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Earthquake Early Warning and Operational Earthquake Forecasting as Real-Time Hazard Information to Mitigate Seismic Risk at Nuclear Facilities.

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Abstract

Based on our experience in the project REAKT, we present a methodological framework to evaluate the potential benefits and costs of using Earthquake Early Warning (EEW) and Operational Earthquake Forecasting (OEF) for real-time mitigation of seismic risk at nuclear facilities. We focus on evaluating the reliability, significance and usefulness of the aforementioned real-time risk-mitigation tools and on the communication of real-time earthquake information to end-users. We find that EEW and OEF have significant potential for the reduction of seismic risk at nuclear plants, although much scientific research and testing is still necessary to optimise their operation for these sensitive and highly-regulated facilities. While our test bed was Switzerland, the methodology presented here is of general interest to the community of EEW researchers and end-users and its scope is significantly beyond its specific application within REAKT.

1 Introduction and motivation

A major nuclear disaster occurred in 2011 in the coastal region of the Fukushima prefecture of Japan following the March 11th earthquake and large tsunami. This accident triggered: a vivid scientific (e.g. Lay et al., 2013), technical (e.g. Mori and Eisner, 2013) and public discussion on the safety of nuclear power plants (NPPs) worldwide; the key role of geosciences in properly assessing maximum magnitudes (e.g. Zoller et al., 2014) and earthquake hazard levels over different time scales (e.g. Satake et al., 2013; Hoshiba and Aoki, 2015); and the need to account correctly for the likelihood of extreme events in the engineering design of critical facilities. Over four years later, the dramatic social, environmental and overall estimated economic impact (~ 150 to 250 billion USD according to different sources) of the meltdown of three of the plant's six reactors still dominates the public and political debate on nuclear safety.

The International Atomic Energy Agency (IAEA, https://www.iaea.org/) considers the automatic shutdown of NPPs based on automatic SCRAM trip systems (ASTSs) as a potential option to ensure the safety of NPPs when an earthquake occurs (IAEA, 2011). ASTSs are generally implemented in high seismicity areas like Japan and California. In many other regions in the world earthquake-related ASTSs are not used. This is because of lower seismicity levels and the fact that automatic reactor shutdown is a delicate earthquake damage mitigation action. Shutting down a reactor takes several steps and a long time. With traditional SCRAM, i.e. triggered by the exceedance of a predefined peak ground acceleration (PGA) threshold, the earthquake shaking typically hits the plant during the initial stages of such a critical process. “During this phase some pieces of equipment will function and some not, and also some safety systems will be shut down. That is, during the shutdown procedure the risk is higher compared to full operations” (Renault 2014, personal communication). This is conceptually depicted in Figure 1, where the vulnerability curve associated with a nuclear reactor is sketched as a function of time. The reference dashed line in Figure 1 shows the vulnerability level under normal full operations, while the solid curve shows how vulnerability would vary after initiating emergency SCRAM. Indeed, IAEA points out that “the automatic SCRAM is best utilised if it leads to reactor trip before the maximum shaking of the earthquake” because of the risk of dangerous cumulative effects between seismic strong motions and transients that will result from the trip itself. Consequently, the IAEA implicitly opens the way to the technology of Earthquake Early Warning Systems (EEWSs; Gasparini et al., 2007), which under favorable conditions may constitute the only ASTSs able to initiate the automatic shutdown of NPPs before the arrival of potentially-destructive strong motions. Therefore, EEW is consistent with the international regulatory framework for the management of emergency situations at NPPs. IAEA recommends that each NPP puts in place a local network of sensitive weak-motion seismographs (velocity sensors) combined with a network or array of strong-motion accelerometers directly at the NPP site; thus suggesting the combined use of a regional (e.g., Cua and Heaton, 2007; Cua et al., 2009; Satriano et al., 2011; Behr et al., 2015a) and on-site EEW approach (e.g., Wu et al., 2007; Böse et al., 2009). Even so, the decision to implement an EEWS at a NPP and the identification of mitigation actions in response to EEW have to be informed by the reliability, usefulness and significance of the alert, along with the costs and benefits of the operational setup.

Figure 1 about here.

Is it appropriate to provide an NPP with an EEWS? Asked during the stage of a feasibility study, this question boils down to considering the pertinence of the use of an EEWS over time, including its reliability and speed, and an assessment of the set-up/operating costs in comparison with typical recurrence intervals of damaging earthquakes and the life-span of the NPP. The probability of occurrence of large events at a given site can be computed from the cumulative frequency-magnitude distribution typically used as input to Probabilistic Seismic Hazard Assessment (PSHA). If the EEWS is maintained by an academic or governmental institution system costs would typically include development and maintenance of the end-user software (e.g., 50% of a post-doc / scientific developer position), project management and liaison with end-users (e.g., 10% of a senior scientist position) as well as a partial cost (typically 1%) for operation of the existing seismic networks.

Assuming an existing EEWS, what would be the criteria and conditions to use the early warnings provided? Asked ahead of the operational setting-up of an EEWS to operators who are involved in the set-up, or at least when they are already convinced of the usefulness of EEWSs, this question considers only benefits and costs associated to a given warning and does not take into account operating costs.

Providing the elements for answering the above questions was the subject of a feasibility study on using EEW to mitigate risk at NPPs carried out between 2012 and 2014 by the Swiss Seismological Service (SED) at ETH Zurich and BRGM (the French Geological Survey) at Orleans within the framework of work package WP7 (Strategic Applications and Capacity Building) of the EC-funded project REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction, FP7, contract no. 282862, 2011-2014, www.reaktproject.eu). Swissnuclear, the nuclear energy section of swisselectric, representing the Swiss NPP operators (www.swissnuclear.ch), was involved in this study in the role of potential end-user of the application to provide proactive feedback about the applicability in practice of the scientific and technical solutions discussed in the feasibility study. Swissnuclear represents the Swiss electric supply companies in charge of operating the four NPPs (five reactors in total) of Beznau, Gösgen, Leibstadt and Mühleberg. These nuclear plants together meet roughly 40% of the current electricity needs of Switzerland. The role of swissnuclear as an end-user of REAKT was intended for educational purposes only and justified by the Swiss directive ENSI-B12/d indicating that existing Swiss NPPs may be equipped with new technical systems for emergency protection whenever these systems contribute to decreasing the risk. Hence, it was pertinent to investigate to what extent current EEW solutions could answer this goal.

While details about the development of our feasibility study in REAKT are documented elsewhere as project deliverables and conference contributions, we focus in this manuscript on documenting the main outcomes of our study. Swissnuclear recognised the benefit of EEW to improve preparedness of the operators in the NPP control rooms and motivated us to develop: (a) a methodological framework for independent end-user evaluation of the reliability and usefulness of EEW for mitigating seismic risk in real-time at nuclear facilities; (b) a simplified methodology for assessing costs and benefits of EEW; (c) a user-friendly risk-oriented display (Cauzzi et al., 2015 and 2016) of EEW information to be installed within NPP control rooms with focus on seismic risk considerations, as documented in the following sections. This manuscript accounts for the end-user perspective on the use of real-time hazard information to mitigate seismic risk at nuclear facilities. Exhaustive details about swissnuclear feedback to our joint study can be found in Cauzzi et al. (2014). While our test bed was Switzerland, the approach presented in this contribution is of general interest for the community of EEW researchers and end-users and its scope is significantly beyond the specific application within REAKT.

