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Feasibility study on earthquake early warning and operational earthquake forecasting for risk mitigation at nuclear...

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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).

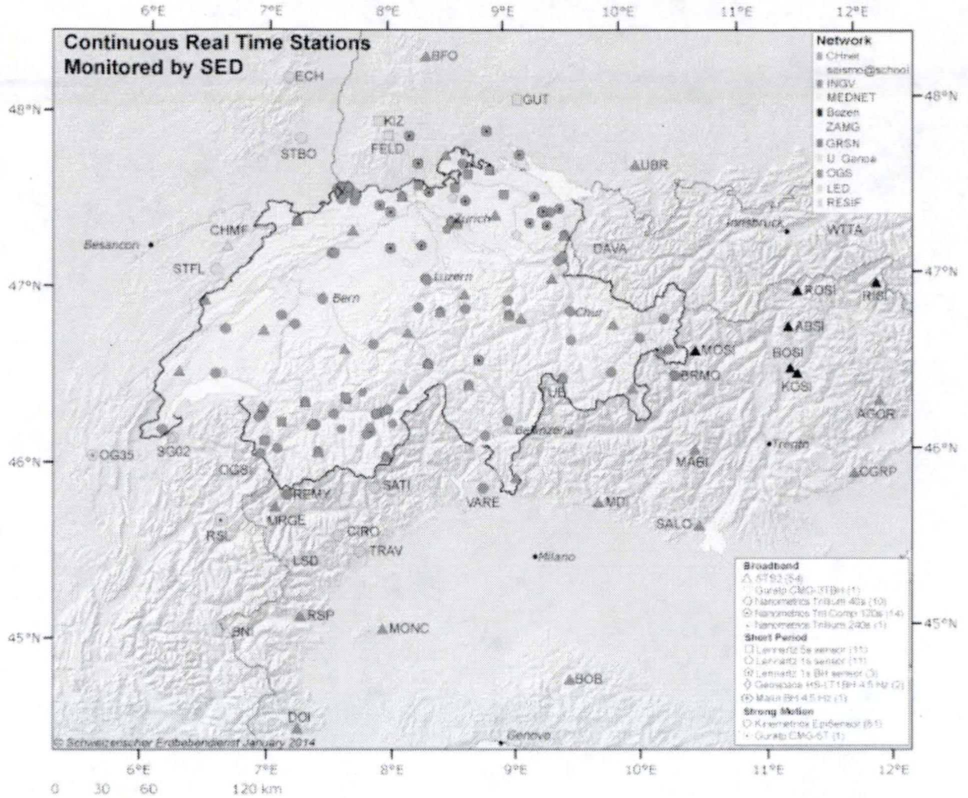

Figure 1. Map of real-time stations (velocity and acceleration sensors) used by the Swiss Seismological Service for continuous monitoring of the seismicity in the greater Swiss region (January 2014).

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.

