

Development of earthquake early warning systems in the European Union

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ABSTRACT

Utilization of Earthquake Early Warning Systems (EEWS) in Europe is lagging significantly in respect of pioneer applications in Japan and Mexico. The first reported implementation of a EEWS in Europe is the on-site system designed to protect the Ignalina nuclear power plant in Lithuania.

At the beginning of this century, some research groups in Europe started to develop EEW to protect the cities of Istanbul and Bucharest and the territory of Campania, in Southern Italy. Coordinate research effort involving all the groups interested in earthquake early warning started EU FP6 SAFER (Seismic eArly warning For EuRope) project and is continuing with the activities of the EU FP7 REAKT (Strategies and tools for Real Time EArthquake RiSk ReducTion) project.

INTRODUCTION

Utilization of Earthquake Early Warning Systems (EEWS) in Europe is lagging significantly in respect of pioneer applications in Japan and Mexico. The first system designed to protect a specific infrastructure, the Shinkansen railway fast transport system, was deployed in Japan in the late sixties. This system evolved into the UrEDAS (Urgent Earthquake Detection and Alarm System) in 1984. It uses the first 3 seconds of a P-wave to estimate earthquake parameters and to give an alarm. The 1995 Kobe earthquake, which caused extensive and severe damages to viaducts and other structures, prompted the implementation of an improved version called Compact UrEDAS which became operational for railways and metro in 1998. The 2004 M6.6 Niigata-Chuetsu earthquake was the first to require the activation of Compact-UrEDAS. It issued a warning 1 second after P-wave detection, which resulted in electric power shut down and emergency brakes activation on 4 trains moving at the speed of 200 km/h in the epicentral area. Only one carriage of one train derailed with no victim because its speed had been sufficiently reduced. (Kanamori, 2007, Nakamura et al., 2011)

After the Kobe earthquake the Japanese Government launched the development of a national EEW system. More than 2,000 seismic and strong motion stations were installed with a constant density all over Japan. The Japan Meteorological Agency (JMA) started to test EEW methods extensively in 2004. JMA began EEW national service for advanced users in August 2006 and to the public in October 2007. Mandate and responsibility are clearly defined by the Meteorological Service Law approved in 2009. The EEWS performed efficiently for general public, industries and railways in several cases. (see Hoshiba et al, 2008; Kamigaichi et al, 2009, Doi, 2011).

A seismic alert system (SAS) was implemented in 1991 for Mexico, where damages are produced by large earthquakes occurring in the subduction zone off the Pacific coast at a distance of about 300 km from the capital. The earthquake detector system was aligned parallel to the Pacific, allowing for a warning time of 58 to 74 seconds. The warning is used to alert schools, governmental agencies, and some industries (Espinosa Aranda et al., 1995, 2011).

In Taiwan a network consisting of about 100 accelerometers covers the island with sensors' density similar to that of Japan (1 sensor every 20 km). A virtual sub-network algorithm was developed to locate earthquakes and to calculate their magnitudes using P- and S- wave energy. The system is still in an experimental stage, and a promotion plan aiming at implementing several applications between 2013 and 2016 was developed (Wu and Teng, 2002; Hsiao et al., 2009).

An Earthquake Alarm System (ElarmS) was developed and tested in California. It uses the frequency content of the P-waves first detected at any station of a seismic network to estimate

earthquake magnitude and arrival times to estimate location. Radial attenuation relations are utilized to predict ground shaking at a given site. The potentiality of the system for several cities of California was estimated (Allen and Kanamori, 2003, Allen, 2007, Allen et al., 2009)

EEW IN EUROPE AT THE DAWN OF XXI CENTURY

The first reported implementation of a EEWs in Europe was designed to protect a nuclear power plant. International regulations on the security of nuclear power plant in seismic areas demand that on site accelerometers must be used to monitor PGA (Peak Ground Acceleration). When PGA is higher than a threshold a system halting the reactor is activated. Systems of this type exist in many nuclear power plants around the world. However they are not EEWs as the alert occurs when the PGA exceeds a given threshold value and not before. The on-site system designed to protect the Ignalina nuclear power plant in Lithuania (Wieland et al, 2000) is a real EEW system. It consisted of six stations encircling the power plant at a radius of 30 km plus a seventh station installed within the plant. The ground motion was measured continuously at each station by three accelerometers and a seismometer. The system generated an alert when the ground acceleration at one station exceeded a threshold value of 0.025 g. The alarm was meant to be used to stop nuclear reactions by the insertion of control rods. The operation required 2.5 s, whereas the alarm arrived at least 4 s before peak ground oscillation if the distance to the earthquake focus was more than 30 km. The Ignalina power plant was completely dismantled on December 31, 2009. No report is available on the performance of the EEWs.

