J. McGuire (2022a) Testing the ShakeAlert Earthquake Early Warning System using Synthesized Earthquake Sequences, *Seismol. Res. Lett.* XX, 1–17, https://doi.org/10.1785/0220220088.

Böse, M., J. Andrews, R. Hartog, and C. Felizardo (under review). US West Coast ShakeAlert Warning System: Development and Performance of Finite-Fault Rupture Detector (FinDer) v.3, subm. to *Bull. Seismol. Soc. Am.*

2.2 Central America

As the population density of Central America countries increases and most of the building stock remains vulnerable, ground shaking from subduction and shallow crustal earthquakes can be expected to cause collapse of infrastructure and loss of life. Alternative ways to mitigate the increasing earthquake risk for vulnerable populations are a priority. National seismic agencies in Guatemala (INSIVUMEH), El Salvador (MARN), Nicaragua (INETER) and Costa Rica (OVSICORI-UNA) are collaborating with SED/ETH-Zurich to develop solutions for public EEW in the ATTAC project (Alerta Temprana de Terremotos en América Central, Massin et al. 2018, Massin et al. 2020, Porras et al. 2021).

Each national ATTAC EEW system operates on existing high quality permanent seismic networks and implements the ETHZ-SED SeisComP EEW (ESE) system that uses the Virtual Seismologist and the Finite-Fault Rupture Detector algorithms. The seismic stations have been optimized to allow minimum latency data and are complimented by 70 new low-latency EEW-ready accelerographs, deployed across the region (Fig. II.4).

The current EEW alerting performances are analyzed in terms of accuracy and ground-motion parameters in Figures II.5 (single event example) and II.6 (since beginning of monitoring). We demonstrate that EEW in the region is fast and accurate for all felt earthquakes. Typical first alert delay times range from 10-15s for shallow on-shore seismicity, and between 20-25s for off shore or deep events. False alerts occur, and are typically related to configuration and metadata errors, hence it remains a priority to improve network practice and EEW software management.

Current test select users can receive alerts from digital TV and a mobile app, each of which can be expected to scale to the population. We intend to provide EEW alerts across the region through realistic technologies and to extend alerts to the public. The ESE framework will be extended with a cockpit to monitor EEW performance; and a decision module that combines results from different algorithms and provides tailored alerts; tools for automatic supervision; fault-specific FinDer solutions, and future data types (e.g., cellphone, GNSS). Within the next 2 years, we expect nation-wide public EEW to become operational amongst the participant countries.

References:

Massin, F., Strauch, W., Andrews, C. J., Böse, M., and Ramirez, J. (2018). Building EEW in Nicaragua: Performance and Perspectives. Seismol. Res. Lett. 89 (2B), 717–966. doi:10.1785/0220180082

Massin, F., Clinton, J., Racine, R., Böse, M., Rossi, Y., Marroquin, G., et al. (2020). "The Future strong Motion National Seismic Networks in Central America Designed for Earthquake Early Warning," in EGU General Assembly Conference Abstracts, Vienna, Austria, 19437. doi:10.1785/0220200043

Porras J, Massin F, Arroyo-Solórzano M, Arroyo I, Linkimer L, Böse M and Clinton J (2021) Preliminary Results of an Earthquake Early Warning System in Costa Rica. Front. Earth Sci. 9:700843. doi: 10.3389/feart.2021.700843