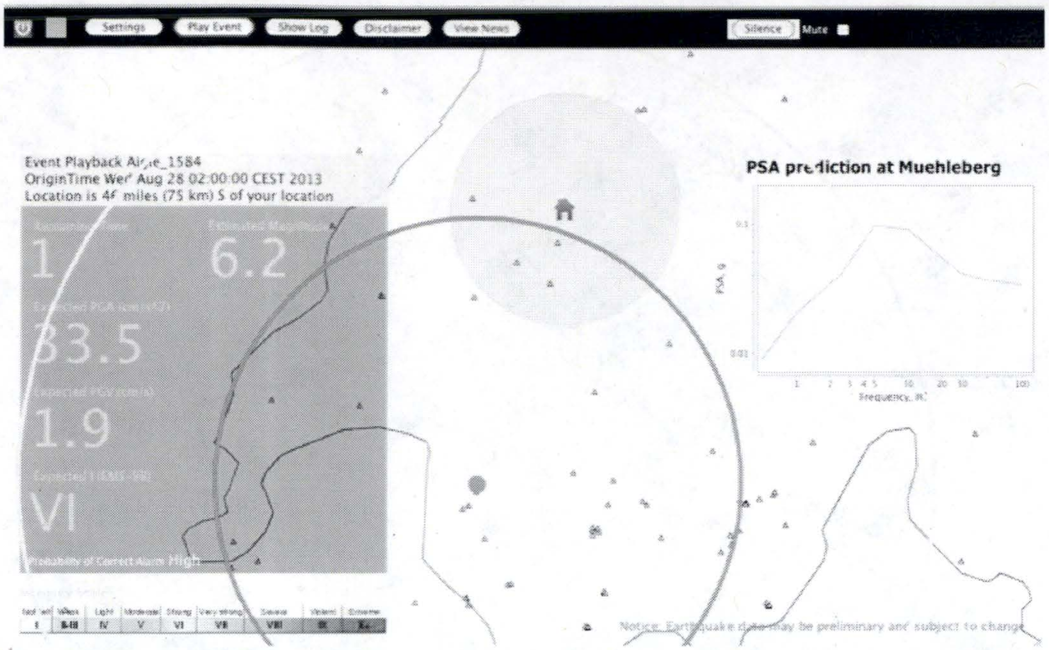

Figure 2. Example UserDisplay screenshot showing peak ground motion and response spectrum predictions at the site of Mühleberg, based on the location and local magnitude of the 1584 Aigle event. The grey-shaded area around the target is the expected blind zone. The red and yellow circles are the S- and 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 $PGA \sim 0.1$ 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.

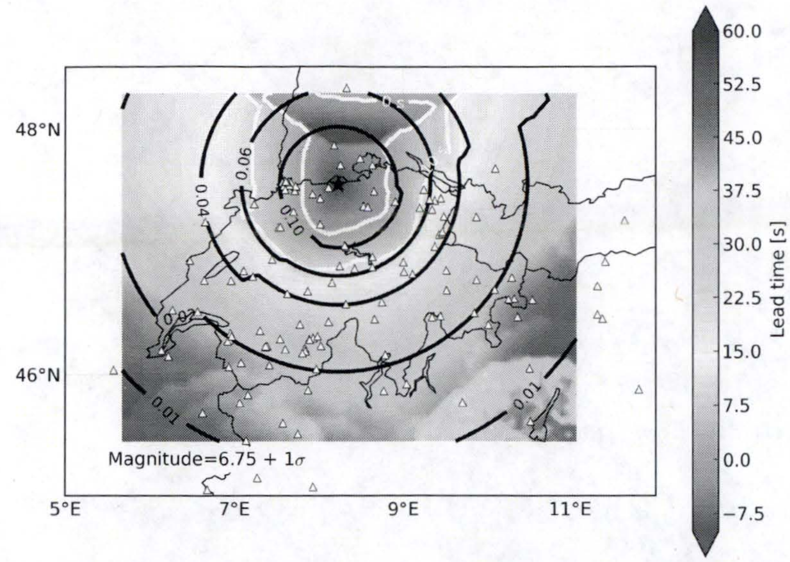

Figure 3. Map of expected lead times at Beznau for earthquakes of magnitude 6.75 potentially occurring at any point in the coloured area, using a minimum number of six station triggers for event declaration. Contour lines of lead time equal to 0 s (i.e. the blind zone) and 10 s are depicted as white 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.

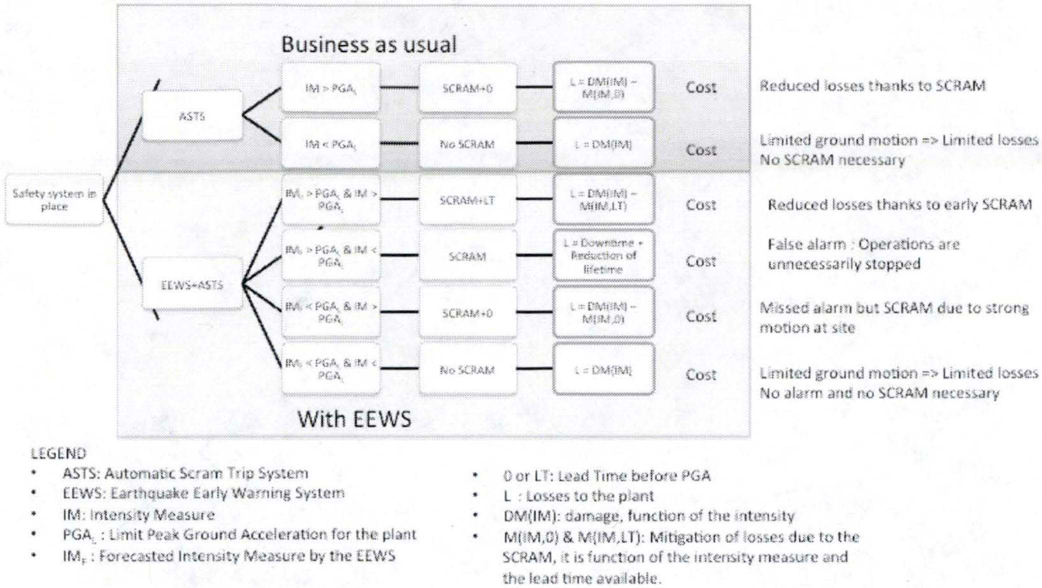

Figure 5. Proposed decision tree for a potential mitigation action in response to EEW at a NPP.