Europe has the potentiality to develop and apply extensively EEW methods. In fact the European territory is covered by many high quality seismic networks, managed by national and European agencies, including local networks specifically designed for seismic early warning. Real time analysis of signals from these networks offers the possibility of implementing EEW for issuing alerts and for giving information useful for after event crisis management, such as real time shake maps and information on expected damage and rapid loss estimation. They can provide emergency managers with a better capability of planning rescue actions based on reliably described scenarios.

The timely information provided by earthquake early warning systems can also be used to forecast the time evolution of an earthquake sequence as well as triggered events, such as landslides and tsunamis. This is a relevant feature as a large percentage of the casualties and economic losses resulting from strong earthquakes occurred in the European territory in the last few centuries are due to triggered industrial accidents (such as at Izmit in 1999), tsunamis (e.g. the Messina earthquake in 1908 and the Lisbon earthquake in 1755), fires (e.g. Messina 1908), and landslides (e.g. South Italy earthquakes in 1857). A thoughtful application of EEW systems can be very efficient in reducing such effects. No EEW for the protection of lifelines, transport systems, strategic buildings (hospitals, schools, etc.) is active up to now in Europe.

At the beginning of this century, some research groups in Europe started to develop EEW to protect the cities of Istanbul and Bucharest and the territory of Campania, in Southern Italy.

The EEW system developed for Bucharest takes advantage of the highly localized source of large earthquakes in the Romanian Vrancea zone of the south-eastern Carpathians. The four strong events (M 6.9–7.7) observed during the last century all occurred in the same region at hypocentral distances of ~160 km. A regional network in the Vrancea region is used to detect earthquakes and issue a warning to industrial facilities in Bucharest, providing 20–25 sec warning time (Wenzel et al. 1999; Böse et al. 2007, Marmureanu et al., 2011).

After the north Anatolian fault ruptured close to the Marmara Sea in 1999 generating two catastrophic M 7+ earthquakes and a westward migration of earthquakes along the fault toward Istanbul was forecasted, plans and preparations for the installation of the Istanbul earthquake rapid response and early warning system (IERREWS) for the city were initiated. The system used a dense strong motion network. It was aimed at giving a fast loss estimate (rapid response) and a 8-10 sec warning to industrial users in the city (Alcik et al., 2009, 2011, Sesetyan, 2011).

The system in Naples (ISNET) was originally designed to give an alert to the Napoli Civil Defence Office within a few seconds or tens of seconds after an earthquake occurrence in the neighbouring Irpinia region, the same area where a disastrous earthquake was generated on the 23rd of November 1980. At present, real time accelerometric data are telemetered to the national Department of Civil Protection in Rome. Information can be used to generate real-time shake maps and damage scenarios to help emergency actions. The whole system is meant to be utilized by other end users (authorities managing fast trains, life lines, hospitals, etc.) to trigger active protection control systems. (Weber et al., 2007; Zollo et al., 2009)

The Virtual Seismologist (VS) algorithm was a further approach being developed in Europe and USA (Cua and Heaton, 2007). It is a Bayesian approach to regional, network-based earthquake early warning (EEW). Earthquake magnitude, location, and peak ground motion distribution are estimated from observed ground motion amplitudes and triggers, predefined prior information, and appropriate ground motion prediction equations. In the Bayesian approach, incoming observations contribute to continuously updated estimates of EEW information; prior information constrains the EEW estimates at an early stage of the event when not enough observations are available. The VS estimates (magnitude, location, peak ground shaking) are updated each second until no more new picks are reported (Cua and Heaton, 2007).

In September 2004, in the framework of the EC FP6 SSA NaRaS (Natural Risk Assessment) Project, a Workshop was organized in Naples, Italy on “ Seismic Early Warning of European Cities: toward a coordinated effort to raise the level of basic knowledge”. Researchers attending the meeting from eight European countries (France, Germany, Greece, Iceland, Italy, Portugal, Switzerland, Turkey), United States, Taiwan and Japan unanimously approved a recommendation submitted to the European Commission, stressing the still unresolved basic questions for full application of early warning to society’s need and asking for future calls to contain specific reference to seismic early warning methods (Gasparini et al., 2007).