2 Reliability, usefulness and significance of EEW alerts

The feasibility of using EEW to mitigate earthquake risk in real-time at a NPP should be based on end-user/stakeholders' acceptable levels of reliability, usefulness and significance of the available EEW algorithms. With the term reliability we refer herein to the capability of the EEWS to correctly detect the onset of seismic events throughout a region of interest for the end-users and to minimise false and missed detections (see also Iervolino et al., 2006). Usefulness refers to the capability of the EEWS to be fast enough to ensure that mitigation actions can be undertaken (triggered by humans or by automatic systems). Significance conceptually means the convolution of reliability and usefulness with the expected level of shaking at the target site, in this case the location of a NPP. We develop in this section an example using a quantitative evaluation of these concepts based on the EEWS run by the SED in Switzerland and California and a critical earthquake scenario based on the historical earthquake catalogue of Switzerland ECOS-09 (Fäh et al., 2011).

EEW efforts at the SED are focused on the Virtual Seismologist (VS) algorithm, a demonstration network-based EEWS that is currently undergoing real-time evaluation in California, Switzerland, Turkey, Romania, Greece, Iceland and New Zealand (Behr et al., 2015b). Within a dense network VS can presently provide earthquake locations and magnitudes within 10 to 20 s of the origin time, potentially providing tens of seconds warning in advance of strong shaking to areas outside the epicentral region. Within the framework of the EC-funded projects REAKT and NERA (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation, FP7, 2010-2014, contract no. 262330, http://www.nera-eu.org/), the original real-time implementation of VS (Cua et al., 2009) was rewritten and optimised (Behr et al., 2013; Behr et al., 2015b). This was done by porting the magnitude estimation component of VS to the earthquake monitoring software SeisComP3 (SC3) and relying on standard SC3 modules for earthquake location. SC3 is an end-to-end architecture that is becoming widely used both in Europe and around the globe, and which is used at the SED for standard automatic and manual earthquake locations and characterisation. VS in Switzerland uses only real-time high-quality strong-motion stations (Cauzzi and Clinton, 2013; Michel et al., 2014) monitored by the SED in addition to all broadband Swiss stations and a large number of real-time streams that the SED continuously acquires from neighboring countries (e.g., Diehl et al., 2014; Figure 2). This means that the detection capabilities of the EEW algorithm are presently consistent with the magnitude of completeness of the Swiss national seismic networks, i.e., practically null probability of missing an event with local magnitude $M_L > 2$ in the Swiss region (Nanjo et al., 2010; Kraft et al., 2013).

We discuss here the current reliability of VS in terms of probabilities of correct and false detections by merging recent observations from Switzerland and California. We complemented the Swiss dataset of correct and false alerts with recent data from Southern California to derive statistics for events with magnitudes larger than 3.5. The summary statistics presented in this section are based on the implementation of VS in SeisComP3, hereafter VS(SC3), which is also installed in southern California since December 2014. The merged catalogue comprises 119 true, 393 false and 184 missed events in the magnitude range 2 to 4.25. A correct detection is declared if the VS event location and origin time is within 100 km and 30 s of the true event (i.e., the official location of the seismic network bulletin) and the VS likelihood is ≥ 0.5. The VS likelihood estimate is a function of station numbers, triggers and magnitudes contributing to the alert (http://www.seiscomp3.org/doc/seattle/2013.200/apps/vs.html), as well as source-station geometry. The VS likelihood provides end-users a real-time estimate of the reliability of a given EEW alert. In other words, the likelihood parameter expresses the degree of belief that the incoming data are caused by a real earthquake, as opposed to non-earthquake related signals. The magnitude definition that we use for true and missed detections is the seismic network magnitude, typically M_L, while the magnitude of false alerts M_{VS} is the VS rapid magnitude estimate. In Switzerland, the initial M_{VS} estimate is typically 0.25 magnitude units lower than the catalogue magnitude M_L (with a standard error of roughly 0.25) and large deviations from this average constant offset are typically associated with large location errors (Behr et al., 2015b). If we restrict the dataset to events with magnitude larger than 3.75, we have nine true alerts and no missed or false events. This means the probability of true, false and missed events of engineering significance in the merged VS(SC3) datasets used in these analyses are equal to unity, null and null, respectively.

These probabilities can be associated with shaking scenarios of, e.g., PGA at a number of selected targets by means of a ground motion prediction equation (GMPE) suitable for the region of interest. The currently preferred model for Switzerland is that of Edwards and Fäh (2013) and Cauzzi et al. (2015a) corrected to include the effects of local site amplification. Based on this prediction model, significant alerts (PGA larger than, e.g., 0.1 g) can be expected to be sent to the Swiss power plants only for events with M_W larger than ~ 6. Earthquakes of this size, although rare, are possible in the greater Swiss region, as shown in Table 1 based on the recently revised earthquake catalogue of Switzerland (Fäh et al., 2011).

Figure 2 about here.

Table 1 about here.

Notable in Table 1 is the 1356, M_W 6.6, Basel earthquake, the largest event ever documented in northern Europe, with epicentral macroseismic intensity reaching degree IX (Fäh et al., 2009) on the 1998 European Macroseismic Scale (EMS-98) (Grünthal, 1998; Grünthal and Levret, 2001). PGA scenarios corresponding to the possible repetition of the Basel 1356 event are shown in Figure 3 and Figure 4. PGA was derived from macroseismic intensity (Fäh et al., 2011; Cauzzi et al., 2015a) using the ground motion to intensity conversion equations (GMICEs) of Faenza and Michelini (2010, their PGA model -1σ). The scenarios in Figure 3 and Figure 4 include amplification due to local site conditions (Fäh et al., 2011; Cauzzi et al., 2015a). The white triangles in Figure 3 and Figure 4 are the real-time seismic stations used at SED for EEW. Superimposed on the shaking scenario in Figure 3 are contour lines of the expected lead-time (i.e., the time interval between the onset of S-wave shaking at the site and the delivery of the EEW) at the power plant of Beznau (the black circle), based on a minimum number of six stations used to declare the onset of a seismic event, and including realistic estimates of VS EEW delays in Switzerland (Behr et al., 2015a). That is, Figure 3 represents a realistic EEW scenario in case of the repetition of the Basel 1356 event. It is clear from Figure 3 that an event with M_W ~ 6.6 occurring in the region of Basel, which might produce a significant PGA ~ 0.1-0.2 g at the power plant of Beznau (with site amplification accounted for as in Cauzzi et al., 2015a), would be associated with a lead-time of ~ 5-7 s. Such a lead-time could, in principle, be used to trigger automatic mitigation actions at the plant, i.e., an EEW alert would be both useful and significant for this scenario. The available lead-time, of course, increases (up to ~ 10 s) if an EEW algorithm based on a smaller number of triggers is adopted, as shown in Figure 4 where a minimum number of two station triggers was assumed to declare an event, along with data latencies with uniform probability between 0.1 s and 2 s and processing latencies with normal distributions ($\mu = 0.7$, $\sigma = 0.5$). That is, Figure 4 represents a credible EEW scenario by the year 2020 based on the continuing research and technical EEW efforts at SED. With a lead-time of ~ 10 s, mitigation actions initiated by well-trained human operators could also be envisaged.

Figure 3 about here.

Figure 4 about here.