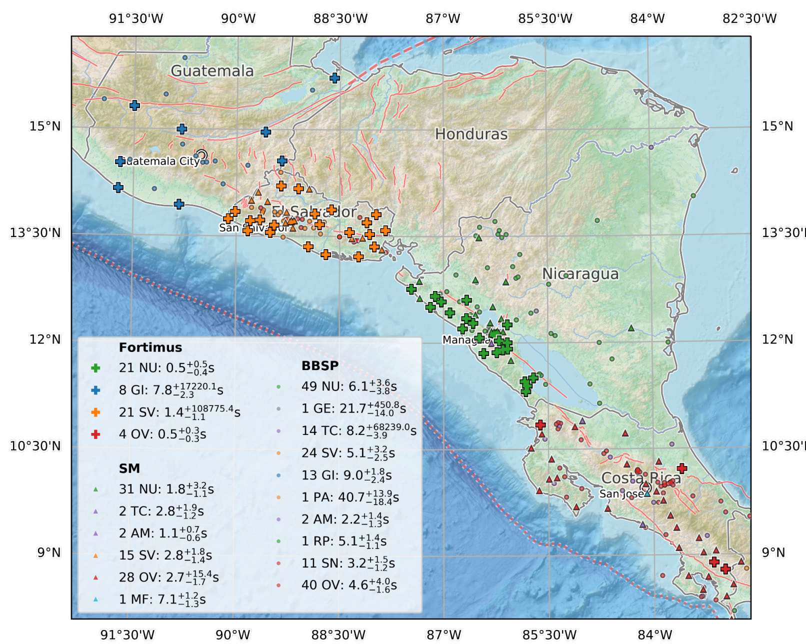

Figure II.4. Permanent seismic network map from October 2022. Stations that include strong-motion sensors (SM) include both force-balance and MEM accelerometers. Stations with only a velocity sensor (BBSP) includes either seismometers or geophones - these will clip in strong motion, though are useful for P-wave arrivals. EEW-ready strong-motion seismic stations (Fortimus) have been deployed from 2021

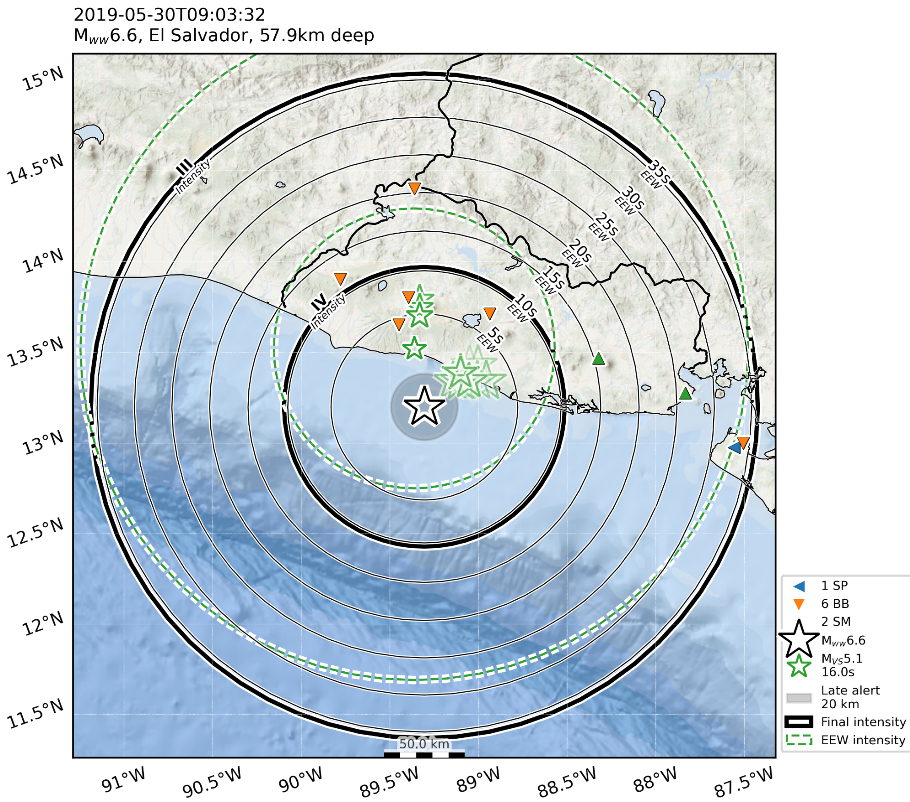

Figure II.5: Summary of ESE EEW performance during the 2019 M_{WW}6.6 El Salvador earthquake as recorded at MARN in El Salvador. VS origins are indicated in green stars (brighter represents earlier estimates) and the final USGS catalog location is the black star. Intensity iso-lines from the catalog origin (solid black) can be compared to the earliest EEW estimates (dashed green lines), following a generic intensity prediction equation (Allen et al., 2012). The late alert area (grey circle) and available warning (lead) time from the EEW (thin black lines, modeled as the time difference between the S-wave arrivals, as predicted from the iasp91 velocity model, and the first EEW solution) are indicated.

