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SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

FEASIBILITY STUDY ON EARTHQUAKE EARLY WARNING AND OPERATIONAL EARTHQUAKE FORECASTING FOR RISK MITIGATION AT NUCLEAR POWER PLANTS

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ABSTRACT

Within the framework of the EC-funded project REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction, FP7, contract no. 282862, 2011-2014, www.reaktproject.eu), a task concerns feasibility study and initial implementation of Earthquake Early Warning (EEW) and time-dependent seismic hazard analyses aimed at mitigating seismic risk at nuclear power plants (NPPs) in Switzerland. This study is jointly carried out by academic institutions (the Swiss Seismological Service at ETHZ and BRGM) and in cooperation with swissnuclear, the nuclear energy section of swisselectric, an umbrella organisation for the nuclear power plants in Switzerland, which provide about 40% of the electricity needs of the country. Briefly presented in this contribution are the main investigations carried out and results obtained throughout the development of this task, with special focus on: a) evaluating the performances of the selected EEW algorithm (the Virtual Seismologist, VS) in Switzerland and California, in terms of correct detections, false alerts, and missed events; b) embedding the VS algorithm into the earthquake monitoring software SeisComP3 (www.seiscomp3.org) routinely used by the Swiss Seismological Service for earthquake detections and locations; c) customising the User Display (a graphical interface originally developed at the California Institute of Technology (Caltech) during Phase II of the ShakeAlert project in California) for optimised use at Swiss NPPs; d) presenting synthetic time-dependent hazard scenarios for

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Switzerland and e) attempting to associate the above input data with potential mitigation actions and related cost and benefits for NPPs in Switzerland.

INTRODUCTION

Swissnuclear, the nuclear energy section of swisselectric, was involved in this study as an end-user and comprises representatives of the Swiss electricity supply companies Alpiq, Axpo, BKW, CKW and EGL, who operate the nuclear power plants (NPPs) at the four sites Beznau, Gösgen, Leibstadt and Mühleberg. These nuclear plants together meet roughly 40% of the current electricity needs of Switzerland.

In compliance with international rules enacted by the International Atomic Energy Agency (IAEA), Switzerland has adopted regulations for the management of emergency situations at NPPs. With a common objective *"to minimize the consequences for people, property and the environment of any nuclear or radiological emergency"* (IAEA GR-S-2), different requirements describe the responsibilities of each actor (operators, regulation agency, Cantons and municipalities) as well as modalities of alerts and warnings. In particular, it is established that when an event like an earthquake occurs, NPP operators should take appropriate actions in order to limit the effects on both staff and the population. To that end, they have to prepare decision support tools such as Severe Accident Management Guidance (SAMG) to: a) stop the process of core-melting; b) retain the integrity of the confinement enclosure; and c) keep the dispersion of radioactive substances as low as possible. While the question of emergency situations induced by earthquakes near NPPs is not explicitly addressed within the Swiss regulation, it is the subject of an IAEA Safety Reports Series (n°66). This report does not explicitly mention earthquake early warning systems (EEWS), but it gives (with IAEA Safety Guide NS-G-1.6) useful indications on potential contributions that this innovative tool may provide for the safety of NPPs, with respects to current international requirements. The Swiss directive ENSI-B12/d indicates that existing Swiss NPPs may be equipped with new technical systems for emergency protection whenever these systems contribute to decreasing the danger. Hence, it is important to specify to what extent an EEWS could answer to this goal.

IAEA considers the automatic shutdown of NPPs based on automatic scram trip systems (ASTSs) as a potential option of interest in order to guarantee the security of NPPs when an earthquake occurs. To date, this kind of system is mainly used in regions with high seismic hazard such as Japan and California. ASTSs usually rely on the exceedance of a ground-motion threshold value (such as peak ground acceleration, *PGA*) and thus cannot be considered as EEWSs. However, 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 EEWSs, which constitutes the only ASTSs able to initiate the automatic shutdown of NPPs before the arrival of destructive strong motions. We can then consider either the use of regional EEWSs or onsite ones taking advantage of NPPs' site-specific seismic monitoring systems. IAEA recommends that each NPP puts in place a local network of sensitive (weak-motion) seismographs combined with a network or array of strong-motion sensors directly at the NPP site. Use of fully automatic actions such as the automatic shutdown of NPPs constitutes an alternative to the traditional way based on manual actions initiated by operators themselves. IAEA considers that each approach presents its own advantages and limitations. As is the case in Switzerland, when national regulations do not recommend one or the other of these approaches, IAEA establishes indicative guidelines to identify which one seems to be more appropriate, based on a set of criteria including: a) the local seismicity rate; b) the seismic design of NPP systems; c) the local level of ambient noise; d) potential effects of the superposition of natural and trip-induced seismic transients; e) other reactor trips; f) the potential consequences of the shutdown of the plant on society; g) the level of operator confidence and reliability; and h) public acceptance. Qualitative rather than quantitative, these criteria leave to choose the option that seems to be the more suitable for each site. Consequently, the decision to make use of EEWSs (and more generally of ASTSs) is up to each operator (in accordance with its safety authorities). It seems to be pertinent to base this decision on a Cost Benefit Analysis (CBA).