(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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SEISMIC ALARM SYSTEM FOR IGNALINA NUCLEAR POWER PLANT

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Abstract

A seismic alarm system will be installed at the Ignalina Nuclear Power Plant (INPP) in Lithuania. There are two reactors, both RBMK 1500 MW units. Each reactor is a water cooled, graphite moderated, channel type reactor. INPP has the most advanced version of the RBMK reactor design series. The first and second units of INPP went into service at the end of 1983 and in August 1987 respectively. Their design lifetime is approx. 30 years. The various buildings and plant have been designed for two earthquake levels, that is the design earthquake and the maximum possible earthquake with peak ground accelerations ranging from 1.2% to 10% of the acceleration due to gravity. Certain parts of the buildings and some of the equipment of the first and second units do not comply with Western seismic standards. As seismic strengthening of the existing buildings and equipment is not feasible economically, a reactor protection system based on an earthquake early warning system was recommended. This system essentially consists of six seismic stations encircling INPP at a radial distance of approx. 30 km and a seventh station at INPP. Each station includes three seismic substations each 500 m apart. The ground motion at each station is measured continuously by three accelerometers and one seismometer. Data is transmitted via telemetry to the control centre at INPP. Early warning alarms are generated if a seismic threshold is exceeded. This paper discusses the characteristics of INPP, the seismic alarm system presently under construction and the experience with other early warning and seismic alarm systems.

1. INTRODUCTION

The group of seven Industrialised Nations (G-7) agreed in March 1992 on an action plan to upgrade the safety of Soviet designed reactors. From the fund, called the Nuclear Safety Account, administered through the European Bank for Reconstruction and Development (EBRD) a grant of USD 38 million was allocated in 1994 for projects to upgrade the Ignalina RBMK plant. The EBRD have set up a project management unit (PMU) at the Ignalina plant, comprised of plant staff and Western experts to manage these projects.

In 1996 a joint venture formed by Electrowatt Engineering and GeoSys was awarded the contract to install an earthquake early warning system at the Ignalina Nuclear Power Plant (INPP), situated in Lithuania in the Baltic area. The purpose of this warning system is to provide information and alarms to allow the safe shut-down of the two reactors in the event of seismic waves from moderate to strong earthquakes approaching the plant.

The power plant was designed for two types of earthquakes. These are the design earthquake and the maximum possible earthquake having peak ground accelerations ranging from 1.2 % to 10 % of the acceleration due to gravity, i.e. 0.012 to 0.1g. The reactor building was designed for

accelerations of 0.026 to 0.051g which may result from rather moderate earthquakes. Some of the buildings and equipment of the first and second units of the INPP do not fully comply with Western seismic standards. Such buildings and equipment should be strengthened. However as seismic strengthening was not considered to be economically feasible, other options have been studied. In order to protect the reactor from earthquake damage, it was decided to install an early warning system and to shut down the reactor should a sufficiently strong earthquake occur in the vicinity of INPP. Accordingly, six seismic stations are to be installed in a ring centred on the plant at a distance of approximately 30 km. The stations are uniformly distributed as shown in Fig. 1. Each consists of three independent substations which are approx. 500 m apart. The ground motion is recorded continuously and transmitted to the control centre via telemetry as discussed in the subsequent sections.

2. CONCEPT OF SEISMIC ALARM NETWORKS

Research in earthquake prediction has shown that we are still some way from the accurate prediction of the time, location and magnitude of strong earthquakes. However, present technology in seismic instrumentation and telecommunications permits the implementation of systems for early warning of earthquakes. Such systems are capable of providing a warning of from several seconds to tens of seconds before the arrival of the strong ground tremors caused by a large earthquake.

An earthquake early warning system has the potential for the optimum benefit as it can provide the critical alarms and information needed (i) to minimise loss of property and lives, (ii) to direct rescue operations, and (iii) to prepare for recovery from earthquake damage (Lee et al., 1996).

The basic features of a seismic alarm network are shown in Fig. 2 (Heaton, 1985). Ground motions recorded by an array of seismometers are telemetered to a central processing site. The main parameters of an earthquake, i.e. the location, time of origin, magnitude, amplitude of ground tremors and reliability estimates are computed. Based on the location and the geological conditions the nature of the ground motions expected at the site is determined. On the basis of this information the appropriate action is taken.