The following year a collaboration call focussed specifically on Earthquake Early Warning was issued in the frame of FP6, which was awarded to the SAFER Project.

THE SAFER PROJECT

The SAFER Project (www.saferproject.eu) was carried out between July 2006 and June 2009 by a Consortium including all the European institutions active on EEW and many other with perspective interest in the methodologies. The Consortium was formed by 20 institutes from 11 European and Mediterranean countries (Germany, Italy, Greece, Romania, Switzerland, Norway, France, the Netherlands, Iceland, Turkey and Egypt), and one each from three of the extra European countries most active in this field: i.e. Japan, Taiwan and U.S.A. (Figure. 1). The Consortium included universities, governmental and non-governmental research institutes and private companies. It was lead by Jochen Zschau, GFZ German Research Centre for Geosciences, Potsdam, Germany.

SAFER was strongly multi-disciplinary, calling upon expertise in seismology, structural and geotechnical engineering, informatics, and statistics. Coherently with call requirements SAFER faced only the scientific and technical aspects. Communication, social science and economy issues were not considered. SAFER was strongly linked with pure (e.g. fundamental physics of the Earth's crust under stress) and applied (e.g. response of structures to ground shaking) research

From the scientific point of view one of the main problems still matter of debate was the forecasting of the magnitude of an earthquake based on the information given by the first 3 seconds of P-waves. The most used parameters were the dominant frequency (τ_c^{\max}), the average frequency (τ_c) or the peak displacement (P_d). The application to $M > 6$ earthquakes was of major concern as the rock fracturing will still be in progress when the forecasting is done. (Allen and Kanamori, 2003; Kanamori, 2005; Wu and Kanamori, 2005)

Once the magnitude and location of an earthquake have been determined, the expected peak ground shaking at a given location must be rapidly determined to trigger early warning actions. Preliminary alert maps should be generated and near real time shake maps should be produced for rapid response. Methodologies for the implementation of these procedures were under way in Japan and California.

The implementation of automated actions for engineering applications required the development of automatic decision making tools for each application based on estimates of uncertainties, and of the expected consequences of false and missed alarms. Facing of all these problems was just starting at the beginning of SAFER.