Recent computations carried out within the framework of a SED project devoted to updating the national Swiss seismic hazard maps (Wiemer et al., 2014; Edwards et al., 2016) showed that the annual probability of exceedance of PGA ~ 0.15 g, at the Beznau site (for rock-like ground type with $V_{S,30}$ ~ 1100 ms^{-1}) would be roughly equal to 2×10^{-4} (Laurentiu Danciu 2015, personal communication). This probability can typically increase by a factor of 100 to 1000 in the aftermath of a significant earthquake. This is the domain of operational earthquake forecasting (OEF) as briefly described later in this paper.

3 Delivering EEW information to end-users

Motivated by our end-user's requests for optimised understandability and ease of use of EEW messages, the automatic detections of the SED along with the rapid magnitude estimates of VS are transferred to swissnuclear through an Earthquake Early Warning Display (EEWD) developed as a side product of REAKT (Cauzzi et al., 2015b and 2016). Inspired by the Californian experience of the CISN ShakeAlert UserDisplay developed by Caltech, the EEWD results from a European effort to develop a prototype client-side EEW end-user software capable of: 1) supporting all alerts generated by the main EEW algorithms used in Europe; 2) allowing configuration for regionalisation of shaking parameter predictions (e.g., local GMPEs, GMICEs and local site amplification); and 3) supporting future developments for configuration according to particular end-user requirements. In addition to real-time operations, the EEWD supports the recording and replaying of real-time earthquake alerts and playback of manually produced planning scenarios (the macroseismic calibration dataset of Cauzzi et al., 2015a is included in the distribution). The vast majority of features implemented in the EEWD followed recommendations of swissnuclear within REAKT.

Adaptation of the EEWD for optimised use at swissnuclear included: 1) the parameterisation (Cauzzi et al., 2015a) of the semi-stochastic ground-motion model of Edwards and Fäh (2013); 2) the implementation of site-specific amplification factors as a function of magnitude and bedrock PGA (swissnuclear, 2013); 3) adopting the GMICEs of Faenza and Michelini (2010); and 4) displaying peak values of ground motions and response spectra in the EEWD graphical user interface, along with two reference spectra for the plant. This latter feature allows comparisons between the key design and regulatory shaking levels (namely, the Operating Basis Earthquake, OBE, and Safe Shutdown Earthquake, SSE, in the USA and the Shaking Level 1 (SL-1) and Shaking Level 2 (SL-2) for countries following the IAEA guidelines) and the predicted shaking intensities at the NPP through the EEWS.

An example EEWD intensity scenario at the Swiss nuclear power plant of Beznau is shown in Figure 5. The scenario refers to the possible repeat of the Churwalden 1295 earthquake (Table 1). The grey shaded circle around the target NPP of Beznau is a simplified representation of the contour line corresponding to zero lead-time. The red shaded circle represents the uncertainty in the location of the event according to the ECOS-09 catalogue. The yellow and red circles centered on the epicenter of the event are the P- and S-wave fronts. The screenshot was taken when the predicted P-wave front hit the NPP, i.e., when the "Remaining Time" prior to significant shaking equals 15 s in this case. Note the display of a regional shaking scenario (macroseismic intensity converted from PGV in this case) in the background: this information is critical if multiple targets are being monitored and for operators of distributed lifeline systems. While Figure 5 shows macroseismic intensity estimates based on the magnitude and location of the event, the users of the EEWD can easily customise the display to show 16-, 50- and 84-percentile levels of PGA, PGV and response spectra, along with VS likelihood estimates (see also Iervolino et al., 2009). A dedicated panel can be activated (bottom left corner of Figure 6) where the predicted 16-, 50- and 84-percentile response spectra (the blue curves) at the NPP are compared with design spectral levels, not shown in this picture (see also Convertito et al., 2008; Iervolino et al., 2011).

Figure 5 about here.

4 Contextualising EEW alerts: the possibilities offered by Operational Earthquake Forecasting (OEF)

OEF and EEW have become research priorities for organizations around the globe that are responsible for earthquake monitoring and information, for the public as well as for decision makers. While EEW provides information about an earthquake that has already happened, OEF estimates what is going to happen in a defined period and thus, delivers a complementary view using real-time information from seismic networks. The term OEF is wide and multiple definitions are spread throughout the scientific community, the engineering community and in the public. This is partly because no standard approach is available for earthquake forecasting (Jordan et al., 2014) despite considerable efforts to improve the quality of current forecasts (Marzocchi et al., 2014). We use a common definition in the seismological community and define the OEF here as forecasting the exceedance probability for an EMS-98 intensity of V and VII in a time period of 24 hours. Both, the intensity measure or the period can be changed to the users' need.

For several years, the SED has been involved with and also led international research projects aimed at developing and optimising methods for operational earthquake forecasting on national scales (e.g., Gerstenberger et al., 2005; Woessner et al., 2010; Marzocchi et al., 2014) or for natural and induced earthquake sequences (e.g., Woessner et al., 2011; Bachmann et al., 2011). The SED short-term earthquake probability (STEP) model is based on the earthquake catalogue and seismic bulletin for Switzerland. The time-independent part (or background) is calculated from the de-clustered ECOS-09 catalog (Fäh et al., 2011), and combined with the time-varying component of ongoing seismic sequences that are modeled with the Gutenberg-Richter relation and the modified Omori-Utsu law (Woessner et al., 2010). STEP is a modular approach that uses parameters of

Reasenberg and Jones (1994) and modifies the parameters spatially depending on the real-time seismicity, updating whenever enough sequence-specific data are available thus using the most recent data to update model forecasts. For evaluation purposes, the STEP algorithm has recently been implemented as a prototype system linked to the SED-alarm system. This is the first system of such a kind implemented for a low-to-moderate seismicity region. The system computes time-varying daily earthquake rate forecasts and probabilities of ground shaking in terms of EMS-98 intensities throughout the country. Model forecasts are updated on a hourly basis in case there are ongoing sequences; otherwise an update is run every 24 hours. The SED maintained a dedicated internal website during REAKT where the STEP maps were updated seamlessly, showing the probability of reaching or exceed EMS-98 intensity V in Switzerland. Based on the ground motion to intensity conversion equation of Faenza and Michelini (2010), EMS-98 intensity V in Switzerland roughly corresponds to a PGA of 0.03 g. The maps include macroseismic intensity site amplification as derived by Fäh et al. (2011).

Following a large earthquake, e.g., a scenario $M_W \sim 6.6$ event in Basel, the STEP maps elaborated by the SED would look like those depicted in Figure 6 as computed a minute after the earthquake origin time. Figure 6A and B show the logarithm ($\log_{10}$) of the probability of exceedance of $I_{EMS\text{-}98}$ = V in 24 hours for rock conditions and when including site amplification based on the values given by Fäh et al. (2011). The bottom panel shows the probabilities as computed for $I_{EMS\text{-}98}$ = VII (~ 0.16 g based on Faenza and Michelini, 2010). The figures quantitatively highlight the expectations and the spatial variations where additional damage might be possible. Although forecasts can be extended to longer periods, the model is focused on forecasts of days to several weeks. Maps similar to those shown in Figure 6 can first of all significantly enhance the preparedness of staff to possible future ground shaking when on display in the control room of an NPP. Secondly, the earthquake rate forecast of an OEF has the potential to operate as a Bayesian prior, i.e., as the degree of belief about the spatial distribution of future events narrowing the search space of EEW detection algorithms. Thirdly, key OEF ingredients, i.e., the Gutenberg-Richter and the Omori-Utsu laws, can also be implemented directly in Bayesian EEW frameworks like the Virtual Seismologist VS (Cua and Heaton, 2007; Meier et al., 2015) to better constrain EEW magnitude estimates.

