SAFER
Seismic Early Warning for Europe

FINAL REPORT

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(Editors)

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EXECUTIVE SUMMARY

1. INTRODUCTION TO THE SAFER PROJECT

SAFER (Seismic Early Warning for Europe) is a project funded by the European Commission in the context of Framework Program 6 under the Theme Sustainable Development, Global Change and Ecosystems. It has the general objective to develop tools and knowledge for increasing the capability of effective earthquake early warning (EEW) in Europe and to implement and test these tools in selected European cities.

Early warning is a important component of the disaster reduction chain (Fig. 1). The need of using early warning methods to reduce natural risks in modern societies is related to their unprecedented dependence upon technology. The growing use of "lifelines" and the interconnection of economies place modern populations at ever increasing risk to large-scale natural disasters such as earthquakes. This dependence motivates efforts to develop systems that have the capacity to reduce the negative effects of such disasters.

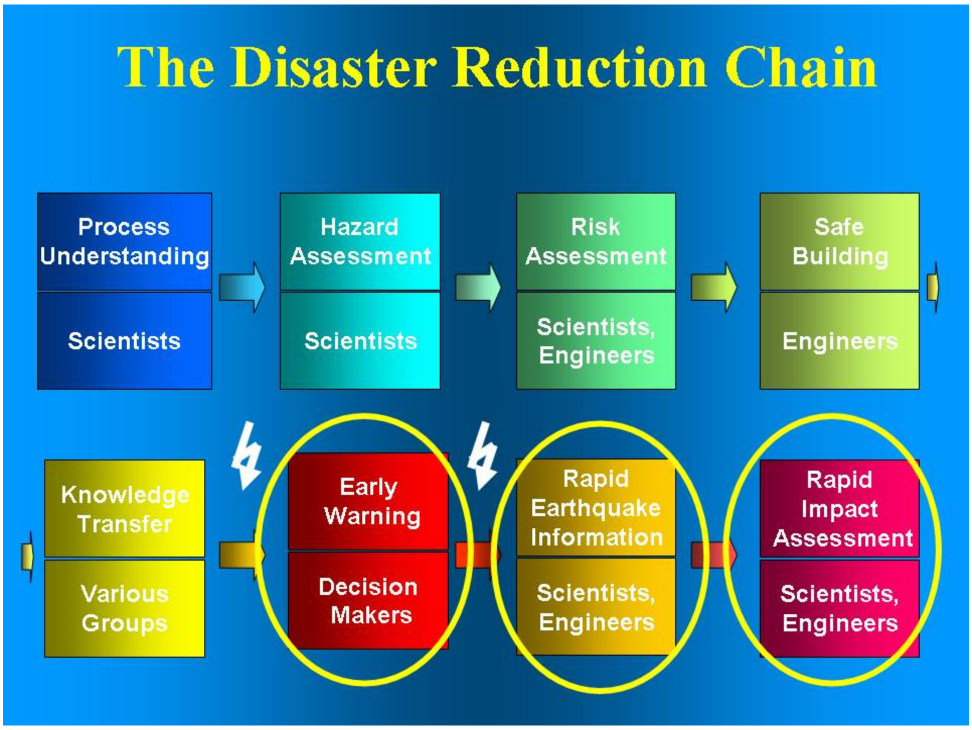


Fig. 1 Early warning is an important component of the disaster reduction chain

The SAFER project has responded to such needs through the development of a range of tools and procedures that will help in real time to mitigate the negative consequences of earthquakes and associated phenomena.

Early warning generally refers to the provision of timely and reliable information allowing to decide upon actions aimed at reducing the effects of a disastrous event. Earthquake early warning (EEW) is based on the time difference between the arrivals of faster travelling low energy P-waves and slower travelling S and surface waves at a given site. While the first one contains part of the information on the characteristics of the rupture process generating the earthquake, the latter two contain most of the energy of the quake and produce most of the damage. The delay is of a few seconds close to the epicentre of shallow (crustal) earthquakes and it increases to tens of seconds and minutes with increasing distance. Using a variety of techniques, it can be determined from the P-waves whether the later S-wave arrivals will be of concern or not. If so, a warning can then be issued via whatever medium is considered appropriate (for example radio, sirens, the internet etc.) allowing the activation of mitigating actions. Time delays for the SAFER test cities are of the order of 10s of seconds only. Therefore, a high degree of automation is required for the information to have any value. Such actions would include shutting down gas lines, initiating safety procedures in industrial complexes, such as nuclear power stations, and the closure of tunnels and bridges.

Europe is covered by many high quality seismic networks, managed by national and European agencies, including local networks specifically designed for seismic early warning. SAFER aims at fully exploiting the possibilities offered by real time analysis of signals from these networks for further protective actions, including the production of 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 tsunami.

Five major earthquake-prone cities have been selected as test areas; Athens, Bucharest, Cairo, Istanbul and Naples. The combined population of these cities is about 40 million inhabitants, and all have experienced severe earthquakes in recent years. These cites either have, or are in the process of acquiring, earthquake early warning systems. While offering a range of different challenges to the SAFER project, they are threatened by earthquakes generated in different tectonic environment and at different distances.

SAFER is strongly multi-disciplinary, calling upon expertise in seismology, structural and geotechnical engineering, informatics, and statistics. It is 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.

The SAFER Project was carried out between July 2006 and June 2009 by a Consortium 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 Japan, Taiwan and U.S.A. (Fig. 2). The Consortium includes universities, governmental and non-governmental research institutes and private companies. The Consortium was led by Jochen Zschau, GFZ German Research Centre for Geosciences, Potsdam, Germany, assisted by a Steering

Committee formed by Paolo Gasparini, AMRA Scarl, Napoli, Italy and Gerassimos Papadopoulos, National Observatory of Athens, Greece.