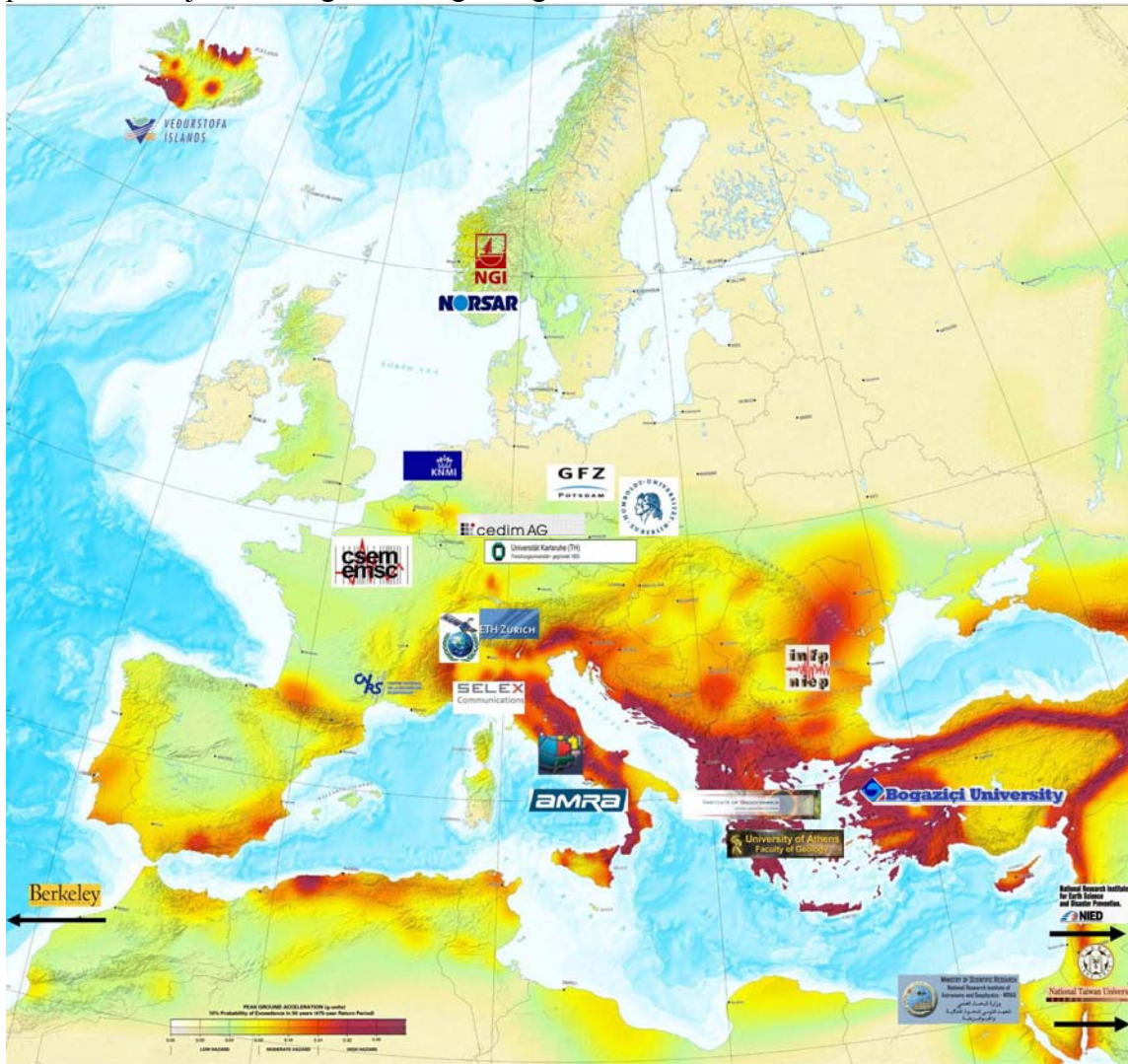


Figure.1 Partnership of the SAFER project

The general objective of SAFER was to develop tools for effective earthquake early warning that can be used for disaster management in Europe and, particularly, in Europe's densely populated cities.

SAFER meant to achieve the general objective through:

- a. the development and implementation of improved algorithms for the fast determination of earthquake source parameters (event location, as well as new approaches for fast magnitude/moment determinations based on strong motion data, modern seismic array technology and the concept of energy magnitude) combining the conflicting demands of rapidity and reliability;

- b. further elaboration of innovative concepts for providing in an evolutionary process real-time alert maps and predicted shake maps within seconds and minutes;
- c. the development of fast algorithms for damage scenario simulations, including forecasting of aftershock time evolution and of earthquake triggered effects (such as tsunamis and landslides);
- d. deployment of decision making procedures for engineering applications of EEW to the real time protection of endangered structures and devices;
- e. Applications to selected test cities (Athens, Bucharest, Cairo, Istanbul Napoli).

A selection of the main achievements of the project is here reported.

a) Earthquake Size and Damage Potential Now Available Within a Few Seconds

Knowing the size (magnitude) of an earthquake in real-time is essential for rapidly estimating the damage potential, deciding whether an alarm needs to be issued, and initiating appropriate response measures. SAFER has explored the information on this parameter that can be extracted from the first few seconds of the fastest seismic wave, the P-wave. In particular, it has provided a novel method that does not only estimate the magnitude of an event within a few seconds, but for the first time also offers the related probabilities which tell the users how reliable the estimate really is. In addition, the method follows an evolutionary approach meaning that as more data become available (longer time series, more triggered seismic stations), the reliability of the inferred earthquake size information improves. PRESTo (Probabilistic and Evolutionary Early Warning System), a tool developed within SAFER, has these features. It is rapid, reliable and provides the related uncertainties allowing appropriate decisions to be made for mitigating actions. (Zollo et al., 2009, Satriano et al., 2010)

Related to the determination of the earthquake size, SAFER has also been successfully testing a new method for obtaining the first rough estimate of the damage potential of an earthquake in near real-time, i.e. even before the earthquake hits or immediately after, when generally there is no other information available on the extent of the damage to be expected. The quantities necessary for estimating the damage potential can be obtained from the first three seconds of the P-wave (Convertito et al., 2009).

b) The Real-time “Shake Map” Technology is Now Implemented in Large Cities of Europe

“Shake Map” is a method that allows to produce maps of peak earthquake ground shaking in real time from information available within seismic networks. If this information comes from the first P-wave arrival before the real ground shaking has reached its peak level, scientists will talk about “alert maps”. In this case the peak ground shaking is predicted and not measured. Both “alert maps” (predicted) and “shake maps” (measured) are important components of the seismic early warning- and rapid response chain because they can contribute to activate disaster mitigation actions within seconds to minutes after the onset of an earthquake.