Within the framework of work package WP7 (Strategic Applications and Capacity Building) of project REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction, FP7, contract no. 282862, 2011-2014, www.reaktproject.eu), the Swiss Seismological Service (SED), swissnuclear and BRGM (French Geological Survey) have jointly worked on a *"Feasibility study and initial earthquake early warning (EEW) implementation efforts for nuclear plants"*. The study comprised amongst other tasks: a) a performance evaluation of the Virtual Seismologist (VS, Cua (2005), Cua and Heaton (2007)) for events in Switzerland, in terms of speed of information, available warning time, accuracy of magnitude and location estimates, expected rates of correct, false, and missed alerts (Behr et al. 2012, 2013a,b,c); b) embedding the VS algorithm into the earthquake monitoring software SeisComP3 (Behr et al., 2013d) routinely used by the SED for earthquake detections and locations; c) the installation and testing of a customised version of the UserDisplay software (a real-time EEW information display originally developed by Caltech and UC Berkeley as part of the CISN ShakeAlert project (http://www.cisn.org/eew/), of which the SED is also a partner) for optimised use at Swiss NPPs (Cauzzi et al. 2013b and c), by means of developing and implementing new Swiss specific ground-motion prediction equations, NPP-specific amplification functions with respect to Swiss reference rock (Poggi et al., 2011) and alerts based on response spectra along with macroseismic intensity and peak motion values at the target sites; d) the development of a methodological framework for the identification of potential mitigation actions at Swiss NPPs in response to EEW along with their costs and benefits; e) investigating the potential inputs that Operational Earthquake Forecasting (OEF) can offer to earthquake risk mitigation for NPPs. It is the subject of this paper to briefly present how the aforementioned investigations were carried out and assembled, with the aim of establishing a methodological framework to assess the usefulness and to quantify the limits of present real-time seismic risk reduction methodologies for application to the nuclear industry.

ON THE POTENTIAL ROLE OF EEW

EEW research and development efforts at the SED are based on the VS algorithm, a demonstration network-based (i.e. regional) EEW system that is currently undergoing real-time evaluation in California, Switzerland, Turkey, Greece, Iceland, New Zealand and off-line testing in Romania. Within a dense network, during a large earthquake, VS can provide earthquake locations and magnitudes within 10 to 20 s after the origin time, thus potentially providing 10s of seconds warning in advance of strong shaking to areas outside the epicentral region. The original real-time implementation of VS by Cua et al. (2009) was based on Earthworm acquisition and processing (Binder) to determine rapid location and origin times using at least four station picks. 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 VS codes were rewritten and optimised by porting the magnitude estimation component of VS to the earthquake monitoring software SeisComP3 (SC3), an end-to-end architecture that is becoming widely used both in Europe and around the globe, and is presently adopted at the SED for standard automatic and manual earthquake locations and characterisation. The public release of the software VS(SC3) was made in July 2013 (Behr et al. 2013d and http://www.seiscomp3.org/doc/seattle/2013.200/apps/vs.html). Using VS(SC3) at the SED has the additional advantage that all real-time high-quality strong-motion stations in Switzerland (Cauzzi and Clinton, 2013a) (in addition to all broadband Swiss stations and a large number of real-time streams that the SED continuously acquires from neighbouring countries) now contribute to the earthquake locations and rapid estimation of magnitude (Figure 1). As a consequence, the detection capabilities of the EEW algorithm are presently consistent with the completeness magnitude of the Swiss national seismic networks, i.e. practically zero probability of missing an event with local magnitude $M_L > 2$ in the Swiss region (Nanjo et al., 2010; Kraft et al., 2013). Since summer 2013, the automatic detections of the SED along with the rapid magnitude estimates of VS are transferred to swissnuclear through the User Display (UD) code, a graphical interface that was developed at the California Institute of Technology (Caltech) during Phase II of the ShakeAlert project in California. Adaptation of the UD for optimised use at NPPs included: 1) the parameterisation of the semi-stochastic ground-motion prediction 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 ground motion to intensity conversion equations of Faenza and Michelini (2010) and 4) displaying peak values of ground motions and response spectra in the UD graphic user interface, along with reference design and serviceability spectra at the plant (Cauzzi et al., 2013b and c).