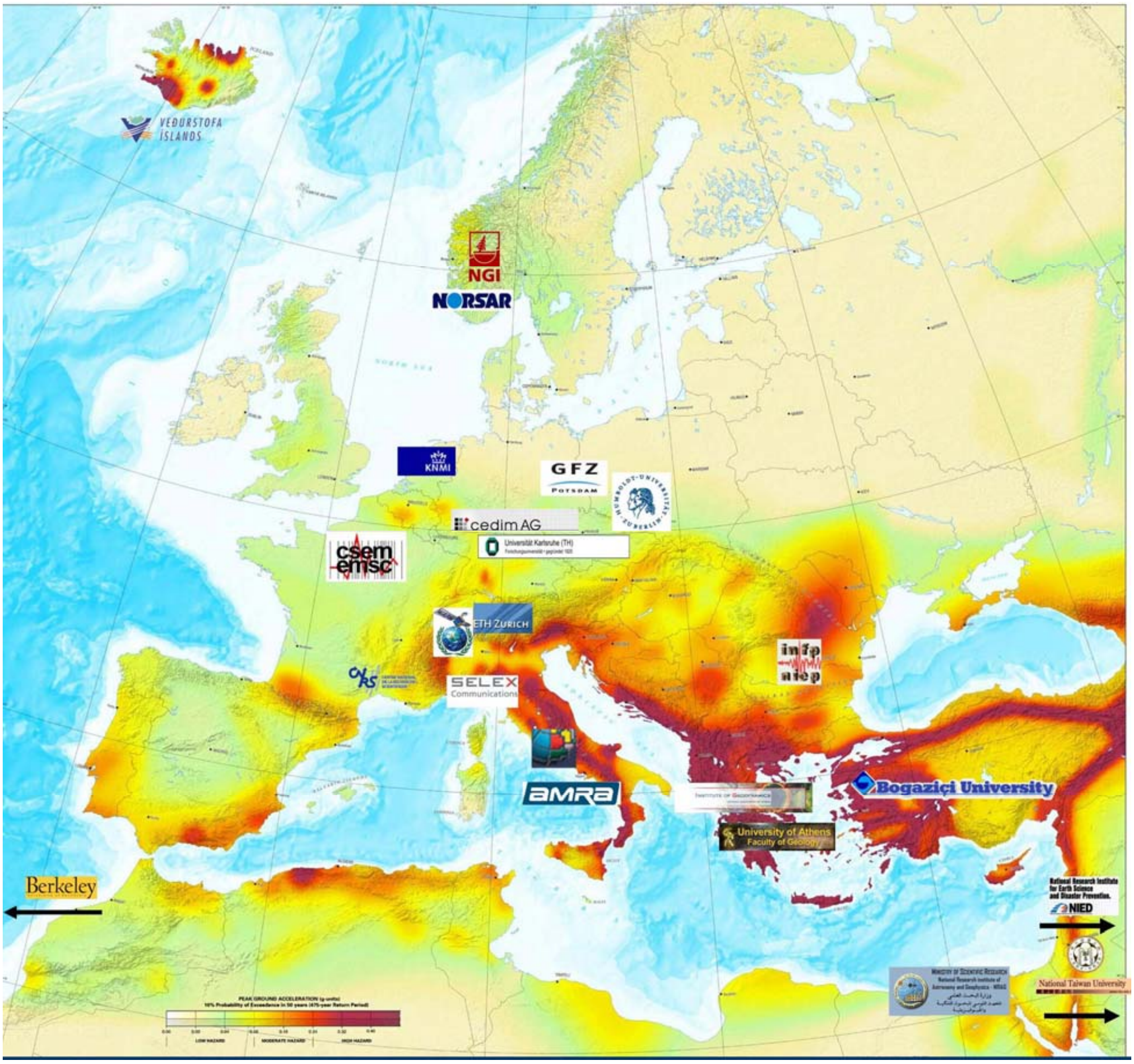


Fig.2 Partnership of the SAFER project

2. WHERE DID WE START FROM?

When the SAFER project was proposed, EEW systems were operative in a few countries. Only Japan had a plan of extensive application of this method. In fact, since 1984 Japan had implemented the Urgent Earthquake Detection and Alarm System (UrEDAS) for the national railways to protect fast trains against earthquakes. The performance of the system convinced the Japan Government to start an extensive program which included the protection of the Tokyo underground and the feasibility of issuing public warnings.

A seismic alert system (SAS) had been implemented for Mexico City, 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 is 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.

EEW systems were operative to protect some nuclear power plants in several countries. The potential of EEW had also been investigated for application in California, and Taiwan. Europe was far behind Japan, U.S.A., Taiwan and Mexico, both in scientific know how and applications. Only Romania and Turkey had started to develop EW capabilities for Bucharest and Istanbul, respectively. Applications for protecting industrial plants, such as the Ignalina power plants in Lithuania, were quite scattered. Although some international collaborations were going on in this field, most of the efforts were isolated and the sharing of strategies and methodologies was scarce. Little attention was given to the scientific challenge implied by a complex use of EEW systems (e.g. to protect life lines, infrastructures, industries) and by the possibility of forecasting the magnitude of an event from the information contained in the first second of the P-wave, although some papers, mostly by California and Japan seismologists, had outlined its feasibility and limitations.

SAFER has taken up this challenge. It is the first large scale scientific project in Europe on earthquake early warning. Between 2006 and 2009 more than 100 scientists within SAFER have contributed to improving the scientific basis of EEW significantly.

3. SOME HIGHLIGHTS

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, Fig. 3), 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.

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.