In Europe the capability of deriving “alert maps” and “shake maps” from seismic data in real-time did not exist before the start of the SAFER-project in 2006. SAFER in close co-operation with the EU-project NERIES (Network of Research Infrastructures for European Seismology) has now implemented this technology in the test cities Istanbul, Bucharest, Naples and Cairo, and by this and after having carefully applied appropriate regional calibrations, has considerably improved the seismic early warning capability in these metropolitan areas. (Erdik et al., 2011, Koehler et al., 2009)

e) Towards a People Centred Early Warning System

The success of EEW systems is very much dependent on how accurately the ground shaking due to an earthquake can be determined in real-time. Serious limitations for this come from the spacing between seismometers in a classical set up of seismic networks which requires interpolation of ground shaking and by this may introduce large uncertainties. The spacing between seismometers cannot easily be reduced mainly due to economical reasons.

SAFER, therefore, proposes a completely new generation of early warning systems, based on low-cost sensors (taken from the air-bag system of the car industry) that are connected and wireless communicating with each other in a decentralized people-centred and self-organizing observation- and warning network.. “Decentralized” means that the total information available in the network will not only be transmitted to a warning centre but will also be available at every node of the network. “People centred” means that people can afford to buy their own sensor and by installing it in their home may not only gain from, but also contribute to the warning network. This would ensure the dense coverage of an urban area with early warning sensors, not tens or hundreds, but thousands or ten thousands, which is necessary to gather accurate warning information. The system has to be “self-organizing” in order to automatically adapt to changes in the network configuration if, for instance, the number of users will increase, or some of the network sensors will fail as a consequence of a strong earthquake.

The prototype of such a low-cost and self-organizing system has been developed in the frame of SAFER and has been successfully tested in the city of Istanbul. It has also been applied to monitoring the health state of critical infrastructures such as the Fatih Sultan Mehmet Suspension bridge across the Bospouros or certain buildings in L’Aquila (Italy) after the strong earthquake of April 6th, 2009. Although the number of nodes for which the network has been configured at present is still conventional, SOSEWIN(Self-Organizing Seismic Early Warning Information Network) as the system is called, has opened a novel avenue for seismic early warning that is extremely promising. (Fleming et al, 2009, Picozzi et al., 2008)

g) When an Early Warning Should be Issued?

Engineering applications of EEW need to be designed in a way to minimize the cost of false alarms. The design is specific for each application and location.

For example, the economic consequences from stopping a train can be different in different countries, and they are certainly different from those of shutting down a gas line. The level of acceptance of a false alarm is the leading decisional parameter for every action to be taken on the basis of early warning. SAFER developed a fully probabilistic framework for applications of earthquake early warning based on cost-benefit analysis. The procedure starts from the real-time prediction of ground motion parameters, including the check of the sensitivity of the EW information to uncertainties in estimations of magnitude and distance. The decision whether to issue an alarm or not is made automatically at each site and for each application using a decisional rule.

For example, assuming that the predicted ground motion intensity measure is the PGA, a simple rule may consist of issuing the alarm if the probability that a critical peak ground motion value will be exceeded is larger than a pre-fixed threshold. The critical peak ground motion and the probability threshold may be established on the basis of cost/benefits and the analysis of the consequences so that the risk reduction provided by the alarm will be higher than the consequences of a false alarm. (Iervolino et al., 2009, Iervolino, 2011)

A decisional methodology was developed and applied to the Campania region, but the concepts and algorithms are of general use. Using a simple model of earthquake source, and the available warning times, an estimate was made of the possible risk reduction actions on the Campania territory.