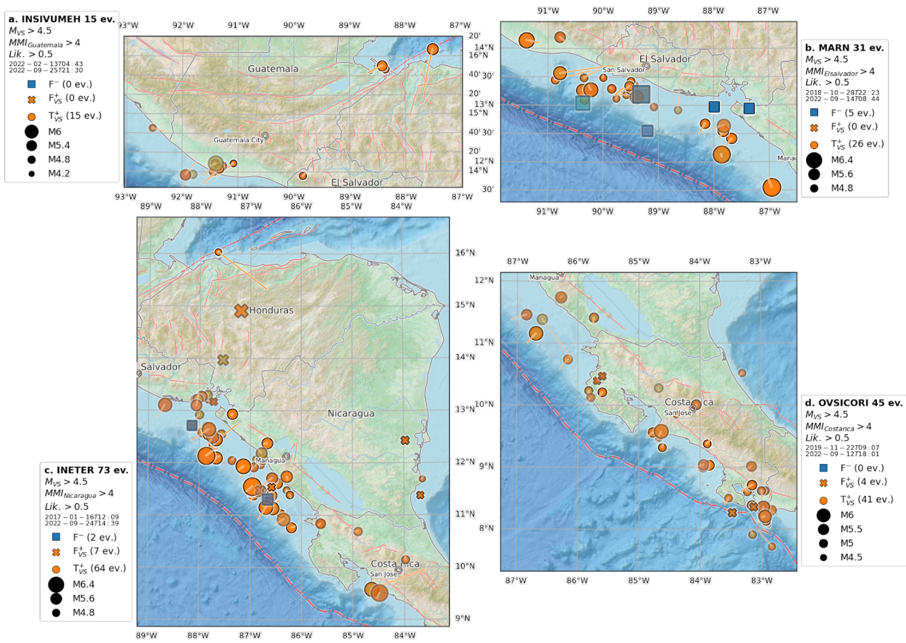

Figure II.6: EEW alert performance up to October 2022 using the VS algorithm, considering EEW solutions exceeding M_{VS}4.5, VS internal likelihood over 0.5, and MMI IV anywhere in each of Guatemala (a), El Salvador (b), Nicaragua (c) and Costa Rica (d) since monitoring began. True positive EEW (T+) are EEW solutions matching an actual earthquake. False positives (F+) are EEW solutions not matching any seismic event, typically related to configuration and metadata errors. False positive (F-) are actual earthquakes without EEW solutions over the alerting threshold, often due to poor likelihood.

3. Research initiatives

3.1 Decision Module to combine generic EEW solutions

Both VS and FinDer provide an independent EEW estimate of the source parameters which allows for redundancy and increases the tolerance to failure of one of the algorithms. Both algorithms have their strengths and weaknesses that may lead to different estimates depending on source properties, network geometry, as well as data quality. Having an efficient real-time method to combine and select a preferred estimate is critical. We have explored how to combine the independent algorithm estimates in a probabilistic manner, adapting the approach outlined in Minson et al. (2017). The estimates are used to predict ground motion envelopes at a set of stations which are then compared with the observed envelopes. The differences in the predicted and observed envelopes are then used to calculate the probabilities that the estimate from an algorithm is correct, when compared with the other estimate(s) (Fig. II.7). In addition, we explored the ways of getting an absolute measure of an algorithm being correct by looking at the goodness-of-fit between the observed and predicted envelopes. The goodness-of-fit module provides a measure which can be used to determine when a preferred solution (obtained by the first algorithm) reaches an appropriate confidence level, or can be used to compare the two (or more) different solutions directly. So far algorithm development has used the 10 largest earthquakes occuring in and around Switzerland between 2013 and 2020. We then perturb the parameters of these events to measure the sensitivity of our approaches to wrong solutions. This approach can be used to suppress false alarms inside a seismic network by either comparing the solutions to noise-only predictions (following the first approach), or by calculating the goodness-of-fit of the false alarm solutions. We tested the false alarms discrimination on a set of false events that occurred between 2013 and 2022, and include quarry blasts, regional earthquakes, teleseismic earthquakes, and other signals which are not of network interest. We intend to publish this promising results in early 2023.

References:

Minson, S. E., Wu, S., Beck, J. L., and Heaton, T. H. (2017). Combining Multiple Earthquake Models in Real Time for Earthquake Early Warning. Bull. Seismological Soc. America 107(4), 1868–1882. doi:10.1785/0120160331

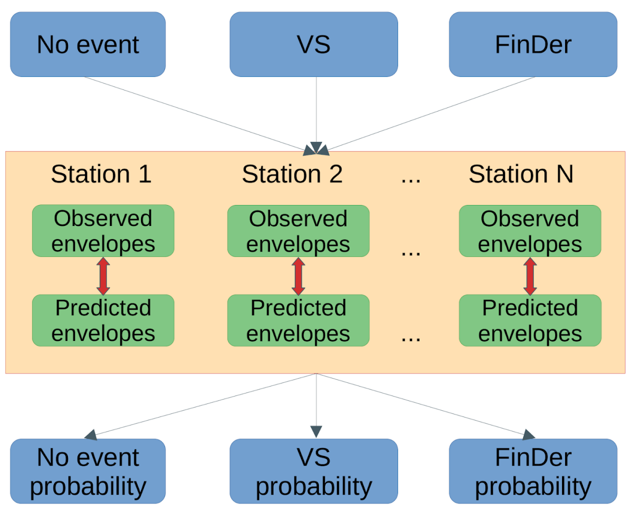

Figure II.7. Overview diagram of the procedure to compare and prefer EEW solutions