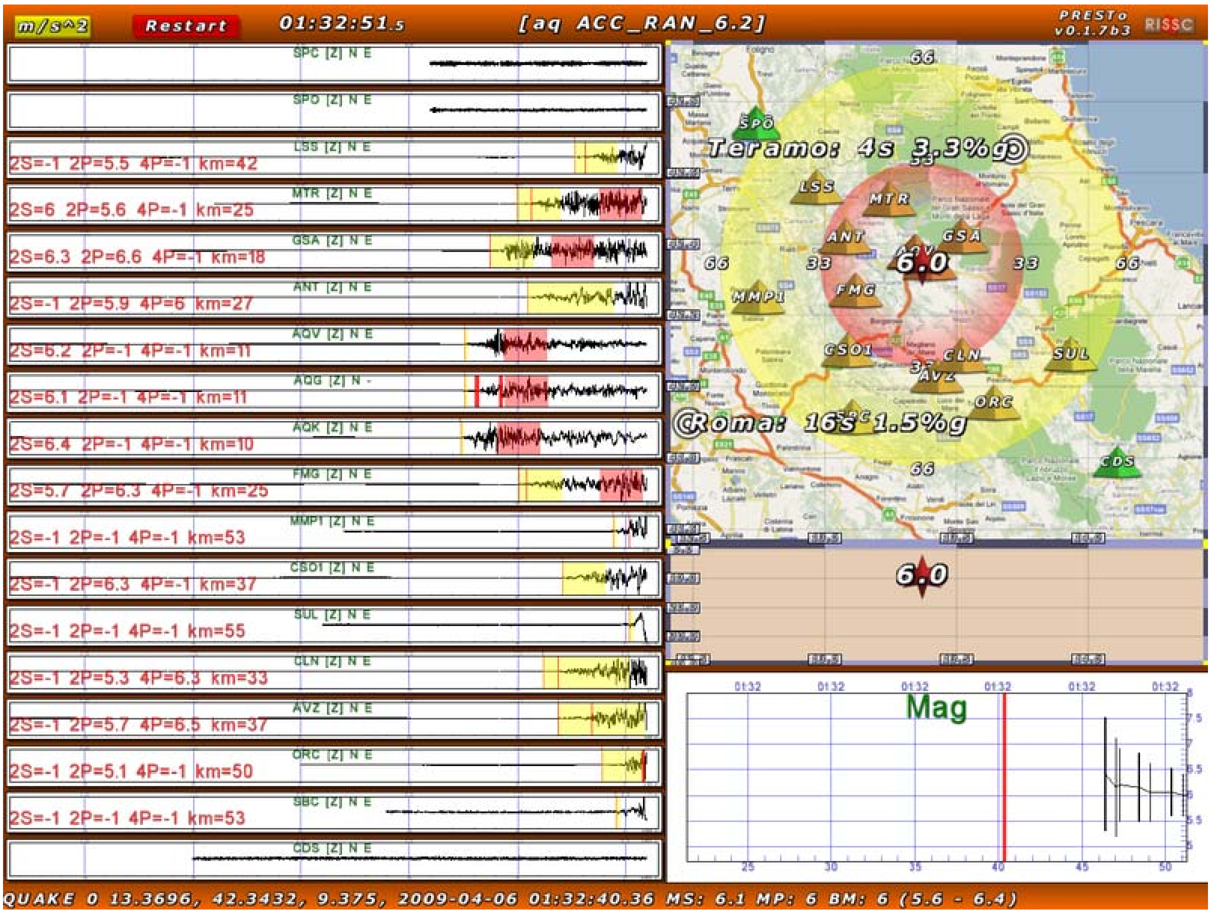


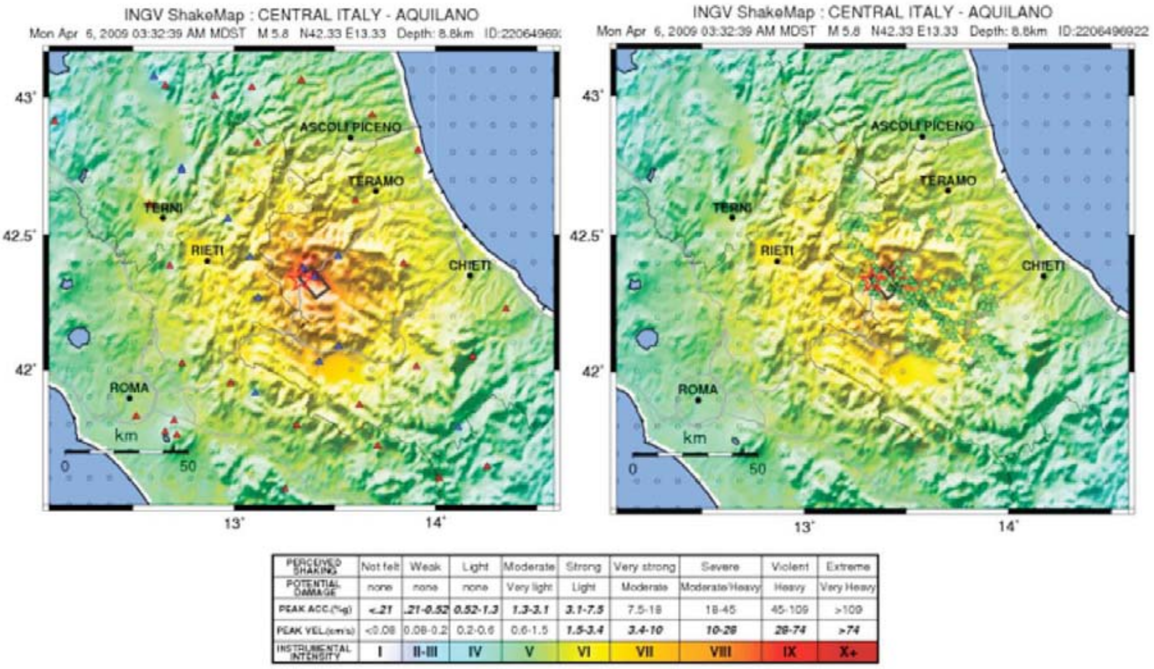
Fig. 3 A screen shot of the PRESTo software showing a snapshot of the simulation of the Mw 6.3 April 6, 2009 L'Aquila earthquake, 10 seconds after the event's origin. Using the data from the National Accelerometric Network (RAN). Recordings are shown on the left, where P-waves are in yellow and the time window of expected S-wave arrivals are in red. Current estimates of hypocenter and magnitude, wavefronts of P and S waves and expected PGA at two targets (Roma and Teramo) are shown in the map. Error on the real-time estimate of magnitude decreases with time (diagram at lower right).

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 (Fig. 4).

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.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.21	.21-0.52	0.52-1.3	1.3-3.1	3.1-7.5	7.5-18	18-45	45-109	>109
PEAK VEL.(cm/s)	<0.08	0.08-0.2	0.2-0.6	0.6-1.5	1.5-3.4	3.4-10	10-28	28-74	>74
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Fig. 4 Instrumentally derived intensities (left) and macroseismic (MCS) intensities (right) in Abruzzo region after the M_w 6.3 (M_L 5.8) April, 6, 2009 earthquake. The two maps are very similar, but the instrumental one can be obtained within a few minutes from the event.

c) Complex Earthquake Features Within Minutes

Earthquake Early Warning requires that information on the earthquake is being made available within a few seconds. This is now achievable for measured ground motion, earthquake location and "Early P-wave Magnitude". However, this can not be achieved at present for more complex features of an earthquake, like focal mechanism, slip distribution and other details of the rupture process. To a certain extent this shortcoming holds also for the determination of the magnitude, because the "Early P-wave Magnitude", obtained within seconds, is only a first rough estimate of the earthquake size based on empirical correlations and not on a thorough understanding of the underlying physical earthquake process. All the above parameters, however, are needed as accurately as possible to obtain a good estimate of the ground motion also in between the seismic stations (where it is not measured) and consequently on the specific distribution of the seismic damage to be expected.

SAFER has been successful in reducing the time necessary for determining the physics based magnitude (moment magnitude) by a factor of 10 to 20: from 30 to 60 minutes down to 2.5 to 3 minutes! It has also developed the capability of calculating the focal mechanism and other details of the rupture process of an earthquake from near-field observations, as well as from teleseismic records within 15 to 20 minutes. This is an important progress, as it has direct application to tsunami early warning and to rapid seismic damage prediction for which, different from seismic early warning, a delay time of a few minutes can be tolerated.

d) "Seismic Ground Shaking Potential" Versus Tsunami Generation Potential

In seismology the size of an earthquake is widely characterised by the moment magnitude. Being determined from the low frequency part of a seismogram it is well suited for characterising the tsunami generation potential of an earthquake, but it does not well describe the ground shaking potential, more relevant for the damage associated with an earthquake. The energy magnitude, on the other hand, being directly related to the energy release during an earthquake, reflects the ground shaking potential associated with an earthquake much better. Unfortunately, the energy-magnitude is not widely used in seismology and methods for its rapid estimation were not in place before SAFER! Now, at the end of the SAFER project, a new method exists, capable of providing the energy magnitude for any earthquake worldwide within only a few minutes. This allows for a fast first estimate of the shaking potential of an earthquake that can be compared to the tsunami generation potential as inferable from the moment magnitude. The method makes use of data from the global seismic network and does not require local networks. Disaster management may be supported by this kind of information in their decision whether to prepare for a tsunami and/or for direct damage due to ground motion.

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 (Fig. 5). "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 configurated 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.