AMRA produced ERGO (EaRly warninG demO), a visual terminal installed at the Faculty of engineering of the University of Naples Federico II on July 25 2008 and has continuously operated since then. ERGO processes in real-time the accelerometric data and it is able to issue an alarm in the case of events occurring with magnitude larger than 3 in the southern Apennines region. The terminal includes a panel showing the time evolution of the Probability Density Functions of PGA at the site, computed from the information on magnitude and distance by the Irpinia EEW network. The terminal also indicates, during the lead time, the time variations of the probability that the critical PGA value will be exceeded, along with the residual warning time and the probability of false alarms.

h) Improving the Earthquake Early Warning Capabilities in Five Euro- Mediterranean Cities

Five major earthquake-prone cities have been identified as test areas; Athens, Bucharest, Cairo, Istanbul, Naples. All these cities in recent years have experienced severe earthquakes. These cities either have acquired, or are in the process of acquiring earthquake early warning systems. They offer a range of different challenges to the SAFER project, as they are threatened by earthquakes generated in different tectonic environment and at different distances. For example, Bucharest is severely affected by earthquakes occurring in a subducting slab underneath the Vrancea region, 150 km north of the city. They occur in a restricted area and depth range, and the involved distances allow warning times in the order of 30 seconds. In contrast, Istanbul is only a few tens of kilometres off the Marmara Sea segments of the North Anatolian strike-slip fault, and warning times may be less than 10 seconds. Both of these cities are expected to experience the effects of events of $M > 7$. Naples is located close to another seismo-tectonic setting. It is about 80 km away from the nearest crustal dip-slip faults of the Apennine range. The seismic early warning network can provide the city of Naples with about 20 sec alert time.

Cairo, on the other hand, is expected to experience earthquakes generally less than M_6 . However, due to the extreme seismic vulnerability its earthquake risk is high. In 1992 a moderate earthquake of magnitude 5.8 caused 561 deaths, 9832 injured and left a direct economic damage of more than 35 million US\$. This earthquake had happened on the Dahshour zone, one of two seismic zones directly covering parts of Greater Cairo. The other zone is the Cairo Suez district that is as well able to generate earthquakes above magnitude 5.5.

SAFER contributed to the advancement of EEW and real-time risk reduction for each test city in a different way, given the great differences in the tectonic and geological situation, the characteristics of available seismic/accelerometric networks and the existing level of information on vulnerability.

THE REAKT PROJECT

The REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction) (www.reaktproject.eu) is a follow up and an enlargement of SAFER. In fact it conveys the experience gained and the results of former FP6 and running FP7 project on seismic risk (SAFER, NERIES, NERA, SHARE, SYNER-g) to establish the best practice on how to use jointly all the information coming from earthquake forecast, early warning and real time vulnerability assessment for real time risk mitigation.(Figure. 2).

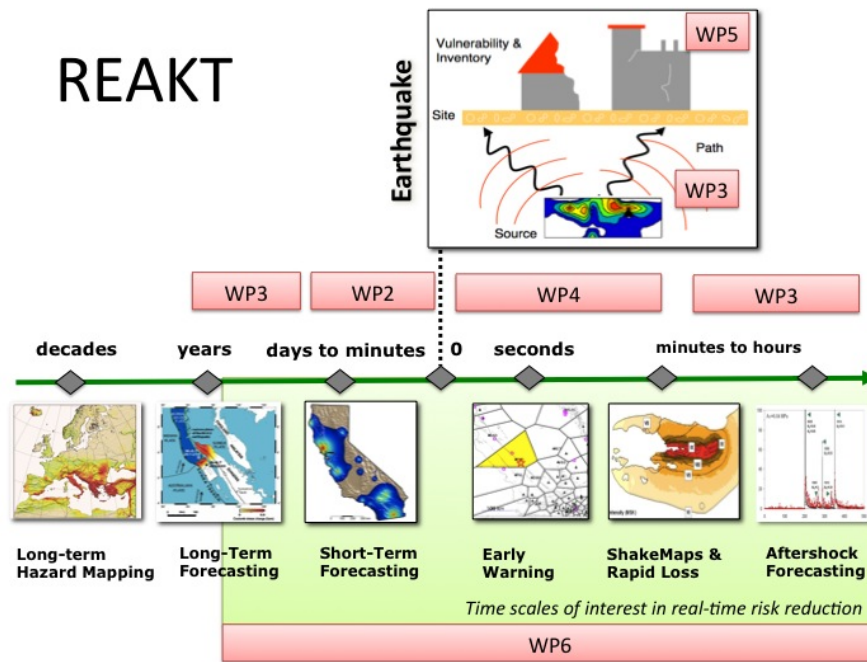


Figure 2: Sketch of the different components and different time scale to be integrated in the used system level approach.