The problem of false alarms is minimised by continuous updates regarding the size of the ground motions at differing stations in the seismometer array or by redundancy from several measurements at the same geographic location.

However, if the user is far from the epicentre, then considerable time is available before shaking begins. This time may be used to receive further information from external organisations

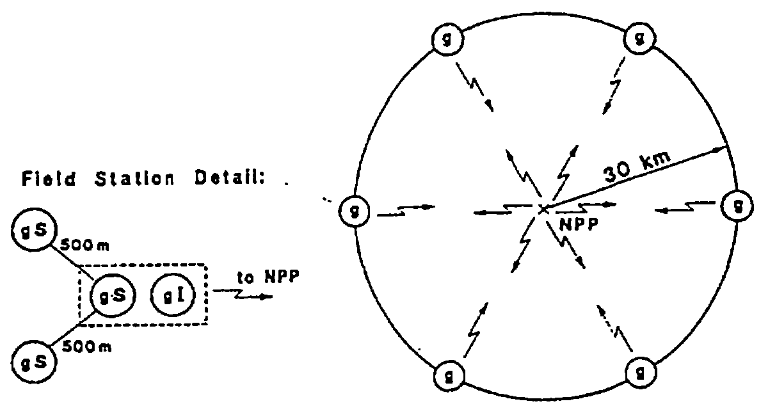


Fig. 1 Layout of seismic monitoring system of Ignalina nuclear power plant (NPP)
(g: station communication by telemetry; gl: substation with borehole seismometer;
gS: substation accelerometer with alarm switch and communication by cable)

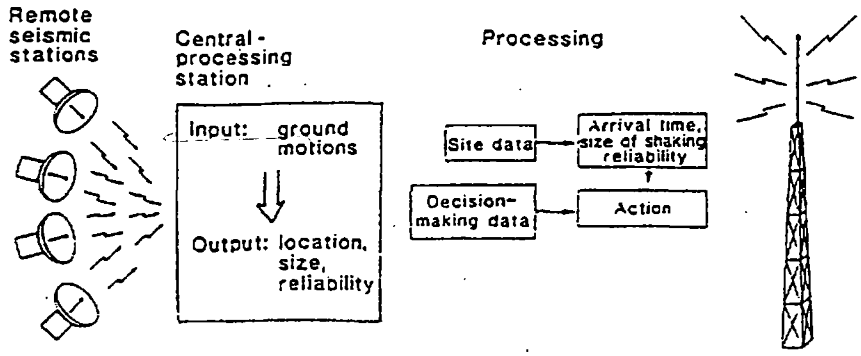


Fig. 2 Conceptual design of an earthquake early warning system

about the size of the earthquake. In this way, users at large epicentral distances take action only for the large earthquakes that present a real hazard, and each user adjusts the decision-making process to the needs of the site.

After the occurrence of an earthquake, the seismometer array provides information regarding the strength of shaking in different geographic locations. This information can be used to estimate regions of substantial damage, so that emergency services can be allocated promptly and properly. Because the seismometers in the array would have a large dynamic range, the seismic network may routinely record ground motions from numerous small earthquakes and teleseismic events. Such data are important for basic research in the fields of ground-motion prediction, earthquake prediction, and earth structure investigation. Also, the routine use of a seismic network for studies of numerous small events would help to ensure that the system operates properly when relatively rare large events occur.

Although relatively large peak accelerations occur at small distances from the numerous smaller earthquakes, they rarely cause great damage because the duration of intense shaking is short. Response spectral velocities of 1 second are usually considered to give a better estimate of damage potential than peak acceleration (Heaton, 1985).

For earthquakes with epicentres within a radius of 30 km of INPP the alarm time is reduced. A seismic station has been installed at INPP that can generate a seismic alarm by the onset of P- or S-waves. At Ignalina, this aspect is of less significance due to the geology and historically low seismic activity at the site. With regard to other nuclear power plants, the seismic properties of the site should be carefully investigated. An extended seismic array could provide seismic protection for seismically active sites.

3. EXPERIENCE WITH EARLY WARNING AND SEISMIC ALARM SYSTEMS

At the moment there are two early warning systems in operation for civilian purposes, i.e.

(i) Urgent earthquake detection and alarm systems (UrEDAS) in Japan.
This real-time earthquake disaster prevention system is used for railways. The special feature is the rapid alarm using information from P-wave data. Systems for different railways have been in operation since 1983 (Nakamura, 1996). UrEDAS detects initial P-wave motions, estimates epicentre azimuth and magnitude, calculates epicentral distance and local depth. This system is not only useful for railways but also for nuclear power plants, etc. Seismic data is transmitted to the interested parties 4 minutes after an earthquake.