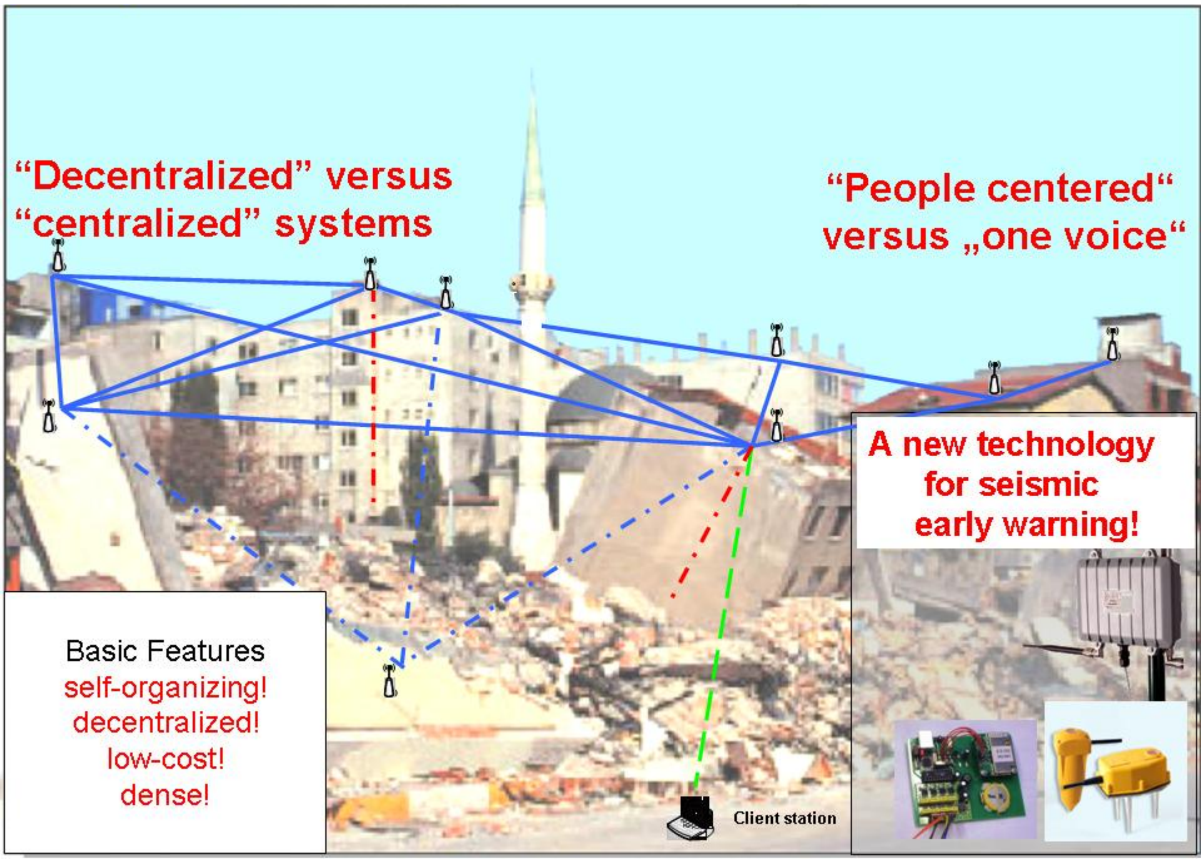


Fig. 5 A conceptual representation of the SOSEWIN people centered early warning system

f) Near Real-Time Detection of the Onset of Foreshock Activity

Many large earthquakes (~ 50 %) are preceded by seismic foreshock activity. However, in most cases we know only after the main shock that the anomalous activity before had been related to the main shock. Near Real-Time capability of detecting and recognizing the onset of foreshock activity before a main shock follows, could, however, be an important indication for the risk management to get prepared.

SAFER has, therefore, made a thorough attempt to develop a system that, based on the seismic activity rate and the so-called seismic b value, can discriminate in near real-time between different types of earthquake sequences including the seismic background, foreshock-, aftershock- and swarm like activity. The FORMA (**Fo**reshock-**M**ainshock-**A**ftershock) system that resulted from this attempt, is currently being tested in near real-time in the Gulf of Corinth.

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. In SAFER, for the first time a fully probabilistic framework for applications of earthquake early warning based on cost-benefit analysis was implemented. 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. Then the procedure automatically defines the criteria for setting an application-specific alarm threshold based on the information provided by an early warning system and on the expected consequences of the earthquake. The developed procedure has been applied to a prototype early warning terminal connected to the early warning network of the Campania region in Italy (Fig. 6).

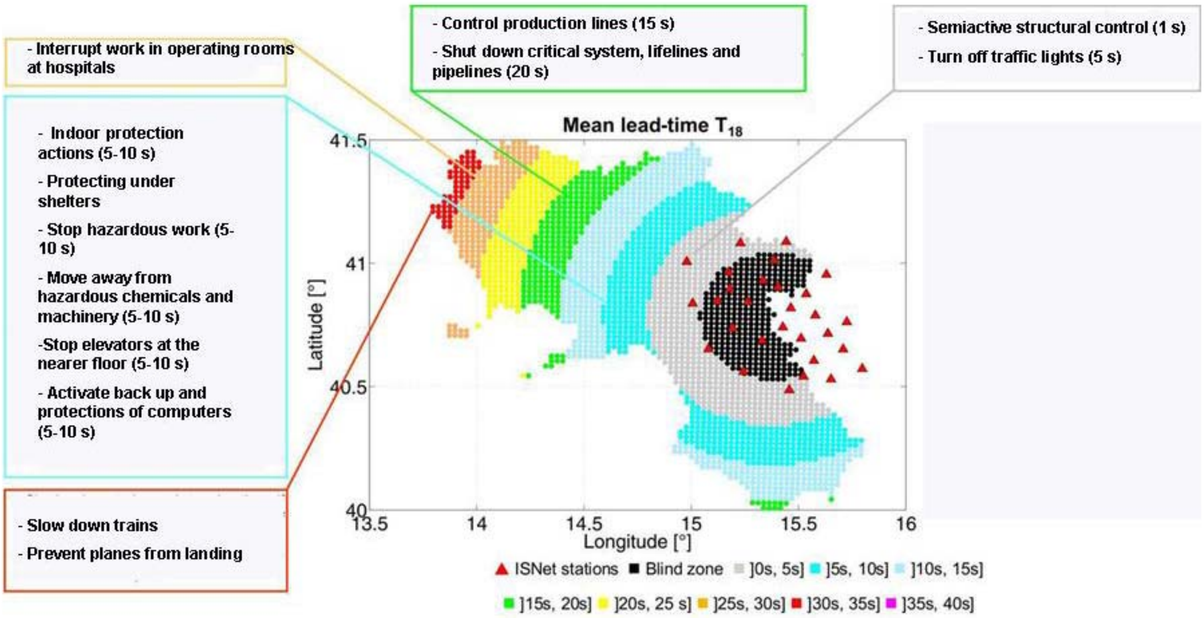


Fig. 6 Lead-time maps for Campania superimposed to real-time risk reduction actions for specific structural systems. These actions can be classified on the basis of the time required to be carried out.

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 M6. 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.