OEF, however, faces many challenges that have been elaborated on by Jordan et al. (2011). First, they operate in an environment that lift occurrence probabilities that usually range on the order of 10^{-6} to 10^{-4} by a factor of 100-1000 for a short period, residing still generally at low probabilities and rapidly decaying again. Secondly, statistical short-term forecasting methods have to deal with the uncertainties of the real-time data stream of the monitoring systems that can hamper predictive skill (e.g., Steacy et al., 2013). Lastly, the parameter estimation procedures are associated with uncertainties, based on fits of empirical relationships to incoming data. These systems are likely most effective for regions with higher seismic activity (e.g., California, Japan, New Zealand and Italy) that provide better opportunities to calibrate this specific model; this is why Woessner et al. (2010) implemented an additional component, describing sensitivity to the choices.

The variety of short-term forecasting models increases with time. These are currently evaluated by ongoing efforts of the Collaboratory for the Study of Earthquake Predictability (CSEP, www.cseptesting.org). Until these evaluations are complete and the uncertainties are clearly outlined and propagated for each model (e.g., Holschneider et al., 2012), OEFs should be used cautiously in the process of decision making and their limitations need to be outlined transparently (e.g., Jordan et al., 2014). Current results imply that building ensemble models, i.e., models that combine skill sets of different forecasting algorithms are better. Our illustration in this respect outlines the potential use of such a system.

Figure 6 about here.

5 Responding to EEW: potential mitigation actions, decision criteria, costs and benefits

The identification of possible mitigation actions at NPPs in response to EEW or OEF has to ensure consistency with the regulations for the management of emergency situations at NPPs. Mitigation actions specifically related to EEW could potentially involve shutdown of primary (e.g., the reactor) and/or secondary systems (e.g., the turbines and generator), early activation of emergency plans, automatic opening of on-site fire-station doors, while actions in response to forecasted heightened hazard might include, e.g., reinforcing inspections, practicing earthquake drills and adapting the outage period, reducing the number of non-essential workers on-site. Following the logic of Figure 1 in the Introduction, a time-dependent vulnerability function could be associated to any elements at risk and the variation of the vulnerability with time would help in justifying which actions should be excluded from further consideration. In addition, this information would help identify those occasions when such actions may be envisioned because the lead-time is sufficient, i.e., it is larger that the time necessary to decrease the plant's vulnerability significantly.

Once potential mitigation actions have been identified, it is critical to define the decision factors whose real-time estimation will condition the mitigation actions to be undertaken when, for example, an EEW is received. EEWSs usually proceed with the estimation of both the magnitude and location (or source-to-site distance) of an earthquake. These parameters are generally used to assess the value of a ground shaking intensity measure (IM) at the target site (this IM could be PGA, PGV, response spectral acceleration, cumulative absolute velocity or another parameter). This assessment of an IM can be considered as a decision factor describing the impact of the earthquake or, in turn, be included in further models to refine the impact assessment, calculating the probability of various damage grades or even estimating the potential losses. Assuming a high seismicity region where ASTSs are automatically implemented, the basic decision tree for the potential mitigation action "early SCRAM" at a NPP in response to EEW would follow the schematic shown in Figure 7, which contains all the key elements to be collected to take a decision based on a cost-benefit approach (CBA).

The CBA can be made, e.g., following the simplified approach of Woo (2013), based on the benefit-cost ratio $R=P \times L/C$, where: an action has a cost C but would prevent loss L, which has a probability P of occurring. Woo (2013) then defines levels of R where actions are justified. Obviously if R is less than unity the action is not warranted but as R increases the confidence increases that an action is justified. This simplified approach is particularly adapted for decision making in OEF, where uncertainties are typically very large. For EEW, a more rigorous CBA can be used. The discrete values P, L and C should be replaced by loss and cost distributions with different conditional probabilities of occurrence and hence the calculation of the expected benefit-cost ratio will be in the form of multiple integrals (e.g., Wu et al., 2013). As presented in Figure 7, the CBA should compare the benefits of following case 2 "Operating an EEWS" instead of case 1 "Business as usual" with the costs induced by case 2 over case 1. There is a benefit in the "real positive" case, when there is an early SCRAM with a lead-time of several seconds. The "false positive" case will induce costs over case 1, when there is an unjustified SCRAM. Both the "false negative" and the "real negative" case are identical to the situation in case 1 so they induced no additional costs or benefits. The identified costs and benefits should then be weighted with their respective probabilities, hence the necessity of knowing beforehand the probability of false and missed alarms of the system. The probabilities will be a function of the hazard (e.g., the probability of experiencing a given PGA at the NPP during its lifetime, as discussed in Section 2) and the risk (e.g., the probability of experiencing a certain loss given the occurrence of a shaking level at the NPP).

Figure 7 about here.

6 Discussion and conclusion

We presented in this contribution a methodological framework aimed at quantifying the capabilities and limits of the current scientific and technical possibilities offered by real-time seismology to mitigate seismic risk at NPPs. Spurred by our experience with swissnuclear within REAKT, we aimed here at designing a transparent and informative support platform for decision-makers. As earthquake scientists, we do not attempt to answer whether it is appropriate or not to use an EEWS or OEF for a NPP. We rather provide the decision-makers and the stakeholders with all the necessary elements and procedures to answer the above question themselves based on present and future knowledge and technologies in this field. Different from Kammerer et al. (2011) who used global ShakeMaps (Worden et al., 2010) and the ShakeCast system (Wald et al., 2008) to inform the IAEA about the potential impacts of earthquakes worldwide typically within minutes of the event origin time, we focused here on real-time hazard predictions, typically prior to significant S-wave shaking at the site. Through this paper we invite nuclear operators and authorities responsible for national regulations to consider the state-of-the-art real-time tools presented herein as potentially useful to mitigate seismic risk at their plants and premises. Although we tailored our discussion to the nuclear industry and focused on examples from Switzerland, the proposed framework can easily be adopted for different industrial applications and in different seismotectonic contexts. That is, although the proposed methodology is valid worldwide, the applications to different countries will require assessing the reliability of the local seismic networks, OEF and EEW systems. Delivering real-time hazard information to end-users will typically require customisation to the local seismotectonic setting, e.g., by using GMPEs and GMICEs suitable for the region of interest. This flexibility is already offered by the early warning display presented in section 3.

We have emphasized the role of CBA as a quantitative and objective tool to inform decision about the adoption of mitigation actions, although we are aware that conducting a CBA in the context of the nuclear industry might be difficult due to ethical issues (e.g., stating the cost of human life, see Rogoff and Thomson, 2014) that require including public and political stakeholders in the discussion, beyond seismologists and engineers. As to the specific application to a NPP, we note that it is advisable to estimate both costs and benefits over a time-period corresponding to the life expectancy of the plant through a probabilistic analysis. However, NPPs are designed in such a way to resist earthquake ground motions that correspond to long return periods (e.g., 10,000 years), and consequently the potential benefits of additional protection systems (such as EEWS) are likely to be associated to these high return period ground-motions. One can thus logically assume that a CBA performed on a time horizon of a few decades (the expected life span of NPPs) will result in clearly negative results, smoothing contributions of extreme earthquakes characterized by a low probability of occurrence (return period greater than those observed in the historical record) and a high magnitude. The safety of NPPs needs to be examined, however, with regard to the frequency and severity of extreme earthquakes. Indeed, there always remains a low probability that the ground motions at a site will exceed the design basis during the lifetime of the NPP because of both extreme events and uncertainty in PSHA. Similarly to the IAEA who recommend applying both PSHA and DSHA when designing/retrofitting NPPs in order to get a "balance between defense in depth and risk considerations", it could be pertinent to carry out a deterministic CBA on extreme earthquakes in addition to the abovementioned probabilistic one. Le Guenan et al. (2015) have recently presented an alternative to CBA for EEWS, namely Multi-Attribute Utility Theory, that may overcome some of the limitations of CBA as applied to NPPs.