3.2 Combining FinDer with Felt Reports

Many countries cannot afford to operate the dense seismic networks required to quickly determine fault rupture geometry. In Böse et al. (2021a) we apply FinDer to felt intensity reports collected by the European Mediterranean Seismological Centre (EMSC) for 36 global earthquakes (6.0 ≤ M ≤ 7.3). We find that the resulting FinDer line-source models achieve good agreement with the finite-source models published in the literature for many earthquakes. In April 2021 we started to automatically calculate FinDer line-source models for global earthquakes within 10 to 120 minutes of their occurrence, provided a sufficient number of felt-reports is available. More than 100 global earthquakes (5 ≤ M ≤ 7.5) have been detected and processed so far. The resulting models are currently shared internally with the SED and EMSC groups to evaluate the results and optimize the processing.

Reference

Böse, M., S. Julien-Laferriere, R. Bossu, and F. Massin (2021a). Near Real-Time Earthquake Line-Source Models Derived From Felt-Reports, *Seismol. Res. Lett.* 92 (3), 1961–1978. doi: https://doi.org/10.1785/0220200244.

3.3 Embedding FinDer in ShakeMap - application in New Zealand

Motivated by FinDer's promising playback performance in the M7.8 Kaikoura and other recent strong earthquakes in New Zealand, the Institute of Geological and Nuclear Sciences (GNS Science) and the ETH EEW Team have set-up a SeisComP system to compute FinDer models in real-time for on- and off-shore seismicity in New Zealand. The system has been live since October 2022. The resulting models will support the generation of rapid response information and may be integrated into national ShakeMaps in the future (Böse et al., 2022b).

Reference:

Böse, M., Y. Behr, F. Massin and J. Andrews (2022b). Testing the Finite-Fault Rupture Detector (FinDer) in New Zealand, 2022 Annual Meeting Seismological Society of America Technical Sessions, 19–23 April, Bellevue, Washington

3.4 Combining Seismic and Geodetic Data for EEW – FinDerS(+)

In Böse et al. (2021) we propose two extensions to FinDer, called FinDerS and FinDerS+, which have the advantage of taking into account a geological property of the source fault, its structural maturity, as well as its relation to the earthquake slip distribution. These two new algorithms calculate real-time earthquake slip profiles by backprojecting seismic and/or geodetic displacement amplitudes onto the FinDer line-source. This backprojection is based on a general empirical equation established in previous work that relates dynamic peak ground displacement (PGD) at the stations to on-fault co-seismic slip. While FinDerS projects PGD onto the current FinDer line-source, FinDerS+ allows the rupture to grow beyond the current model extent to predict future rupture evolution. For an informed interpolation and smoothing of the estimated slip values, FinDerS and FinDerS+ both employ a generic empirical function that has been shown to relate the along-strike gradient of structural maturity of the ruptured fault, the earthquake slip distribution, and the rupture length (Hutchison et al., 2020).

References:

Böse, M., A.A. Hutchison, I. Manighetti, J. Li, F. Massin, and J.F. Clinton (2021b). FinDerS(+): Real-time Earthquake Slip Profiles and Magnitudes Estimated from Backprojected Slip with Consideration of Fault Source Maturity Gradient, *Front. Earth Sci.* 9, doi: https://doi.org/10.3389/feart.2021.685879.

Hutchison, A. A., Böse, M., & Manighetti, I. (2020). Improving early estimates of large earthquake's final fault lengths and magnitudes leveraging source fault structural maturity information. *Geophysical Research Letters*, e2020GL087539.

3.5 Cost Benefit Analysis

In Böse et al (2022c) we develop a multi-level framework for a loss-based performance evaluation and seismic network optimization for EEW. We use warning time as a key performance indicator and assess the loss-based performance of an EEW system for a given spatial distribution of earthquakes, sensors, and exposures. Using a genetic algorithm, we optimize this senor network by proposing sites for new stations in order to optimize its EEW performance while minimizing the costs for this investment. We demonstrated this approach for Switzerland using a stochastic earthquake catalog, which samples the earthquake rate forecast of the Swiss Hazard Model in space and time. We adopt a simple consequence model to relate the predicted intensities to losses (here: fatalities). We assume that the number of fatalities can be reduced, the longer warning times are provided, and optimize the sensor network accordingly. The output of this work provides the input to a more detailed cost-benefit analysis for EEW in our companion paper (Papadopoulos et al., under review).