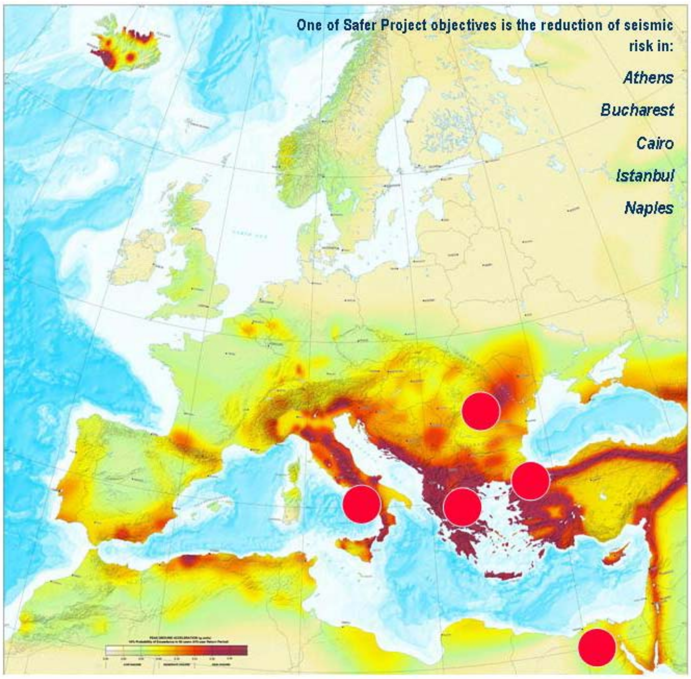


Fig. 7 SAFER testcCities

Athens

Before the beginning of the SAFER project, no efforts were made for developing EEW at Athens and in Greece in general. Within SAFER such an effort started in two main directions. The first one aimed at developing a prototype hybrid seismological network, i.e. an integration of regional and on-site systems. The network

infrastructure is installed in the area of the Corinth Gulf, which has a very high seismicity.
The second effort was focussed on the problem of an online characterisation of the evolution of an on-going seismic activity, in particular on detecting a possible transition from background seismicity to foreshock activity in near real-time. For this aim a particular algorithm called FORMA (Foreshock-Mainshock-Aftershock) was developed and tested in several seismogenic areas of Greece.

Bucharest

The main progress brought by SAFER to the early warning and disaster management capability of the city concerns the rapid magnitude determination of Vrancea earthquakes, the development of a new azimuth dependent attenuation law to fit the geology of the region, and the integration, in an early warning approach, of alert-, shake- and damage maps. The EEW system generates a preliminary shake map (alert map) for Bucharest within 4-5 seconds after the earthquake has been detected in the epicentral area of Vrancea. This alert map is improved and converted step by step to a measured shake map as the real-time data from accelerometers installed in the Bucharest area become available. The improvements account for the prominent nonlinear site effects due to the thick sedimentary layer underlying the city. In order to make rapid damage assessment possible, these data can be combined in the EEW-System with vulnerability information. For this purpose, existing tools for damage and loss assessment were tested and further improved for application to Bucharest.

Cairo

With a total population of 16 million Cairo can be considered as one of the largest megacities in the world. At the beginning of SAFER, Cairo already had a modern digital seismic network with wireless data transmission in place. However, no seismic early warning capability existed, because real-time and/or near real-time early warning technology had not been implemented, and various types of input data that are crucial for early warning had not been gathered so far. Now, at the end of the SAFER project the real-time shake map technology has been installed in Cairo and its performance, after being optimized retrorespectively for major earthquakes in the past, is currently being tested online in connection with the seismic monitoring system. In addition, a magnitude calibrated intensity attenuation relation has been derived for Cairo, microtremor measurements for characterising site dependent ground motion amplification have been conducted and vulnerability composition models were constructed for all the considered 43 districts of Greater Cairo. These in conjunction with a specific Dynamic Decision support Module (DDSM, Fig. 8) developed within SAFER, enable to simulate possible earthquake damage scenarios in the future, and together with the seismic monitoring system and the implemented shake map technology, provide the basis for an operational earthquake early warning and rapid response system.

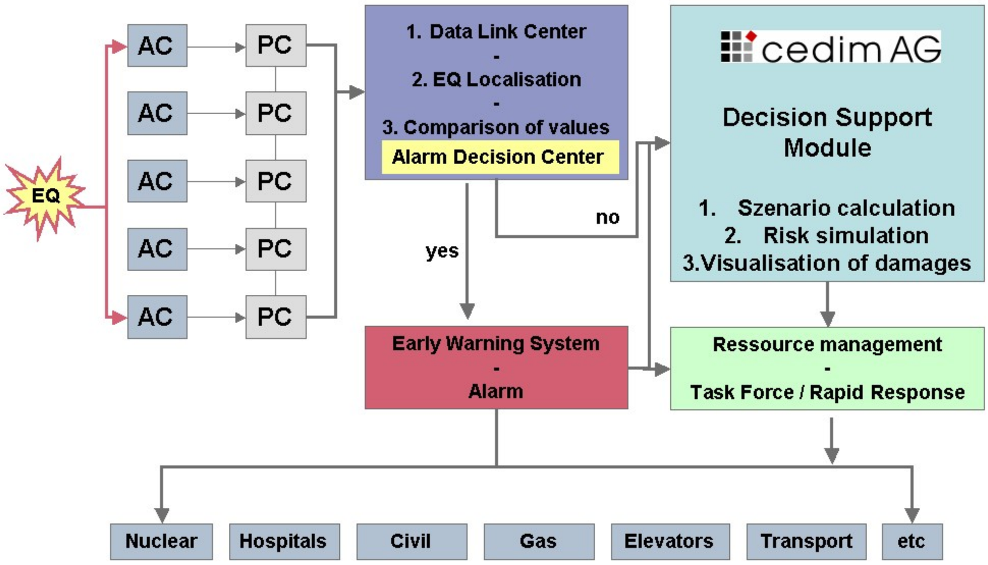


Fig. 8 Concept of the decision earthquake Information system developed for the city of Cairo.

Istanbul

This test site had already earthquake early warning and rapid response networks in place at the beginning of SAFER. Signal processing for earthquake parameter determination was quite advanced, but each network had its own algorithm. The SAFER Project dealt with the comparability of results obtained from the different networks and started the parameter optimization in the Istanbul Earthquake Early Warning System. An improvement of the quality of real time shake maps and an estimate of site effects at the Marmara Sea stations were obtained. A major achievement is the installation of the new type of early warning networks which is called SOSEWIN (Self-Organizing Seismic Early Warning Information Network). It integrates into the existing EEW and rapid response systems, providing a higher spatial resolution of real-time ground motion. The determination of its potential for application to monitoring critical infrastructures and life-lines is currently in progress.

Naples

A few years before SAFER, the Civil Protection of Regione Campania started a feasibility study on EEW for earthquakes located in the Apennine region close to Naples. It was based on the existence of a high quality densely spaced seismic network around the Irpinia fault zone. During the SAFER years, and through the SAFER project, an intensive activity was dedicated to the development of a prototype EEW system (PRESTo) and to the identification of criteria for directing engineering applications and automatic decision making. For the first time , the whole approach, from the evolutionary method for rapid earthquake parameter determination to real-time engineering applications, follows a strictly probabilistic pattern. The resulting products include advanced methods for the real-time production of shake maps. In addition, the capability of real-time risk assessment for Naples has been improved with an off line test of the SELENA method.