(ii) Seismic alert system (SAS) for Mexico City.
Most of the large earthquakes which are likely to cause damage in Mexico City have their source in the subduction zone of the Pacific coast at a distance of about 320 km. The warning time varies between 58 and 74 seconds.

The Seismic Alert System for Mexico City consists of four elements: the Seismic Detection System, a Dual Telecommunications System, a Central Control System and a Radio Warning System for public and corporate users. The seismic detector system consists of 12 digital strong motion field stations located along a 300 km stretch of the Guerrero coast, arranged 25 kilometres apart. Each field station includes a microcomputer that continually processes local seismic activity which occurs within a 100 km radial coverage area around each station.

The Dual Telecommunications System consists of a VHF central radio relay station, located near Acapulco, and three UHF radio relay stations located between the Guerrero coast and Mexico City. Two seconds are required for information sent by one of the field stations on the Guerrero coast to reach Mexico City, this data is sent digitally coded.

The Central Control System continually receives information on the operational status of the field stations and communication relay stations, as well as the actual detection of an earthquake in progress. Information received from the stations is processed automatically to determine magnitude and is used in the decision to issue a public alert.

The Radio Warning System for users disseminates the seismic early audio warnings via commercial radio stations and audio alerting mechanisms to residents of Mexico City, public schools, government agencies with emergency response functions, key utilities, public transport agencies and some industries. Public and some private buildings, factories and offices are equipped with specially designed radio receivers to obtain the SAS alert. In each place there is a person in charge of the SAS receivers whose duties are to check the status of the receivers and co-ordinate all the activities of a disaster prevention including evacuation exercises and drills. There are a total of 98 radio receivers in operation of which 28 are installed in schools. During rush hours approximately 4.4 million people are covered by the system. The system has been operating since 1991. The system cost USD 1.2 million to develop and install and has running costs of USD 0.2 million per year for operation and maintenance (Espinosa-Aranda et al., 1996).

Other early warning systems have been reported by Shin et al. (1996), however, these are still in an experimental phase.

4. CHARACTERISTICS OF IGNALINA NUCLEAR POWER PLANT

4.1 General

The Ignalina NPP contains two RBMK-1500 reactors. This reactor type is the most advanced and powerful version of the RBMK reactor design series. The first unit went into service at the end of 1983 and the second unit in August 1987. Their design life is about 30 years. A total of 17 such reactors have been built in the former Soviet Union. In August 1991 INPP came under the authority of the Lithuanian Republic.

INPP belongs to the category of channel type boiling water reactors. The entire building of the two units covers an area of 600 m by 51 m and the reactor building is 61 m high. A cross-section through the reactor building of one unit is shown in Fig. 3. (Almenas et al., 1994).

4.2 Site Conditions

The INPP is located in an area with neotectonic motion of approx. 3.5 mm per year. The surface elevation varies from 150 to 180 m above sea level. The surface layer with a depth of 60 to 200 m consists of quaternary sediments which are very non-homogeneous. They were formed during the retreat of the last glaciers. Later on, alluvial, marsh and lake sediments were formed.

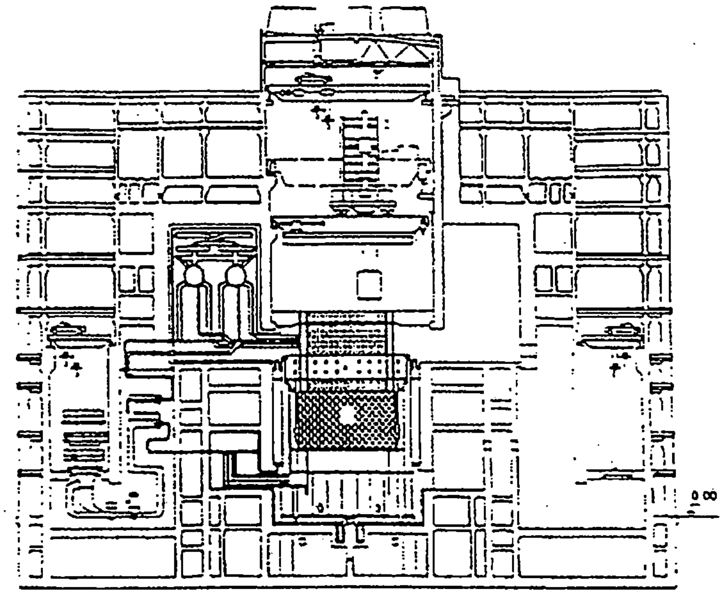


Fig. 3 Cross-section through reactor building of one unit of Ignalina RBMK-1500 nuclear power plant

The Baltic region is usually regarded as a region of low seismicity. In comparison to Latvia, Estonia and Belarus, Lithuania has the lowest seismic activity. However, the available data indicates, that there is a possibility of strong earthquakes occurring. The maximum possible earthquake in the surroundings of INPP is estimated to have a magnitude of 4.5 and a focal depth of 5 to 8 km.