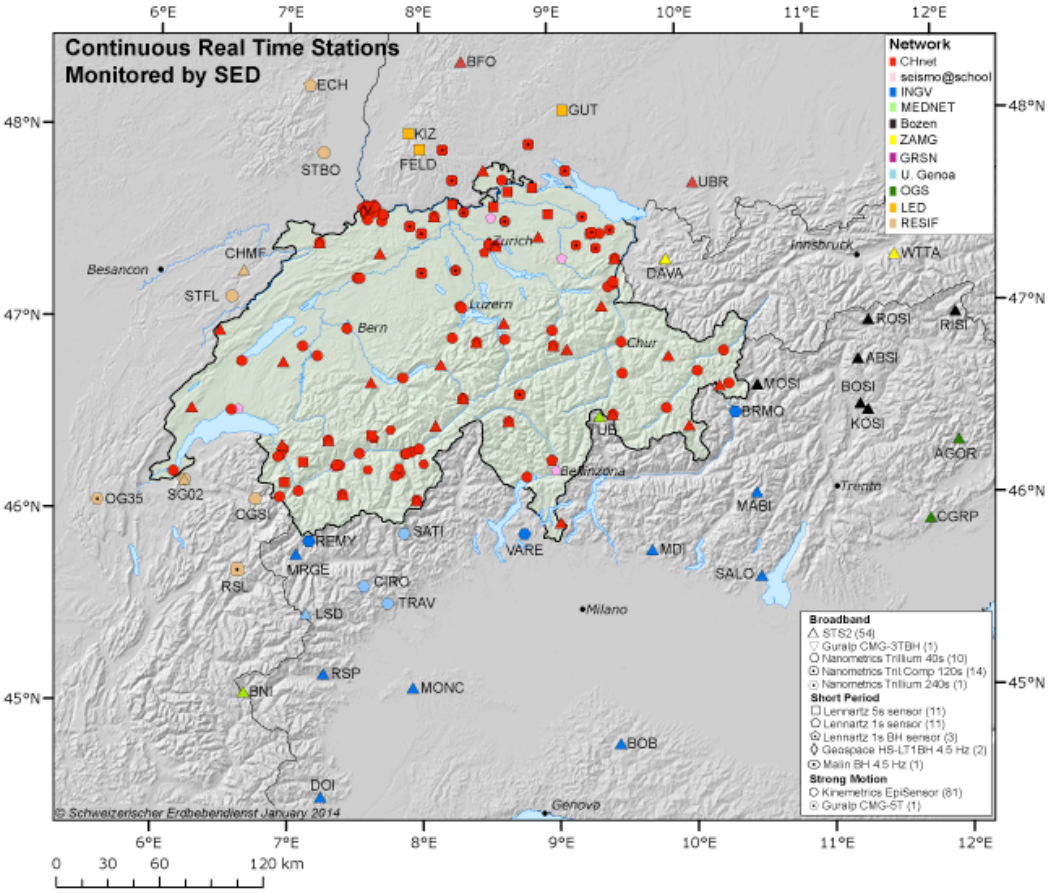

Figure 1. Map of real-time stations (velocity and acceleration sensors) used by the Swiss Seismological Service for continuous monitoring of the seismicity in the greater Swiss region (January 2014).

We complement herein the VS performances documented by Behr et al. (2012, 2013a,b,c) with recent observations from Switzerland and California. The goal of the present analysis is to provide an updated estimate of the current probabilities of correct and false detections using VS(SC3), i.e. the implementation of VS in the earthquake monitoring software SeisComP3 in use in Switzerland. The Swiss dataset of correct and false alerts was augmented with recent data from California (where the implementation is still based on Earthworm Binder) in order to derive statistics for events with magnitudes larger than 3.5. The main features of the Swiss and Californian dataset used in the analyses are listed in Table 1. The total number of false alerts in Switzerland was computed by restricting the dataset of false events to alerts with VS likelihood (Behr et al. 2013d) equal to 0.99 from the first solution available and depth < 30 km, i.e. to those events that would be naturally interpreted as true ones by the operator of the UD. The missed events in California are mainly due to suboptimal network geometry in Northern California with respect to events located in the region of the Mendocino triple junction. The magnitude definition used for the false alerts, M_{VS}, is the VS rapid magnitude estimate. In Switzerland, M_{VS} 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 to very large location errors (Behr et al., 2012, 2013a,b,c). Since the aforementioned constant offset is not observed in California, it is most likely due to differences in the M_L magnitude calibration in the two regions. After conversion of all magnitude definitions into M_W using the conversion equations valid for Switzerland (Goertz-Allmann et al., 2011), the Swiss and Californian observations were merged, resulting into a dataset comprising 206 events with $M_W > 2.17$. The number of correct detections is 145 (70%) while false detections are 61 (30%). Assuming Swiss