4. LEARNING WITHIN THE SAFER PROJECT

SAFER was monitored by two scientific advisors, one being an expert in seismology and the other one in earthquake engineering, to account for the two main scientific communities involved in the project. The lessons learnt from the project are based on their comments and reports and on the management experience as well. SAFER was recognized by the advisors as a successful project not only because it contributed significantly to the development of EEW methodologies, but also because it has formed a European community of young researchers and also has networked the majority of the institutions active on this issue.

However, some features typical in a large project can be improved. One main issue is the way non - European partners are allowed to participate to this kind of projects and the lack of an adequate European policy in this respect. Their participation in the project could be made more effective if financial contributions for them would come from both sides, not only from the external partner but also from the European project itself. General research agreements existing between EU and non EU countries should be extended and made more effective. In this respect, agreements with non EU countries for facilitating the issue of visas (when necessary) to researchers participating to EU projects would greatly improve the effectiveness of external participation and the knowledge exchange between EU and extra EU countries.

The interaction with the European Commission officers was very efficient and the project coordinating team had the chance to present the project achievements and its vision of future developments in several contexts. The discussions with end users has shown the existence of a gap between the scientific and technological progress in EEW systems ready to be applied, and the real level of its application. The gap is partly due to the hesitation of many potential end users mainly because of the unclear normative and legal context with respect to EEW existing in several parts of the world (excluding Japan and, possibly, Taiwan), and the people’s unawareness of the reactions needed to take advantage of an operational system.

5. THE ADDED EUROPEAN VALUE FROM SAFER

The results of SAFER well meet the EU priorities concerning “Global Change and Ecosystems” because they do *“improve the capacity and power of real time seismology to deliver timely integrated information in order to enable actions to be taken immediately before destructive shocks occur and to provide information and warning in the subsequent phases of the event.”* They have contributed to the preparedness for, and the mitigation of the negative consequences of potentially catastrophic seismic events, particularly in large towns and highly populated areas of Europe.

SAFER has 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 is quite visible and well considered even in countries, like Japan, who are the traditional leaders in this field.

SAFER has 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 project has also attracted more than 30 young researchers, an European young community able to continue and forward the research in this field.

6. THE VISION FOR THE FUTURE

Although parts of Europe, the US and Japan have populations that are exposed to similar levels of high earthquake hazard, the relative vulnerability of the European population is some 10 times greater than in Japan, and 100 times that of the US. In addition, the seismic protection of critical infrastructure and life-lines poses a serious problem within the EU. In order to counteract this vulnerability, the European Council requested in 2004 the development of a European Programme for Critical Infrastructure Protection (EPCIP). Since then, comprehensive preparatory work has been undertaken, which has included of a Green Paper, where the question was posed as to whether EPCIP should be based on an all-hazards approach, an all-hazards approach with a terrorism priority, or a terrorism-hazards approach.

Preventive actions, such as retrofitting and building and the diffusion of construction codes, are of course essential. They are not sufficient. In Europe a substantial proportion of the population in areas of higher earthquake hazard still reside in older (historical) buildings that do not meet modern earthquake resistant standards, and cannot currently be strengthened in an economically viable manner. In many areas of high earthquake risk there are also cultural centres of great importance.

The European Union must have the objective of reducing the individual vulnerability of the population of Europe to a level comparable to that of Japan and the US. As demonstrated in Japan EEW has the potential of significantly contributing to this goal.

Future research on EEW in Europe should be focused on the implementation of EEW to protect life-lines, infrastructures and strategic buildings, and it should include training of administrators and people who can fully exploit the technological advantages offered by EEW systems. In particular it should foresee extensive cost-benefit analyse for each potential application, the identification and solution of legal problems (e.g. liability in the event of false or missed alarms), education and training, both for mitigation and response, as well as detection and processing within 1 second of the first seismic wave arrivals. As further objective it should include the development of people centered EEW, specialized IT and decision making support systems, integration of sensors, communications and decision making systems, integration into programs of eco-sustainable development, and integration with other EW systems (all hazard systems).

FINAL REPORT

1. THE STARTING POINT

The problem of earthquake risk mitigation is faced using different approaches, depending upon the time scale being considered. Over time scales of years and decades, the implementation and improvement of land use regulations and of building codes, along with the improvement of people information and education, are the most effective methods to decrease the risk. On very short time scales (seconds to minutes), new strategies for earthquake risk mitigation are being conceived and are under development worldwide. They are based on the real-time information about natural events provided by advanced monitoring infrastructures, denoted as "early warning systems".

Early warning generally refers to the provision of timely and reliable information allowing to decide upon actions aimed at reducing the effects of a threatening event. Earthquake early warning (EEW) has the peculiarity that the warning time (lead time) is very short, typically of the order of tens of seconds. EEW is based on the time difference between the arrivals at a given site of faster travelling low energy P-waves and slower travelling S and surface waves. While the former contain part of the information on the characteristics of the rupture process generating the earthquake, S- and surface waves contain most of the energy of the quake and produce most of the damage. The delay is of a few seconds close to the epicentre of shallow (crustal) earthquakes and it increases to tens of seconds and minutes with increasing distance. Using a variety of techniques, it can be determined from the P-waves whether the later S-wave arrivals will be of concern or not. If so, a warning can then be issued via whatever medium is considered appropriate (for example radio, sirens, the internet etc.) allowing the activation of mitigating actions. As the lead times are very short, a high degree of automation is required for the information to have any value. Mitigation actions would include shutting down gas lines, initiating safety procedures in industrial complexes, such as nuclear power stations, and the closure of tunnels and bridges.

At the beginning of SAFER EEW capabilities were existing in Japan, USA, Mexico, Taiwan, Turkey, Romania and Italy (Fig. 9). EEW methods were first applied in Japan in the mid 1960s by the Japanese National Railways to protect the Shinkansen line. 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, its speed having been sufficiently reduced to cause no victims.

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. An early warning was issued 4-5 s after the first detection of P-waves and 16 seconds before the arrival of S-waves at the city of Senday during the 2005 M7.2 earthquake occurring offshore the coast of the Miyagi Prefecture.

A seismic alert system (SAS) had been 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.