We have mentioned the role of SCRAM and ASTSs as potential earthquake risk mitigation tools, emphasising though the criticalities associated to the shutdown of nuclear reactors. We additionally recall here that ASTSs alone might be insufficient or even inadequate if secondary emergency equipment does not work correctly and secondary hazards are not properly taken into account, as dramatically shown by the Fukushima accident in 2011. Consistent with the aforementioned IAEA recommendations and Japanese governmental regulations, shortly after strong earthquake shaking was detected at the Fukushima NPP, the three operating reactors SCRAMmed, i.e., control rods were automatically dropped into the cores to immediately stop the fissile reaction. While fission stopped almost immediately, fission products in the fuel continued to release sufficient heat to require active reactor cooling for several days so as to keep the fuel rods below their melting points. Although direct earthquake damage to the safety systems of the NPP cannot be ruled out, the ultimate cause of the disaster was the failure of emergency power generators (and therefore the cooling system) of the nuclear plant due to tsunami inundation not accounted for in the design, when a run-up height of ~ 15 m overwhelmed the 10 m seawall based on a design height ~ 6 m. The Fukushima accident confirmed that resilience of the built environment to earthquakes should be achieved by the convolution of excellent engineering practice with excellent geoscience investigations and dramatically showed how reality can be far from optimal, in spite of significant safety margins beyond design conditions may exist (see the European "Stress Test": http://ec.europa.eu/energy/nuclear/safety/stress_tests_en.htm). In this context, EEWSs may be helpful in the future as they provide an additional tool to define the base for a refined quantification of margins for such scenarios. Moreover, EEWSs may provide a societal benefit by increasing the confidence that the society has in nuclear safety, which is particularly important in the post-Fukushima context that is characterized by societal distrust of NPPs.

It is worth articulating in more detail the practical concerns over implementation of EEW at nuclear facilities, in particular the enormous implications of an unnecessary shutdown. The main costs associated to an emergency shutdown (SCRAM) are: (a) the cost of powering up; (b) the lost revenue from power sales; (c) the reduction in lifetime of the reactor and (d) the application for a permission to restart the plant. In Switzerland, (b) and (d) are presently approximately equal to 1 million USD/day and 250 million USD/SCRAM. (d) can take many days or weeks (or even years, e.g., in Japan) and during this time the overheads need to be paid and the apparent value of the NPP on which debt could be raised is much reduced. With this background, the reader should get a sense of the quandary faced by nuclear facility managers. Conversely, if we exclude the possibility of a controlled shut-down of the reactor, the costs associated to possible mitigation actions in response to forecasted heightened hazard are lower and typically already accounted for in the plant management (costs of undertaking technical inspections and emergency drills). OEF may prompt actions that should be being undertaken anyway but they may have been forgotten or not prioritised.

We also note that the seismic alert systems installed in many NPPs worldwide (see, e.g., http://www.asn.fr/Reglementer/Regles-fondamentales-de-surete-et-guides-ASN/Guides-de-l-ASN-et-RFS-relatives-aux-REP/RFS-I-3.b.-du-08-06-1984) comprise accelerometers installed in free-field conditions along with accelerometers located in the basement and at different elevated levels of the reactor building, so that the triggering of the safety procedure with respect to the exceedance of a specific seismic shaking threshold does not necessary refer to the shaking recorded by free-field sensors. The EEW and OEF tools presented in this paper provide hazard information in free-field conditions.

Since nuclear accidents have the potential for widespread transnational impacts, risk mitigation and emergency actions require international cooperation and coordination. In this perspective, optimisation of EEW and OEF efforts for the nuclear industry would profit from establishing a coordinated framework where real-time seismic data exchange occurs among different countries and research institutions and different algorithms are run and made available to the end-users. The already existing European Integrated waveform Data Archive (EIDA, http://www.orfeus-eu.org/eida/) and the European Centre for Earthquake Early Warning that is presently being established within the context of European Plate Observing System, will constitute in the coming years the technical and political basis to support this effort.

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Figures and figure captions

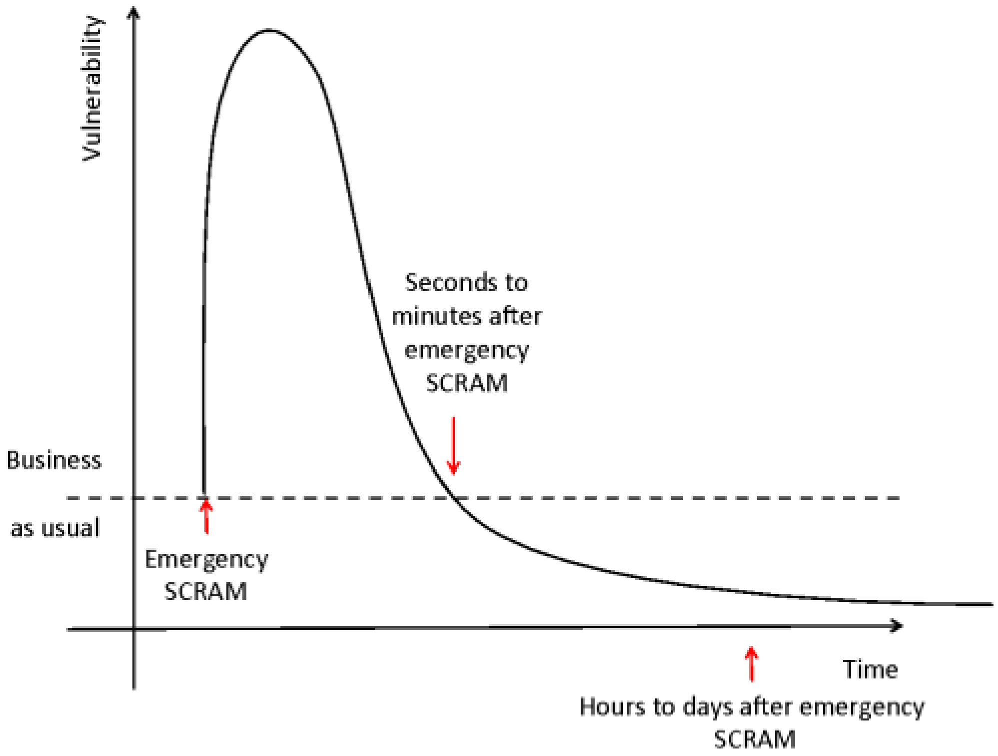


Figure 1 - Sketch of the vulnerability of a nuclear reactor following emergency SCRAM. Note the period of heightened vulnerability shortly after triggering the shutdown.