network performance, the number of missed events was assumed equal to zero. Segregating the data into magnitude bins resulted in the probabilities listed in Table 2. Note that the frequency of occurrence of false alerts is expected to decrease in Switzerland in the near future, once a more robust quality-checking algorithm is applied to EEW, following a strategy similar to that used for the national network alerts. Also, the probability of false alerts for significant events, e.g. magnitude larger than ~ 5.5, is expected to be close to zero.

Figure 2. Example UserDisplay screenshot showing peak ground motion and response spectrum predictions at the site of Mühleberg, based on the location and local magnitude of the 1584 Aigle event. The grey-shaded area around the target is the expected blind zone. The red and yellow circles are the S- and P-wave fronts, respectively.

Table 1. Main features of the Swiss and Californian datasets used for estimating the current probabilities of correct and false detections using VS(SC3).

	Swiss dataset	Californian dataset
Observation period	04.2013 - 12.2013	01.2012 - 12.2013
# events	74	190
# correct detections	30 ($2 \leq M_L \leq 3.5$)	115 ($3.5 \leq M_L \leq 5.6$)
# false alerts	44 ($2.0 \leq M_{VS} \leq 3.1$)	17 ($3.5 \leq M_{VS} \leq 5.4$)
# missed events	0 (excluding downtime)	56

The probabilities listed in Table 2 can be associated with shaking scenarios of, e.g. peak ground acceleration (*PGA*) at a number of selected targets by means of a ground-motion prediction equation (GMPE) suitable for the region of interest, e.g. the parameterisation of the Swiss stochastic model (Edwards and Fäh, 2013) by Cauzzi et al. (2013b), corrected to include the effects of local amplification phenomena. Irrespective of the NPP chosen for the analyses, significant alerts (e.g. with *PGA* larger than 0.1 g and event location outside the blind zone) can be expected to be sent to the power plant 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 3 based on the records of the recently revised earthquake catalogue of Switzerland (Fäh et al., 2011). Notable in Table 3 is the 1356, M_W 6.6, Basel earthquake, the largest event ever documented in northern Europe.

Table 2. Current probabilities of correct and false detections using VS(SC3). Upper bound of available data is M_W 5.4.

Magnitude	$M_W \leq 3.0$	$3.0 < M_W \leq 3.5$	$3.5 < M_W \leq 4.0$	$4 < M_W \leq 4.5$	$M_W > 4.5$
Correct detections	27	51	48	12	7
False alerts	40	7	11	2	1
Total	67	58	59	14	8
P(correct)	~ 40%	~ 88%	~ 81%	~ 86%	~ 88%
P(false)	~ 60%	~ 12%	~ 19%	~ 14%	~ 12 %

Table 3. Earthquake with $M_W > 6$ extracted from the earthquake catalogue of Switzerland.

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

Focusing on the NPP of Beznau and on the expected shaking and EEW lead times at the selected test site for events at the upper magnitude bound of the historical earthquake catalogue of Switzerland, depicted in Figure 3 are *PGA* shaking scenarios (84-percentile predictions) for earthquakes potentially occurring at any point in the greater Swiss region, with M_W equal to 6.75. The black curves in Figure 3 represent the *loci* of the earthquake locations that would cause *PGA* equal to a given threshold (e.g. 0.1, 0.06, 0.04 or 0.01 g) at the selected target site (denoted by the star). The predictions overlie a map of the expected lead time at the power plant, based on a minimum number of six stations used to declare the occurrence of a seismic event, and including realistic estimates of VS EEW delays in Switzerland. Contour levels of expected lead times of 0 s (i.e. the blind zone) and 10 s are also shown as white curves. Apparent from Figure 3 is that an event with $M_W \sim 6.75$ occurring in the region of Basel, which might produce a significant *PGA* ~ 0.1 g at the power plant of Beznau, would be associated with a lead time of ~ 7 s, that could be in principle used for triggering automatic mitigation actions at the plant. The available lead time of course increases if an EEW algorithm based on a smaller number of triggers is adopted. According to recent preliminary computations carried out within the framework of a SED project devoted to updating the national Swiss seismic hazard maps (Danciu 2014, personal communication), the annual probability of exceedance of *PGA* = 0.2 g, *PGA* = 0.1 g and *PGA* = 0.05 g at the Beznau site (for rock-like ground type with $V_{S,30} \sim 1100$ ms^{-1}) would be equal to 10^{-4}, 4×10^{-4}, 2×10^{-3}, respectively. As a rule of thumb, in the aftermath of a significant event, the above probabilities are expected to increase by a factor of 100-1000 (Wössner 2014, personal communication). Finally, we recall that Caprio et al. (2013) developed a methodological approach to investigate the usefulness of an ideal EEW system in terms of its so-called hazard impact, i.e. the ratio at a given site or region of the total hazard (defined as the annual rate of occurrence of macroseimic intensities larger than a given threshold) to the annual rate of positive warning times for the same intensity thresholds. Although affected by some simplified modelling assumptions their investigations showed that the hazard impact in Switzerland is expected to be always positive for I_{MCS} larger than VI.