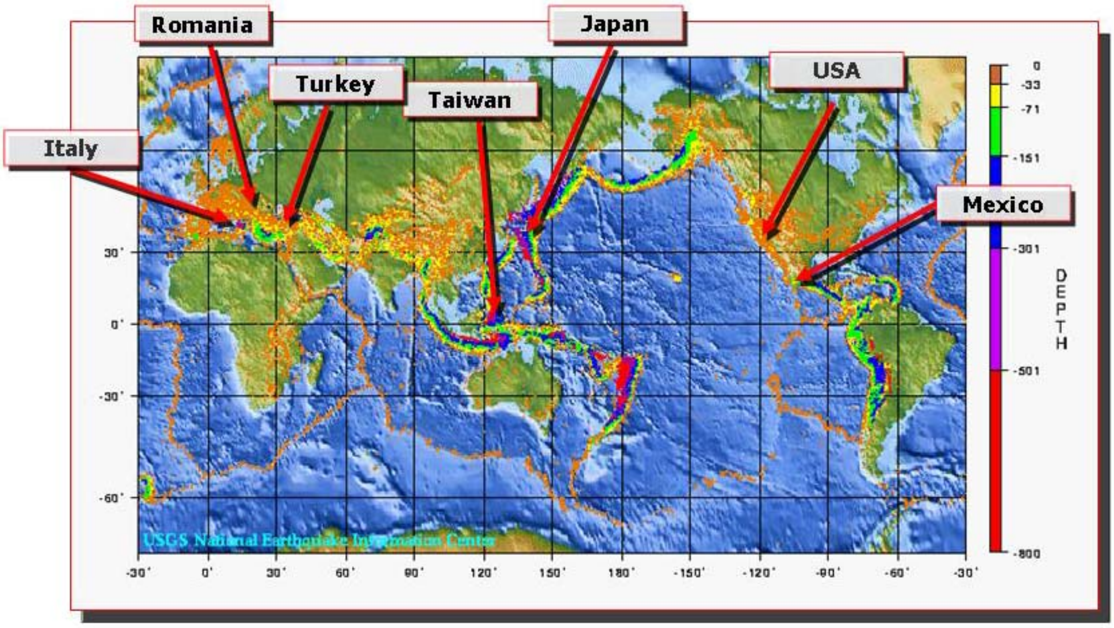


Fig. 9 The regional earthquake early warning networks existing at the start of SAFER

An EEW system was implemented also in Taiwan after extensive damages, due to basin amplification effect, had been produced on November 15, 1986 at Taipei, from a M7.8 earthquake occurring at 120 km of distance. The EEW system started in 1991 and it is still operational to-day.

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, arrival times to estimate location and radial attenuation relations to predict ground shaking at a given site. The potentiality of the system for several cities of California was estimated.

Another approach that began to be developed is the Virtual Seismologist (VS) algorithm. It is a Bayesian approach to regional, network-based earthquake early warning (EEW) estimating earthquake magnitude, location, and peak ground motion distribution 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.

With respect to EEW Europe was far behind Japan, Taiwan, Mexico and U.S.A., both in scientific know how and applications. Only Romania and Turkey had started to develop EW capabilities for their capitals Bucharest and Istanbul, respectively. A seismic network with early warning capability existed in the Vrancea area of the Carpathians. Some earthquake early warning and rapid response networks were also in place around Istanbul. Signal processing for earthquake parameter determination was quite advanced, but each network had its own algorithm. A dense seismic and accelerometric network with EEW capability had just been implemented around the Irpinia active fault zone in the Campanian Apennine. A regional network was active in the Gulf of Corinth area. Applications for protecting industrial plants, such as the Ignalina power plants in Lithuania, were quite scattered. Although some international collaborations were going on in this field, most of the efforts were isolated and the sharing of strategies and methodologies was scarce. Although EEW applications demands a strongly multidisciplinary effort, involving not only seismologists and earthquake engineers, but also experts on information technology and signal processing, in many cases the integration of different expertises was not strong.

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 ($\tau_{c)}$ 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. The problem was discussed by researchers from U.S., Japan and Taiwan (Nakamura, 1988, 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.

The state of progress of EEW at the beginning of SAFER was reviewed by many participants to the SAFER Project in a Springer book (Gasparini et al., 2007).

2. THE INITIAL OBJECTIVES

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).

SAFER was a strongly cross disciplinary project, with the research themes calling upon expertise in seismology, structural and geotechnical engineering, informatics, and statistics. SAFER is first and foremost a research project, both pure (e.g. fundamental physics of the Earth's crust under stress) and applied (e.g. response of buildings to ground shaking).

The geographical focus of SAFER was the Euro-Mediterranean region, with 20 participating institutes from 11 European and Mediterranean countries (Germany, Italy, Greece, Romania, Switzerland, Norway, France, the Netherlands, Iceland, Turkey and Egypt) and three from outside of this region (the USA, Japan and Taiwan). The SAFER consortium includes universities, governmental and non-governmental research institutes and private companies, bringing to the project a broad range of expertise.

3. PROGRESS OUTSIDE EUROPE DURING THE SAFER YEARS

The SAFER project started in June 2006 and had a duration of three years. Outside Europe the most significant progress in the application of EEW was made during these years in Japan. Following the Government decision to consider EEW as a high priority to reduce earthquake risk, the Japan Meteorological Agency (JMA) was chosen as the reference structure for the application of the method throughout the national territory.

The EEW national service became fully operational in October 2007 (Hoshiba et al., 2008). The basic earthquake monitoring structure consisted of about 1,000 seismic and accelerometric stations used for rapid estimation of the earthquake parameters, covering the whole country with an almost constant spacing of 20 km. In addition about 4000 "seismic intensity meters" were implemented mostly in densely populated areas. Seismic intensity is a parameter, widely used in Japan, to characterize ground motion. It is proportional to the logarithm of the kinetic energy flow per time unit and it is calculated from the measured ground acceleration in the frequency range 0.5 – 10 Hz. These additional stations were exclusively dedicated to the ground motion measurements and they were not connected to the EEW system.

The JMA developed a protocol for the issuance of earthquake early warning to the public and to interested public and private agencies and companies. JMA emended the existing Meteorological Service Law ruling the provision of information services to the public in case of natural threatening events. The emended law clearly defines the responsibilities of JMA and other relevant organizations to secure prompt transmission of EEW to the public. The provision of expected seismic intensity and S wave arrival time for a specific site is regarded as beyond the duty of the national agency, and should be done by other warning service providers. The law establishes the technical standard that any warning service provider must satisfy when it issues an EEW for individual houses and structures. The amended Law came into force on the 1st of December, 2007 (Kamigaichi et al, in press). JMA started a preparatory two-years public education campaign to provide information on the scope and limitations of EEW and on the proper actions to be taken in case a warning is issued.

The JMA protocol prescribes that a warning must be issued to the public when the predicted intensity in a site is 5 (corresponding to VII-VIII level of the Modified Mercalli scale) or higher. From March 2007 to October 2009 a EEW was issued for 9 earthquakes and two were missed because the predicted intensity were below the threshold. Out of the 9 earthquakes 3 were false alarms because the observed intensities were lower than the threshold, contrary to the prediction. The largest event of this period was a M7.2 earthquake which occurred on land on July 18, 2008. The warning was given 4.4 seconds after the first detection of P-waves, so that the "blind" zone (where EEW could not be given before the arrival of the destructive seismic waves) had a radius of about 30 km. An updated EEW for the general public was issued 22.4 seconds after the first detection of P-waves. Outside the blind zone, intensities were still about VIII-IX degree of the Modified Mercalli (MM) scale. The lead time was enough for some risk reduction actions. For instance, an electronics company in Miyagi prefecture stopped supplying chemicals in the factory 12 seconds prior to a strong ground motion, and infants at a nursery in Fukushima prefecture were moved to a pre-assigned safety zone in the room 30 seconds before the strong motion arrival. Other utilizations during this event were announcements in factories, offices, schools, shopping places, elevator control, and deceleration of cars. The EEW system had a similar performance during the Niigata-ken Chuetsu-oki earthquake (M_{jma}6.8) on the 16th of July 2007. At Iizuna-town in the Nagano-prefecture, at about 90 km of distance from the epicenter, seismic intensities of IX-X MM scale were observed. An EEW was issued 16 seconds before the theoretical S wave arrival (Kamigaichi et al., in press).