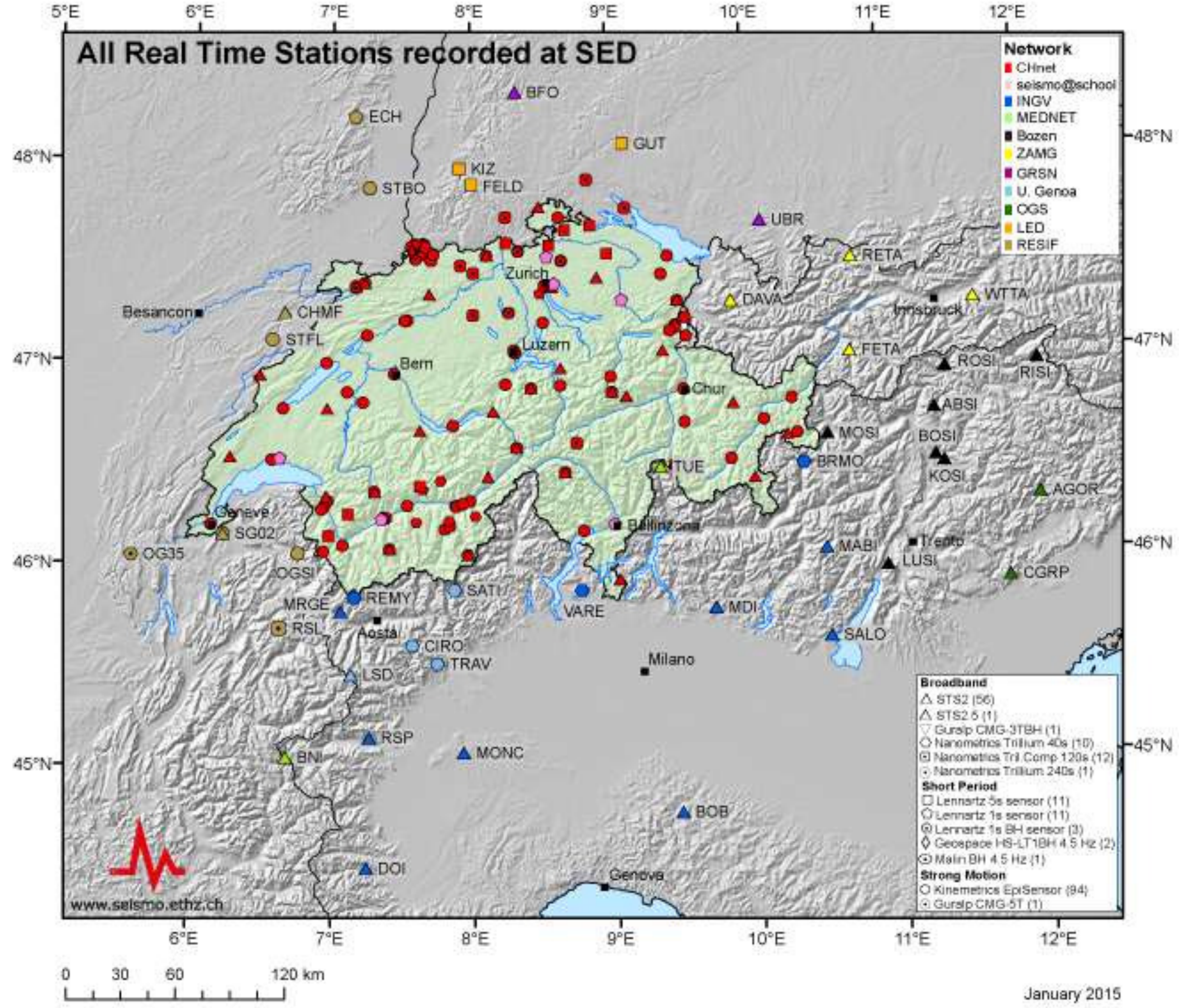


Figure 2 - Map of real-time stations (velocity and acceleration sensors) used by SED for continuous monitoring of the seismicity in the greater Swiss region.

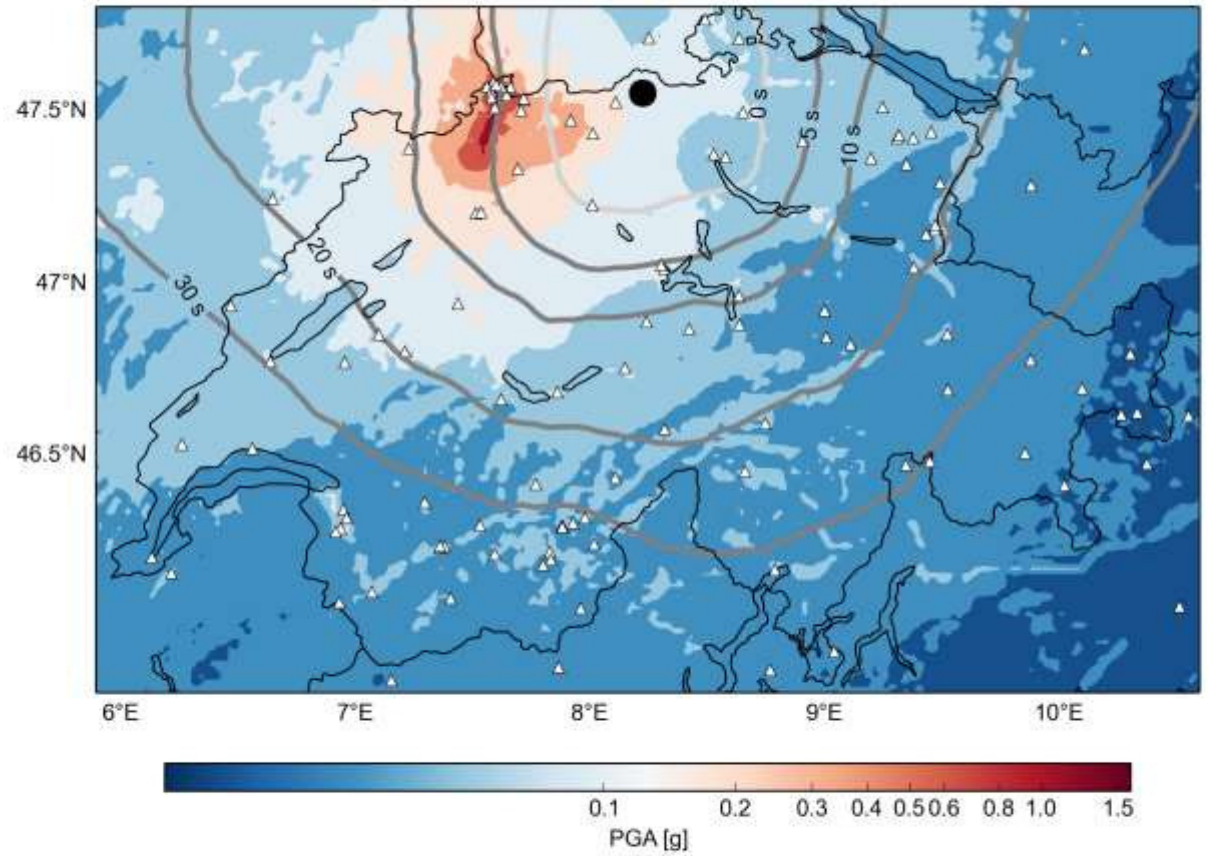


Figure 3 - PGA shaking scenario for the Basel 1356 M_W 6.6. event, computed as described in the text. The grey curves are contour lines of expected lead-times at the NPP of Beznau (the black circle) based on the geometry of the Swiss national seismic network and a minimum number of 6 station triggers to declare the onset of the seismic event.