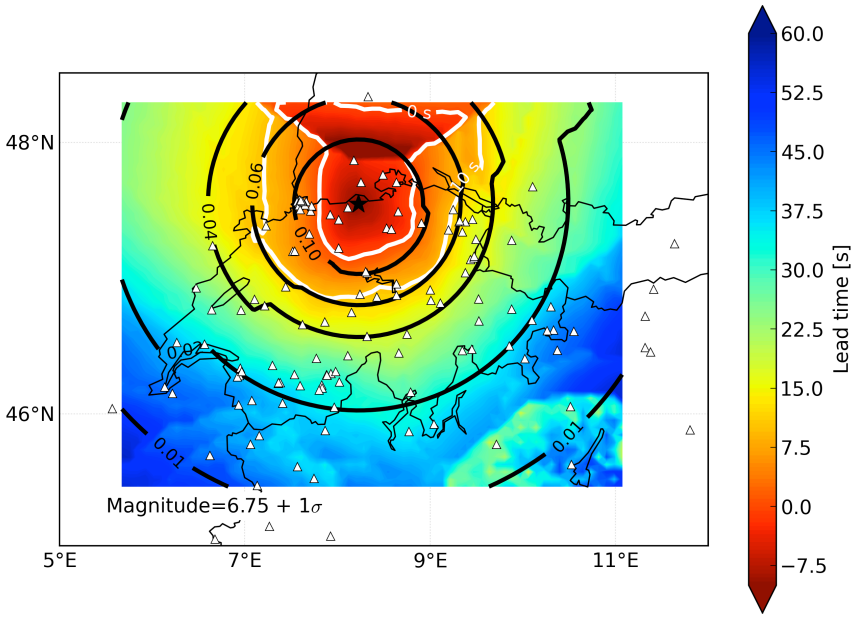

Figure 3. Map of expected lead times at Beznau for earthquakes of magnitude 6.75 potentially occurring at any point in the coloured area, using a minimum number of six station triggers for event declaration. Contour lines of lead time equal to 0 s (i.e. the blind zone) and 10 s are depicted as white curves. The black curves represent the *loci* of the earthquake locations that would cause *PGA* equal to a given threshold (e.g. 0.1, 0.06, 0.04, 0.01 g) at the selected target site (denoted by the star). Predictions are based on the parameterisation of the stochastic model of Edwards and Fäh (2013), with maximum stress drop of 60 bar (Cauzzi et al., 2013b), corrected for local site effects. For earthquakes occurring within the blind zone, there would not be enough time to alert the nuclear power plant before the onset of the shaking induced by the S-waves.

ON THE POTENTIAL ROLE OF OEF

Since several years the SED is involved in international research projects aimed at developing and optimising operational earthquake forecasting (OEF) methods. Since 2010, the SED routinely runs a short-term earthquake probability (STEP) algorithm that computes time-dependent 24-hour probabilities of ground shaking in terms of EMS-98 macroseimic intensity levels throughout the country. Data driven, the STEP method is based on the earthquake catalogue and bulletin for Switzerland, along with observational laws including the Gutenberg-Richter relation and the Omori-Utsu aftershock frequency distribution law. STEP is a modular approach that uses adapted parameters of Reasenberg and Jones (1994) and modifies the parameters depending on the real-time feed from the seismicity, updating whenever enough sequence specific data is available. These parameters serve as the basis to compute earthquake rates and thereafter ground motion exceedance probabilities. Based on the STEP model of Wössner et al. (2010), SED maintains a dedicated website where the STEP maps are seamlessly updated, showing the probability of reaching or exceed EMS-98 macroseismic intensity V in Switzerland, based on the past and present earthquake distribution. Based on the ground motion to intensity conversion equation of Faenza and Michelini (2010), EMS-98 intensity V in Switzerland roughly corresponds to a peak ground acceleration of 0.02 g. The maps include macroseimic intensity site amplification as derived by Fäh et al. (2011).