4.3 Earthquake Resistant Design

For Soviet designed nuclear power plants two levels of earthquakes were taken into account, i.e. the design earthquake and the maximum possible earthquake. The first is a maximum earthquake which may happen during the service life of the plant . The second is the maximum possible earthquake in the area . For INPP the design and maximum possible earthquakes have peak ground accelerations, respectively, of 0.012 to 0.05g and 0.025 to 0.1g. This was considered appropriate for the seismic activity of this region.

Depending on their function during and after an earthquake, all buildings and equipment were subdivided into different seismic categories. For each category different seismic design criteria were applicable. The earthquake analyses were performed using a response spectrum method.

This approach to earthquake resistant design has not been adopted in Western standards. A review of the structural integrity of the plant was carried out in 1995. Measures aimed at strengthening the building structures and equipment were considered and judged to be uneconomical. Consequently it was decided to install an earthquake warning system as a first step to increase plant safety in the event of an earthquake.

5. CHARACTERISTICS OF THE IGNALINA SEISMIC ALARM SYSTEM

5.1 Description of the System

Usually, a time period of 2 seconds is required for the insertion of the control rods of the nuclear reactor. After that, the nuclear thermal capacity is strongly reduced and the reactor core is

prevented from meltdown in the case of a severe accident. A core meltdown would entail the risk of radioactivity release to the environment.

The existing earthquake early warning systems, see Section 3 of the present report, require by far more than 2 seconds to indicate a seismic event. Therefore, a system had to be designed specifically suitable to nuclear power plants. In the INPP Seismic Alarm System (SAS), six seismic stations using accelerometers are installed at a distance of 30 km from the power plant. The signals are transmitted to INPP by radio waves, which requires virtually no time. Assuming a seismic shear wave velocity of 3.5 km/s, the pre-warning time would be 8.5 s. In practical terms, this is reduced to 4 s by the required transfer and processing times. It is concluded that the Ignalina SAS is able to effectuate the insertion of the control rods before the arrival of the damaging seismic waves, i.e. the shear waves, at the NPP.

At each seismic station three accelerometers are located at substations 500 m apart. The SAS accelerometers input to seismic switches which are factory preset to an initial acceleration threshold of 0.025 g. When this threshold is exceeded the seismic switch produces an alarm signal. These signals are digitally encoded and sent via a separate transmission channel to the control centre.

Here a 2-out-of-3 voting logic is used to determine if a seismic event has occurred and to generate a seismic alarm in the main reactor control rooms.

The alarm system is complemented by a seismic monitoring system (SMS), which provides seismic data recording and processing. One seismometer is located at each seismic stations. In addition, the SMS includes sensors inside of the reactor building and on two key items of equipment namely on the cooling water pump and on the steam separator drum of each unit. The data is processed by two redundant central computers located at each unit.

The program of works foresees the installation of the seismic stations, the telemetry system and the seismic evaluation system at the end of 1997.

After implementation, the Ignalina Nuclear Power Plant will be one of the first nuclear power plants in the world to have an earthquake early warning system using both accelerometers with seismic switches and seismometers.

5.2 Technical Outline of the Seismic Alarm System

The SAS is outlined in the Block Diagram, Fig. 4. The SAS system is seismically qualified. It is based on three separate measurements, transmission and reception channels and a 2-out-of-3 voting logic. This gives a high degree of reliability, operability and protection against false alarms. Each seismic station has three substations designed to Western seismic standards. An external power supply is required for each seismic station. Triaxial accelerometers are used as sensors in each substation. To reduce the effect of signal noise the analogue signals from each sensor are digitised at its substation. The seismic switches and radio frequency data transmission telemetry equipment of the three substations are located in the cabin of the seismic station. The signals of the seismic switches are transmitted to the power plant by radio communication in the Ultra High Frequency (UHF) band. UHF communication requires line of sight conditions, which poses comparatively little difficulty in the flat area of Lithuania.