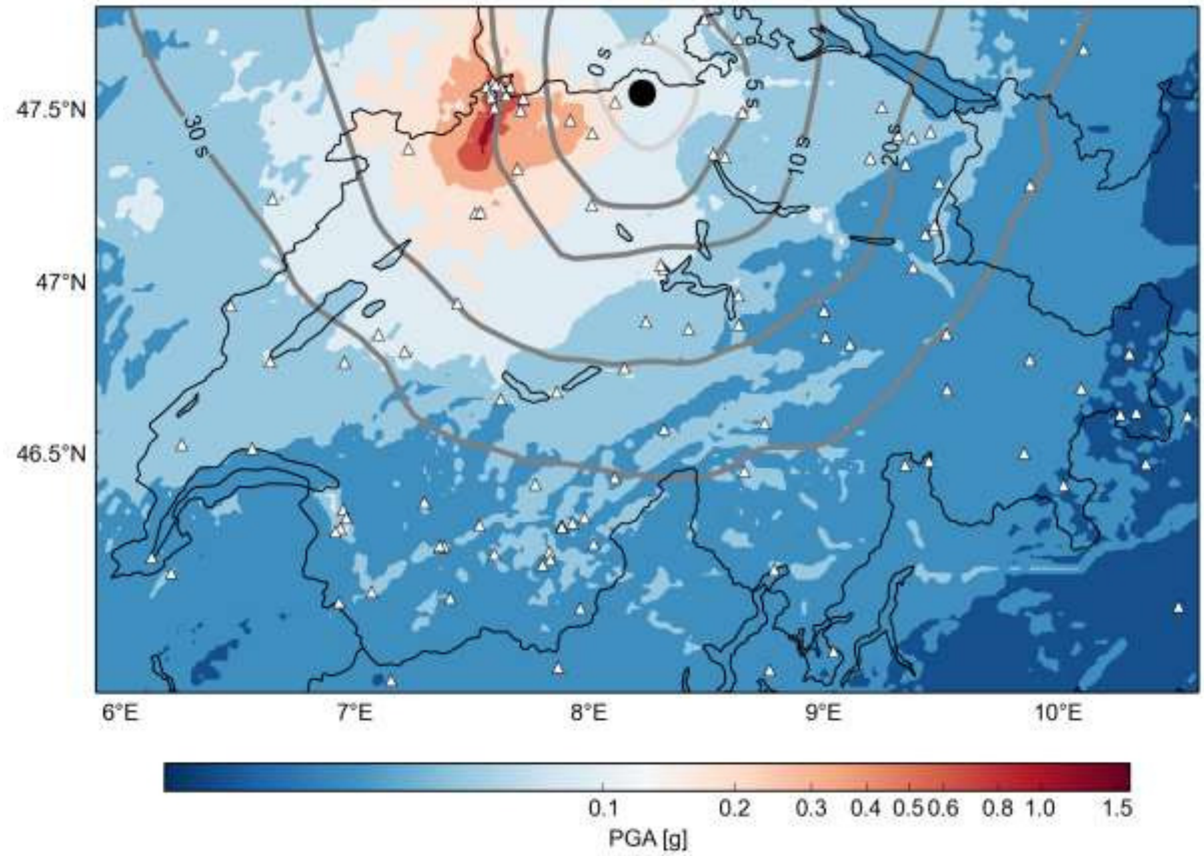
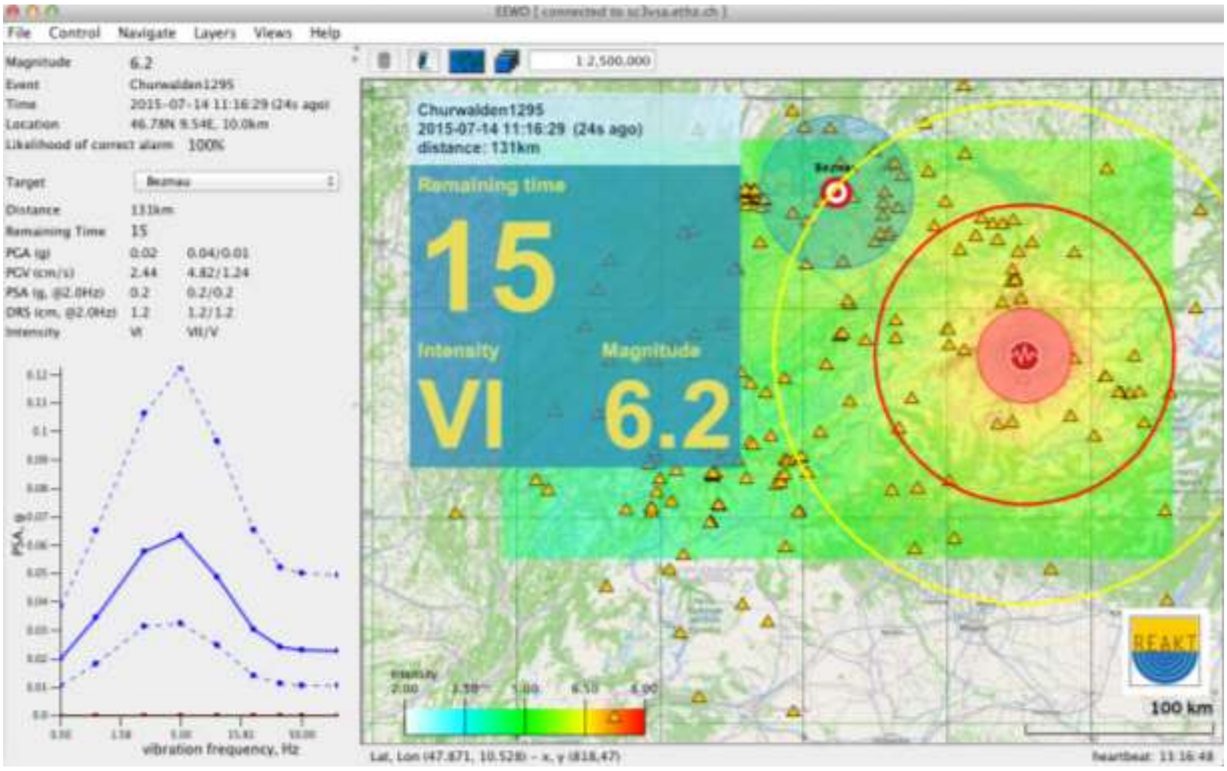


Figure 4 – As Figure 3 but using only two station triggers to declare an event.



Magnitude	6.2	
Event	Churwalden1295	
Time	2015-07-14 11:16:29 (24s ago)	
Location	46.78N 9.54E, 10.0km	
Likelihood of correct alarm	100%	
Target	Beznau	
Distance	131km	
Remaining Time	15	
PGA (g)	0.02	0.04/0.01
PGV (cm/s)	2.44	4.82/1.24
PSA (g, @2.0Hz)	0.2	0.2/0.2
DRS (cm, @2.0Hz)	1.2	1.2/1.2
Intensity	VI	VII/V

Churwalden1295
2015-07-14 11:16:29 (24s ago)
distance: 131km

Remaining time
15

Intensity
VI

Magnitude
6.2

Figure 5 - Example EEWD screenshot showing shaking predictions at the NPP site of Beznau, based on the epicentral location and local magnitude of the 1295 Churwalden M_W 6.2 event. The colored area overlaying the geographic map shows the macroseismic intensity levels predicted throughout the Swiss region. The orange filled triangles are seismic stations: in real-time operation, the stations contributing to the alert would blink red on the display.