In the aftermath of a significant event, 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 4. The left panel of Figure 4 shows the common logarithm (log_{10}) of the probability of exceedance of $I_{EMS\text{-}98}$ = V in 24 hours, as computed a few hours after the earthquake origin time. The right panel shows the same probabilities as computed one day after the origin time of the M_W 6.6 event. Although forecast can be extended to longer periods, the model is targeted to forecasts of periods of several weeks.

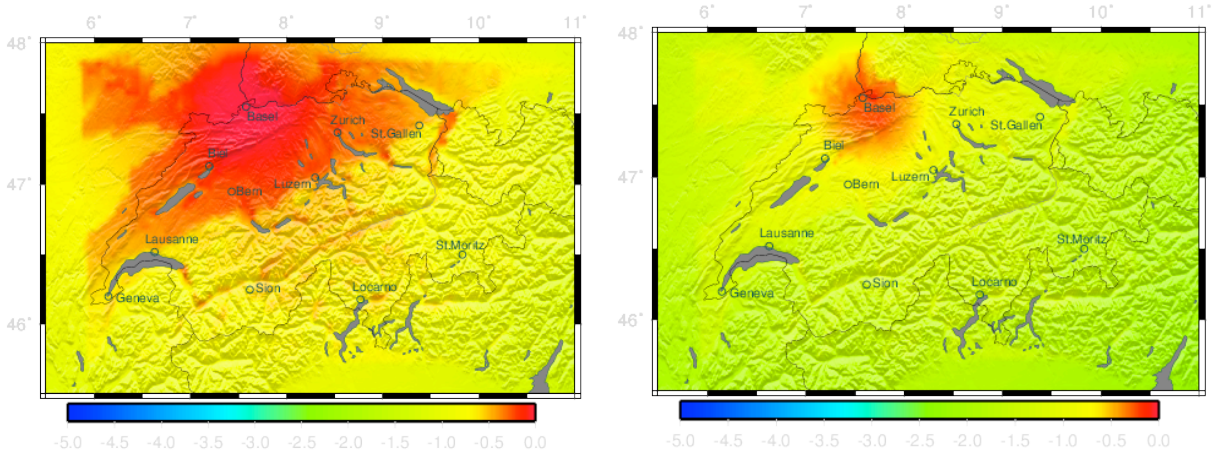

Figure 4. Examples of SED 24-hour STEP maps computed in the aftermath of a scenario M_W 6.6 event in Basel. (LHS) log_{10} of the probability of exceedance of $I_{EMS\text{-}98}$ = V in 24 hours, as computed a few hours after the earthquake origin time. (RHS) same as LHS, but computed one day after the origin time of the mainshock.

ON POTENTIAL MITIGATION ACTIONS, DECISION CRITERIA, COSTS AND BENEFITS

The identification of possible mitigation actions at NPPs in response to EEW or OEF should be carefully carried out in order to ensure consistency with the regulations for the management of emergency situations at NPPs, as mentioned in the introduction. 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), while actions in response to forecasted heightened hazard might include, e.g. reinforcing inspections, taking reactors offline in controlled manner, practicing earthquake drills, adapting the outage period and reducing the number of people at risk within the perimeter of the plant.

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 once, e.g., 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 the *PGA*, peak ground velocity, 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, included in further models to refine the impact assessment, calculating the probability of various damage grades or even estimate the potential losses.

The typical decision tree for a potential mitigation action at a NPP in response to EEW would follow the schematic shown in Figure 5, which contains all the key elements to be collected to take a decision based on a cost-benefit approach. The decision tree of Figure 5 allows reformulating the question *"Is it appropriate to use an EEWS for a NPP?"* as two sub-questions for the power-plant operators.

(1) Is it appropriate to provide a 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 in particular an assessment of the setting-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 PSHA. Focusing on the region of Basel, the following annual probabilities were obtained by averaging different tectonic models, for events with M_W larger or equal to 5.5, 6.0 and 6.5: 1.67×10^{-5}, 5.13×10^{-6}, 1.28×10^{-6} respectively (note that the probabilities concern a small area of 0.05°x0.05°). If the EEWS is maintained by an academic/governmental institution, system costs would typically include development and maintenance of the software, project

management and liaison with end-users and a partial cost for operation of the existing seismic networks.