The REAKT project started on September 1, 2011 and has a duration of 36 months. REAKT consortium is formed by 23 partners, 18 coming from ten European countries and one each from Barbados, Jamaica, Japan, Taiwan and United States. Many of them had participated to SAFER and the other above mentioned project. The Consortium is lead by Paolo Gasparini, AMRA Scarl, Napoli.

REAKT aims to address the issues of real-time earthquake hazard estimation and emergency response from end-to-end, with work packages focused on operational earthquake forecasting, earthquake early warning (EEW), real-time vulnerability systems, and optimized end-user decision-making with uncertain information. This will be pursued through the following specific objectives:

- a better understanding of physical processes underlying seismicity changes on a time scale from minutes to months;
- the development, calibration and testing of models of probabilistic earthquake forecasting and the investigation of its potential for operational earthquake forecasting;
- the development of time-dependent fragility functions for buildings, selected infrastructures, and utility systems;
- the development of real time loss estimation models over the lifetime of structures and systems due to foreshocks, main shocks and their subsequent aftershock sequences.
- the construction of a detailed methodology for optimal decision making associated with an earthquake early warning system (EEWS), with operational earthquake forecasting (OEF) and with real time vulnerability and loss assessment in order to facilitate the selection of risk reduction measures by end users;
- the study of the content and way of delivering public communication, recognizing the value of a degree of self organization in community decision making;
- the application of real time risk reduction systems to different situations.

REAKT will use a system-level earthquake science approach that requires that the various temporal scales of relevance for hazard and risk mitigation in the various WPs are integrated through common tools, databases and methods (as sketched in Figure 2).

Some scientific aspects relevant for the improvement of EEW applications will include:

- the development of off-line testing and implementation of a new approach for early warning where the network-based and on-site methods are integrated and used in the very first seconds after a moderate to large earthquake to map the most probable damaged zones;
- a new threshold-based approach representing a step forward in respect of the presently developed EEW methodologies. It allows to by-pass the problems and uncertainties related to the real-time magnitude and peak motion predictions through empirical ground motion equations;
- the real-time Virtual Seismologist (VS) and PRESTo algorithms, developed in the FP6 SAFER Project, will be extended from an EEW approach to a more generalized earthquake information system with continuous characterization of uncertainty as a function of time from the earthquake origin;
- new functionalities of the real-time VS codes, with a focus on real-time;
- test installations in Switzerland and other European test sites, and the PRESTo algorithm will be developed to include the threshold based approach, with application in southern Italy and Turkey;
- the possibility of predicting the frequency content by an EEW (also integrating the on-site and regional/hybrid EEW) will be investigated;
- a life cycle-cost approach will be developed to evaluate the performance of semi-active EEW driven control systems vs. passive control systems (e.g. seismic isolation);
- study of feasibility, design and off line testing of a mobile early warning system to be rapidly implemented during seismic crises;
- SOSEWIN system will be adapted to monitor on going damages within buildings during seismic crises, with the integration of a digital video camera.

The ten industrial facilities selected as test sites include the SINES industrial complex in Portugal, nuclear plants in Switzerland, power plants and power transmission systems in Iceland, natural gas distribution networks and the Fatih Sultan Mehmet bridge in Istanbul, a section of the Circumvesuviana railway in Campania, Italy, the Rion-Antirion bridge in Patras, and the port and AHEPA hospital in Thessaloniki. The feasibility of a regional EEW system to protect industrial facilities in the Eastern Caribbean is also being investigated. Some end-users are interested in in-depth feasibility studies for use of real-time information and development of rapid response plans, while others intend to install real-time instrumentation and develop customized automated control systems to initiate damage-mitigating actions in the event of strong shaking. From the onset, REAKT scientists and end-users will work together on concept development and initial implementation efforts using the data products and decision-making methodologies developed in the various work packages, with the goal of improving end-user risk mitigation. The aim of this scientific/end-user partnership is to ensure that scientific efforts are applicable to operational, real-world problems. The close collaboration between scientific and end-user partners, from the beginning of the project, is among the innovative aspects of REAKT.

SAFER and REAKT created a core community of top European seismologists and engineers working in the field of EEW. The requests that the SAFER research group is continuously receiving to organize meetings or to present the results to international meetings, shows that SAFER and REAKT are quite visible and well considered even in countries, like Japan, who are the traditional leaders in this field.

Both projects prompted the exchange of information and methodologies amongst most of the European institutions running local seismic networks for early warning and amongst the research groups active in this field. The projects attracted more than 40 young researchers, an European young community able to continue and forward the research in this field.

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