The trigger threshold of each seismic switch is software adjustable. The initial setting of 0.025g will be assessed after a trial period and optimised. The records of the Seismic Monitoring System will be used for this assessment.

Receiving antennas are mounted on the reactor building roof. The telemetry equipment is located nearby. For each seismic station, this equipment and the associated cabling is separated into

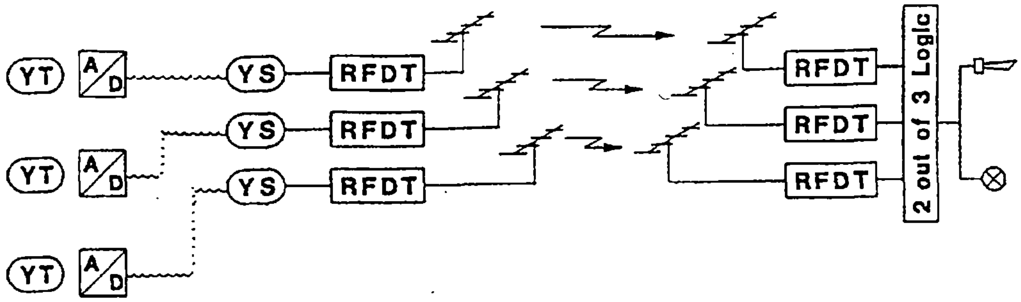


Fig. 4 Seismic Alarm System SAS, Block Diagram, one of six stations

three measurement channels up to the 2-out-of-3 voting logic located adjacent to the reactor control room. This logic initiates the alarm signals to the main control room for each reactor.

The seismic alarm system for INPP has been designed to provide an economical and adequately comprehensive solution to concerns regarding the seismic integrity, with respect to Western standards, of some of the INPP buildings and equipment. The use of accelerometers and seismic switches by the seismic alarm system maximises the available warning time.

5.3 Technical Outline of the Seismic Monitoring System

The SMS is outlined in the Block Diagram, Fig. 5. The system includes six seismometers, one at the cabin of each seismic station, plus one seismometer and two accelerometers at INPP. Each seismometer is located in a bore hole. The location of the seismic stations have been chosen so as to be remote from environmental noise.

Four triaxial accelerometers are located in the reactor building three on the base of the building and one at the 20 m level. Biaxial accelerometers are located on the cooling water pump and on the steam separator drum in each unit.

The values measured by the field SMS seismometers are combined into data packets, which are transmitted to the power plant by radio communication. Separate radio frequencies are used to permit continuous transmission of data. At the power plant data is digitised and input to the central processor using RS-485 links. Sampling rates up to one or two hundred samples per second will be possible. Data is stored and processed in two central computers.

The provision of the seismic monitoring covering off-site and on-site locations permits the determination of the seismic transfer function from the off-site locations to the NPP and a quantitative measurement of the building and equipment response to seismic activity. This can be used in two ways. Firstly, to assess the stress caused by seismic activity in order to confirm that the integrity of the plant has not been compromised. Secondly, in conjunction with a reactor seismic model to identify potentially susceptible plant. Once identified the necessary structural improvements can be determined.

5.4 Central Data Recording and Processing

On the central computers, a PC based QNX multitasking, multi-user operating system is installed. The management of data acquisition is performed by the SEISLOG application software and the analysis is accomplished using the SEISAN earthquake analysis software. SEISLOG and SEISAN were developed by the Institute of Solid Earth Physics, University of Bergen, Norway. The SEISLOG data acquisition system is used as the major data collection system in the national seismic networks of Norway, United Kingdom, Ireland and in several countries of Central America. In addition, SEISLOG is used at about 40 stations in eight other countries in Europe, Africa and Asia.