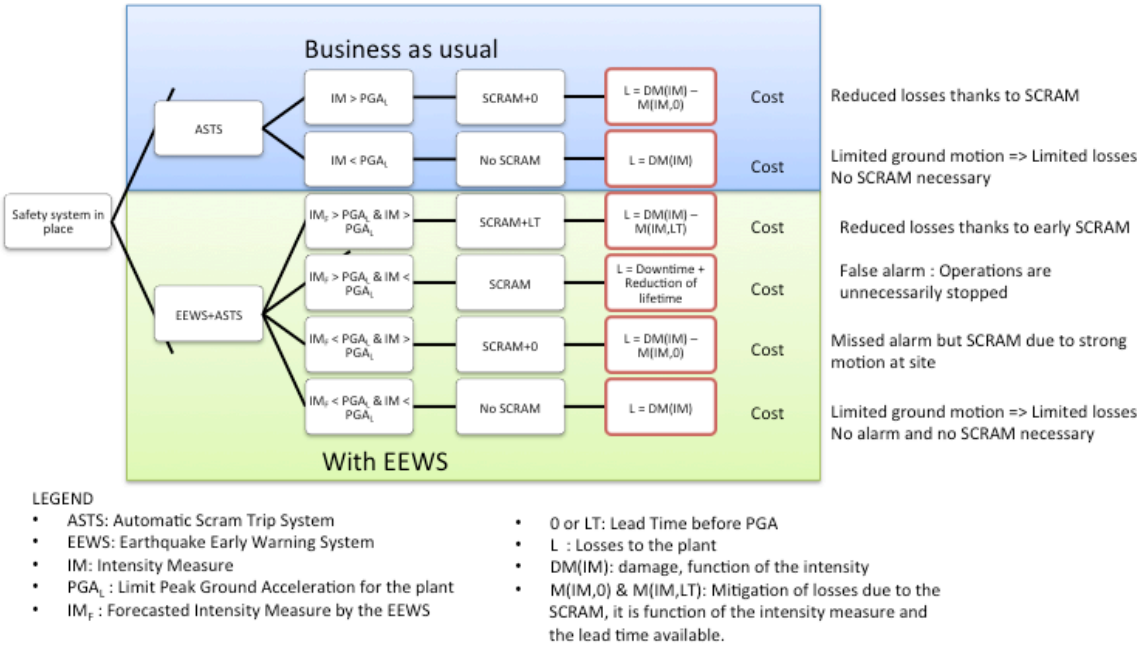

Figure 5. Proposed decision tree for a potential mitigation action in response to EEW at a NPP.

(2) *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 setting-up process, 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. For example, focusing on secondary systems like the steam turbines, one could identify costs and benefits as listed in Table 4. A similar exercise can be in principle carried out also for primary systems like the reactor (although EEWS obviously cannot prevent the onset of structural damage if the design levels are dramatically exceeded). Under the assumption of a severe structural damage, involving also release of radioactivity to the environment, the monetary assessment of costs and benefits would involve assigning a price to human life, which is not further discussed in this paper.

It is critical for assessing costs and benefits associated to a mitigation action in response to real-time hazard information to carefully evaluate the available lead time at the target site, based on potential earthquake locations, seismic station distribution and seismic network performance in terms of communication and processing delays (see Section "On the potential role of EEW"). A remarkable example in this sense can be made by focusing on the potential shutdown of the reactor. This is by far the most delicate mitigation action because during the shutdown procedure the risk is the highest (compared to full operations). The problem is that shutting down takes several steps and a long time. During this phase some pieces of equipment will function and some not, and also some safety systems will be shut down. Thus, if an early warning is issued and there are only a few seconds lead time, the plant would be in the beginning/middle of such a critical stage when the strong ground motion hits the plant. As some systems will already be shut down, they would not be available for mitigation actions and this is more dangerous than having all systems online during the shaking. As to secondary elements like the turbines, they also continue to rotate/operate for some hours after their shutdown until they reach their stop position. Thus lead time of only a couple of seconds would cause benefit only if a 'safe' rotor speed (expressed as a percentage of the critical speed) could be reached. Following the logic of the above examples, a time-dependent vulnerability function can be associated to any elements at risk and its variation with time would actually help in justifying which actions should be excluded from further consideration and to see whether there are some occasions (e.g. a large earthquake at a great distance) when such actions may be envisioned because of the long lead time available. Clearly seen as a benefit from the NPP operators is the preparedness of the persons in

the control room (in case of EEWS and OEF), but there is presently no clear idea how to practically quantify a benefit (or money) beyond modelling this preparedness as an increased lead time.

Table 4. Costs and benefits associated to a potential mitigation action concerning e.g. the steam turbines system.