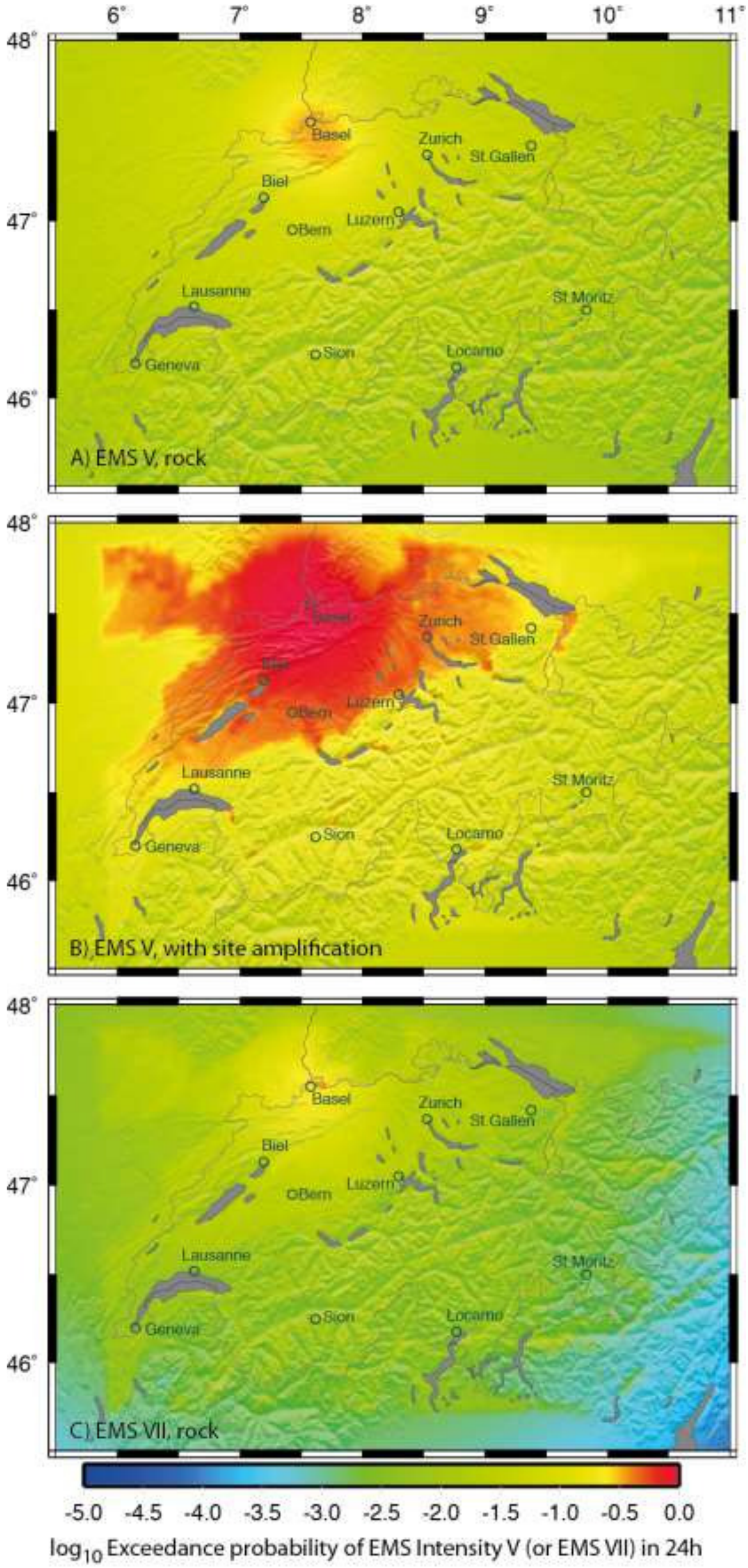


Figure 6 - Examples of SED 24-hour STEP maps computed in the aftermath of a scenario M_W 6.6 event in Basel showing the $\log_{10}$ of the probability of exceedance in 24 hours of A) I_{EMS-98} = V for rock conditions, B) I_{EMS-98} = V with site amplification following Fäh et al (2011), and C) I_{EMS-98} = VII for rock condition. Colorscale limited to same range. Forecasts are computed in the minute after the earthquake origin time.

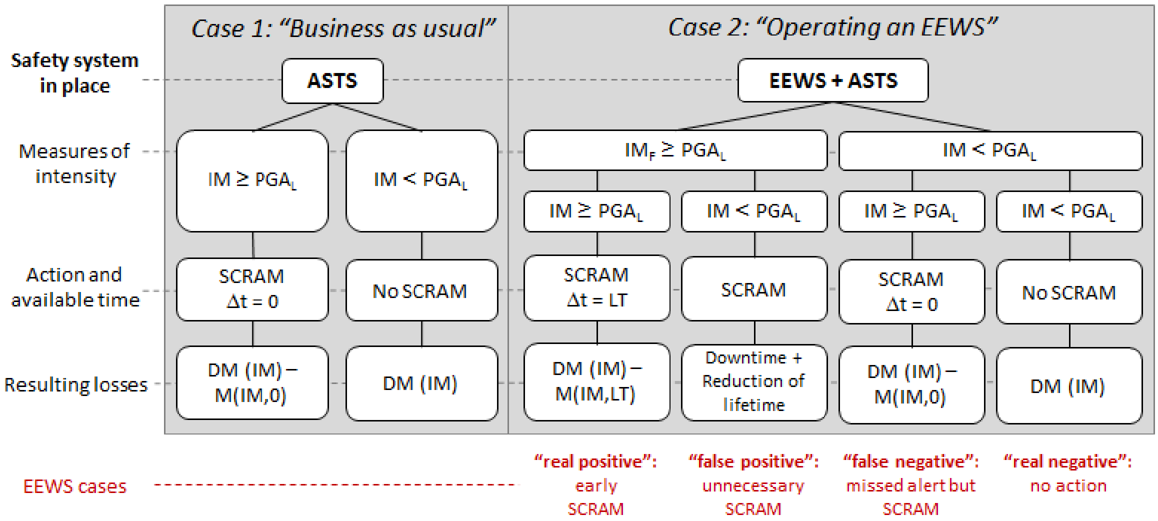


Figure 7 - Proposed basic decision tree for a potential mitigation action in response to an EEW at a NPP. With IM_F the early forecast of the real intensity measure IM, PGA_L *the PGA threshold value for SCRAM, Δt the* available time between the initiation of SCRAM and the arrival of strong motions to the NPP, LT the early-warning lead-time, DM(IM) damages due to IM, and *M(IM,Δt) the mitigation of losses due to the SCRAM in function of IM and Δt.*

Table and table caption

Table 1 Excerpt of the Swiss earthquake catalogue ECOS-09 (Fäh et al., 2011) listing events with $M_W > 6$.

Date	Lat. (deg)	Lon. (deg)	Depth (km)	M_W	Epicentral Intensity (EMS-98)	Epicentral Area
1295/09/03	46.78	9.54	Unknown	6.2	VIII	Churwalden (Swiss Alps)
1356/10/18	47.47	7.60	Unknown	6.6	IX	Basel (Swiss Foreland)
1855/07/25	46.23	7.85	10	6.2	VIII	Stalden-Visp (Swiss Alps)