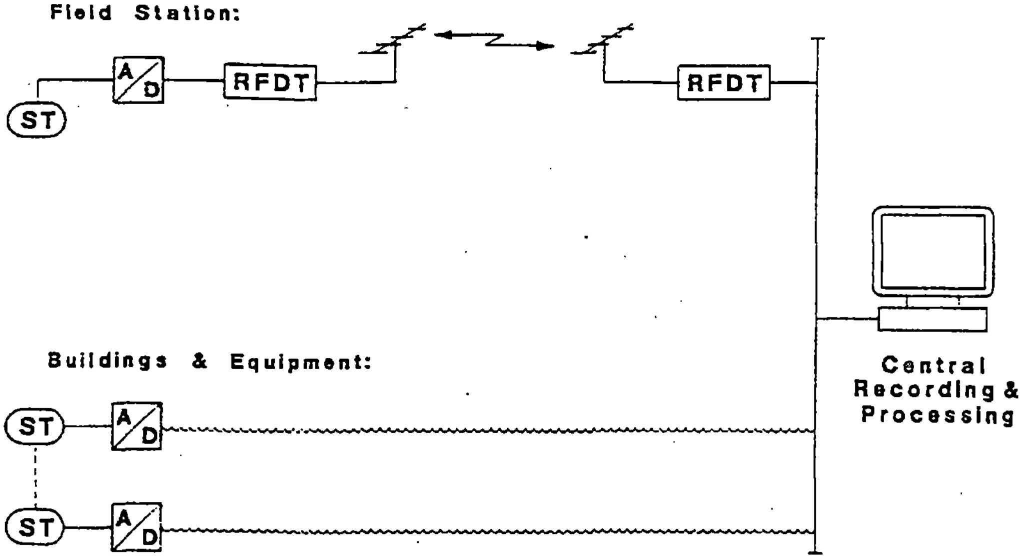
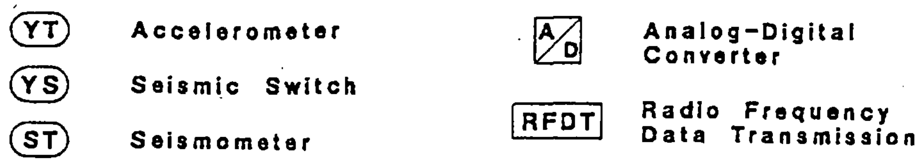


Fig. 5 Seismic Monitoring System SMS, Block Diagram, one of six field stations, typical instrumentation of buildings and equipment



Legend to the Block Diagrams

The digitised data packets, sent from the Seismic Monitoring System, are displayed on the central computer terminal by SEISLOG. When each page of data is accumulated, it is printed out in the analogue mode. This approach of printout is recommended because it provides the least cost and most reliable method of obtaining hard copies of the signals. Alternative plotting methods are selectable. SEISLOG has flexible user defined trigger criteria which can be tailored to both local and distant earthquakes. The system can be set up with up to five different trigger criteria sets in order to independently trigger on local and distant earthquakes.

The data sets are transferred from SEISLOG to the processing and analysis software SEISAN by floppy disk, tape, removable disk, modem or Ethernet. SEISAN has been in operation since 1988. It is used as the main processing tool in the SEISLOG installations mentioned above. SEISAN has the advantage of being a complete system with a data base and integrated processing tools. In addition to working smoothly with data from SEISLOG, SEISAN can also process data from many well known data acquisition systems and data banks. In particular, it has been well integrated with International Seismological Centre data formats. Large amounts of data can be processed either manually or automatically.

SEISAN can calculate all normally used magnitudes. It locates earthquakes with the latest global model (IASP91) or with user selectable models. Earthquake location can be done with several thousand stations and arrival times. More than 100 types of phases can be used. The data base can be searched for more than twenty different criteria. The results are displayed in terms of the hypocentral distribution in time and space and a statistical analysis can also be carried out.

A seismic model of the reactor will be developed and the predicted response spectra compared with monitored data. By developing the seismic model of the reactor an assessment will be possible of the stress caused by seismic activity to different parts of the reactor building and equipment.

5.5 Future Developments

The following future developments in the field of earthquake early warning systems are foreseen:

1) discrimination techniques to distinguish seismic activity from environmental noise;
2) investigation into satellite transmission systems for data communication over long distances or hilly areas;
3) development of stand alone seismic stations which are independent of an external power supply;
4) closer and faster data transfer links with international seismological monitoring organisations;
5) improved data telemetry equipment which can transmit more data in a given band-width.

6. CONCLUSIONS

A seismic "fence" having a radius of 30 km will be installed around the Ignalina Nuclear Power Plant to provide an alarm before potentially damaging earthquake tremors reach the reactors. The alarm threshold is preset at 0.025 g, which will be adjusted according to the experience gained.

Seismic safety upgrading of a nuclear power plant by means of a seismic fence is an economical solution for existing plants with inadequate or unknown seismic resistance of vital components in the case of strong earthquakes. It is also a recommended solution for existing power plants where earthquakes have occurred which exceed the level anticipated at the time of design and construction of the power plant.

This system cannot only reduce the consequences of a reactor accident caused by an earthquake but help confirm plant integrity following an earthquake.

Because of the many benefits and the low cost, earthquake early warning systems have excellent prospects in connection with increasing safety demands for nuclear power plants.

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