Potential losses / impact of earthquake	Mitigation action in response to EEW	Benefit(s) / Losses prevented	Monetary benefit(s) / Losses prevented	Costs of action	Monetary cost of action
(a) Heavy damage / total failure of the turbine due to occurrence of a high-amplitude stable nonlinear limit cycle vibration induced by dynamic shaking on the rotating machine. (b) As a consequence of (a), malfunctioning of generator unit until turbine(s) is repaired / replaced. (c) Grid instability as a consequence of a) and b).	Manual or automatic trigger of emergency governor of the turbine (assuming SCRAM is not triggered)	*(if alert is true)* (1) Avoid / minimise potential losses a), b), c). (2) Early awareness of control room operators to potential emergency conditions.	*(if alert is true)* (1) Cost of a turbine (assuming e.g. that major damage would prompt to replacement instead of repair). (2) Minimise lost revenue from power sales.	*(if alert is true)* None.	*(if alert is true)* None.
		(if alert is false) None	*(if alert is false)* None	*(if alert is false)* Missed power generation and sale due to downtime.	*(if alert is false)* Monetary estimate of missed power generation and sale due to downtime.

Once all the necessary elements have been identified, 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. For a rigorous CBA the discrete values P, L and C should be replaced by loss and cost distributions with different probabilities of occurrence and hence the calculation of the benefit-cost ratio will be in the form of an integral. The probabilities will be a function of the hazard (e.g. what is the chance of a certain PGA occurring?) and the risk (e.g. given this PGA what is the chance of a certain loss?). When conducting a CBA aiming at answering the question of the interest to provide a NPP with an EEWS, it is advisable to estimate both costs and benefits over a time-period corresponding to the life expectancy of the NPP 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. 1’000 to 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 contribution of extreme earthquakes characterized by a low probability of occurrence (return period greater than those observed in the historical record) and a high magnitude. However, the safety of NPPs needs to be examined with regard to the frequency and severity of extreme earthquakes, as

recently highlighted by the Fukushima-Daiichi accident. 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 SHA), and it is precisely in that kind of situation where EEWS may be very helpful by offering a gain of safety that could avoid – in some cases – the "cliff edge effect". Moreover, EEWS may provide a societal benefit by increasing the confidence that the society has in nuclear safety, which is particularly important in the post-Fukushima-Daiichi context that is characterized by societal distrust of NPPs. Similarly to the IAEA who recommend applying both PSHA and DSHA when designing/retrofitting NPPs in order to get a *"balance between defence 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.

CONCLUDING REMARKS

Quantitatively evaluating the usefulness of real-time earthquake risk mitigation procedures for a nuclear power plant located in a region of low-to-moderate seismicity is a challenging task. While it seems to be pertinent to base this evaluation on a CBA, the actual implementation of mitigation strategies in response to EEW or OEF must ensure consistency with a consolidated and highly-regulated decision-making framework, where the identification of emergency safety measures is dominated by strict regulations, that leave little room for exploring alternative options and dramatically penalise decisions based on alerts associated with positive (although small and to some extent unavoidable given the current technologies in EEW and OEF) probabilities of being false. The common understanding of the engineering seismology community and the general public is that there must be some pieces of primary or secondary equipment that would benefit from a shut down a few seconds prior to strong shaking. In fact, this view is too simplified and the process needs to be carefully evaluated by NPP operators based on the time necessary to successfully initiate/complete an emergency shutdown (e.g. in the framework of the probabilistic risk assessment). One remarkable example in this sense is given by the process of an emergency shutdown of a nuclear reactor where, as documented in this report, in case of lead time of the order of 10 seconds, the risk would be even increased with respect to continuous operation under strong shaking. As a matter of fact, the challenge faced herein is that a nuclear reactor is not comparable to other EEW end-user applications and that other installations might have a much simpler cost-benefit evaluation where turning off something and shutting down a piece of equipment has always an immediate and positive effect. With this background, the efforts of assembling the elements for assessing costs and benefits of EEW and OEF for NPPs in a region where strong damaging earthquakes are rare, should be preferably presented as a methodological study on quantifying the capabilities and limits of the current technologies and methodologies in the domain of real-time seismology (as done in this contribution) with the aim of providing a transparent and informative support to decision-makers. That is, the role of the engineering seismology community in the domain of strategic applications to critical infrastructures like NPPs is not to answer the question *"Is it appropriate to use an EEWS or OEF for a NPP?"*, but rather to provide the decision-makers and the stakeholders with all the necessary elements and a methodological framework to themselves answer this question based on present and future knowledge and technologies in this field of research. In this sense, the study summarised in this contribution is of general interest for the community of researchers and end-users, beyond the specific application within REAKT. In particular, it should introduce end-users to available real-time hazard information and help academic partners and end-users identify suitable applications. Finally, it may lead to proposals for both specific actions to be taken under given circumstances and necessary technological improvements as pre-requisites for EEWS implementation.

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