References:

Böse, M., A. N. Papadopoulos, L. Danciu, J. F. Clinton, and S. Wiemer (2022c). Loss-based Performance Assessment and Seismic Network Optimization for Earthquake Early Warning, *Bull. Seismol. Soc. Am.* 112 (3): 1662–1677,https://doi.org/10.1785/0120210298.

Papadopoulos, A.N, M. Böse, L. Danciu, J. Clinton, and S. Wiemer (under review). Effectiveness of Earthquake Early Warning in Mitigating Seismic Risk, subm. to *Earthquake Spectra*.

3.6 Social Science in Switzerland and Central America

EEW systems are well established and provide public alerts in a number of regions including Japan, Mexico, and along the US West Coast (Allen & Melgar, 2019). Despite their specific and often unique characteristics (for example different EEW algorithms, tectonic settings, network geometry), these systems have all faced similar challenges with regard to social issues. When establishing EEW systems, initial efforts focus mainly on the scientific and technical aspects, societal issues were taken into account only at a later stage.

However, in recent years numerous research studies have focused on including the societal perspective in EEW. Following major earthquakes, national surveys were carried out which helped to shed light on the importance of incorporating the public needs perspective in the development of an EEW system (e.g., tolerance of alert limitations, addressing misconceptions, preferred alert threshold). In the course of RISE, Dallo et al. (2022), focusing on Switzerland, and Oriheula et al. (in preparation) took a different approach and have conducted social science surveys prior to the installation of public EEW systems. Thus, the preferences, needs and concerns of the public can be assessed before the EEW system is operating. Dallo et al. (2022) further stressed the importance of the message design, i.e. alerts with pictograms trigger people to protect themselves on the spot. Both studies provide unique perspectives. Dallo et al. (2022) provides information from a region with comparatively lower seismic hazard. Orihuela et al (in preparation) focus on Central America - for the first time looking at the social perspective of EEW in countries with emerging economies.

References:

Allen, R. and D. Melgar (2019) Earthquake Early Warning: Advances, Scientific Challenges, and Societal Needs. Annual Review of Earth and Planetary Sciences

Dallo, I., M Marti, J Clinton, M Böse, F Massin, S Zaugg (2022) Earthquake early warning in countries where damaging earthquakes only occur every 50 to 150 years–The societal perspective. International Journal of Disaster Risk Reduction.

4. Software development and distribution

The EEW group at SED developed the ETHZ-SED SeisComP EEW (ESE) system. It consists of multiple modules that are integrated in the SeisComP software package, the real-time monitoring system that is used by the majority of seismic networks across the world, including many in Europe. This makes distribution, deployment and testing of EEW software easy. Further information is in Massin et al., 2021 and at https://github.com/SED-EEW.

Reference:

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

SUMMARY

This report comprises the deliverable, ***D4.6 - Performance-based early warning systems in Europe***, as part of the requirements in the ***EU H2020 Project, RISE-Real-time Earthquake Risk Reduction for a Resilient Europe***. The report is presented in two parts because of the differences in their objectives.

Part I presents a location- and structure-specific Earthquake Early Warning (EEW) algorithm. It requires a network of EEW ground stations, and instrumented buildings. The approach is based on the comparison of the predicted versus threshold response for structural safety. As an example, we use an instrumented tall building, the Sapphire Building, in Istanbul, where there is also a 10-station early warning seismic network. First, by using available earthquake records from the EEW stations and the building monitoring system, we develop equations for the attenuation of critical shaking parameters from the each EEW station to the building's base. We identify the critical threshold response parameters for the performance of the building and the corresponding critical foundation motions. By using the attenuation equations developed, we then identify the ground motion at each EEW stations that will cause the critical foundation motion at the building. The identified EEW values are used to issue an early warning for the building before seismic waves reach to the building. This would give about 5 to 7 seconds early warning time.

Part II presents seismological applications of EEW, based on records from a network of ground stations. The emphasis is on the studies of the Swiss Seismological Service (SED) at ETH, covering the methods and the software that have been developed. Contributions to operational and emerging EEW systems across the World, including the US, Central America, and New Zealand are also discussed. Moreover, Part II summarizes new research initiatives, such as developing a decision module to combine generic EEW solutions and geodetic data, creating a multi-level framework for a loss-based performance evaluation and seismic network optimization, and incorporating the public needs perspective and social science in the development of an EEW system.