From a scientific point of view an important progress has been the improvement of the rapidity and reliability of earthquake parameter determinations using also the location of the station that have not yet been triggered (Nakamura et al., 2009).

The issue of EEWs in the last two years in Japan resulted in a wider acknowledgement of the advantages of the method. In addition to public warnings, 54 private companies were certified in December 2008 to provide EEW services to industries (including 52 rail companies), construction sites, apartment houses, schools.

An example of risk reduction effectiveness of EEW is given by the data provided by the OGI semiconductor company in the prefecture of Miyaji. This company had suffered from a loss of US$ 15 millions due to fire, equipment damage and loss of productivity produced by two earthquakes in 2003. They spent about US$ 600,000 to install additional fire breaking walls and automated EEW systems to shut down hazardous chemical materials, and move sensitive equipments to a safe position. The two earthquakes that had occurred since these modifications, produced damages of US$ 200,000, and the modifications reduced the days of closure by about 75% (Allen et al., in press).

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.

Several non European countries, including China, India and South Korea, have shown interest to the implementation of EEW although no definite plans exist yet.

4. THE CONTRIBUTION OF SAFER

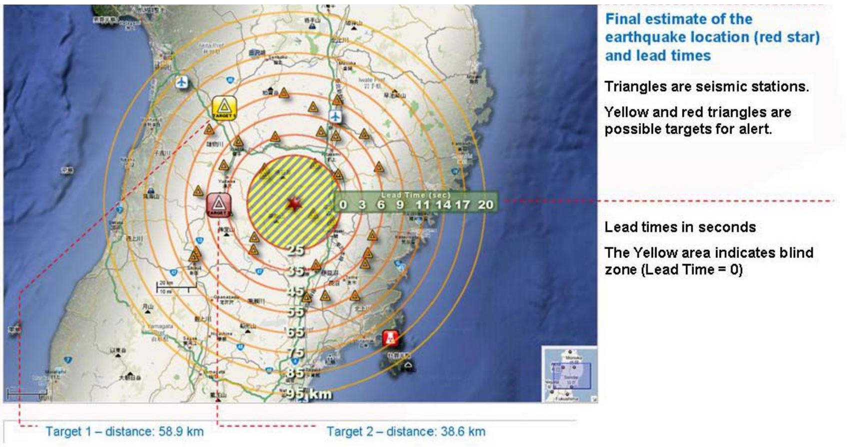
The SAFER Project was pro active in indicating and facing the major scientific challenges behind the practical application of EEW systems in Europe. It improved the consciousness that the data acquired from regional and on site EEW systems can be used to produce in a few minutes detailed information relevant to emergency, such as shake maps, damage assessment, forecast of continuing seismic activity, potential trigger of other threatening events (landslides, tsunami).

In the following pages a synthetic overview of the main contribution of SAFER to the progress of EEW and rapid response methods is provided. It is not exhaustive and a detailed description of the performed activities and the achieved results can be found in the deliverables of the project issued on the SAFER Website: www.saferproject.net

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

Very rapid (within seconds) estimates of earthquake location and magnitude are needed when regional EEW systems are used to predict ground motion which is the basic decisional parameter for any warning action. SAFER has explored how much information on these parameters can be extracted from the first few seconds of the fastest seismic wave, the P-wave. An extensive analysis of reliability and robustness of the main parameters already used for magnitude determination (dominant or average period of the first P-waves, τ_p^{max} and τ_c, and peak displacement of the first P-waves, P_d) has been performed using different data bases (Europe, Japan, Taiwan, Eastern Turkey). The results have shown the reliability of the methods for magnitudes as high as 7.0 and the advantages of using near source strong motion instruments rather than seismometers. In fact strong motion sensors provide unsaturated recordings even of moderate to large earthquakes and, in case of a dense station coverage in the source area, the combination of both P- and S-wave amplitude information can be used to get fast and robust earthquake location and magnitude estimates. A novel algorithm allowing the evolutionary and probabilistic real-time estimation of the event's magnitude, as inferred from peak displacement values (P_d) measured in a short time window (3 sec) after the first P- and S-arrival at a dense strong motion network was developed by AMRA. The method is based on the empirical relationships between P_d and magnitude. At each time step a probability density function for magnitude is computed from the available P- and S-peak measurements, using the Bayes' formula where the previous probability density function is assumed as the *a priori* probability density function.

This algorithm is a component of PRESTo, a stand-alone application with a graphical user interface implemented as an user friendly terminal of the Irpinia EEW network. The outputs of the real-time processing (earthquake location, magnitude, expected ground shaking) are reported graphically and in a compact form through a dedicated data-stream (PRESTo-code) which can be decoded and employed by end users (Fig. 10).



Final estimate of the earthquake location (red star) and lead times

Triangles are seismic stations.

Yellow and red triangles are possible targets for alert.

Lead times in seconds

The Yellow area indicates blind zone (Lead Time = 0)

Target 1 – distance: 58.9 km

Target 2 – distance: 38.6 km

Fig. 10 Results of the real time simulation with PRESTo of the June 14, 2008 Mw 6.9 Iwate earthquake. The alert sent from PRESTo to the yellow and red stations contains the estimated PGA.

A new EEW software was developed at NIEP to give alerts to the city of Bucharest with a lead time of about 25 seconds. The software for real-time data acquisition has been developed in order to minimize the latencies resulting from data packing algorithms.

The algorithm has been tested using offline data from the Vrancea network since 2006. The software also performed successfully on-line when it determined correctly the magnitude of a local $M_w = 5.7$ earthquake in 4 seconds.

Methods for near real-time event detection, localisation and magnitude estimation using array systems and techniques developed at NORSAR were implemented and tested successfully at the Gulf of Corinth network and the Vrancea region.

Besides developing original methods, several existing algorithms were improved and their respective performance compared. These include the UNIKARL preSEIS algorithm, based on Artificial Neural Networks, the ETHZ Virtual Seismologist method and the UniCal Elarms method. They have been applied to data bases of Southern California and Western Turkey.

An improved version of the Virtual Seismologist (VS) algorithm was developed in SAFER. New codes implementing the VS likelihood function (modules that perform real-time waveform processing and EEW estimation) were developed. New approaches were envisaged allowing the VS algorithm to operate robustly in real - time and in a realistic network environment, even in presence of disturbing factors such as heterogeneous station telemetry delay, dropped packets, ambient noise, calibration signal, and broken sensors. These innovations are intended to minimize the number of false alarms, while maximizing the available warning time for correct event detections. The real-time VS codes were installed and are continuously tested in real-time in California. Offline runs on a Swiss dataset (Fig. 11) indicate that the algorithm will achieve similar performance levels if installed in European networks.

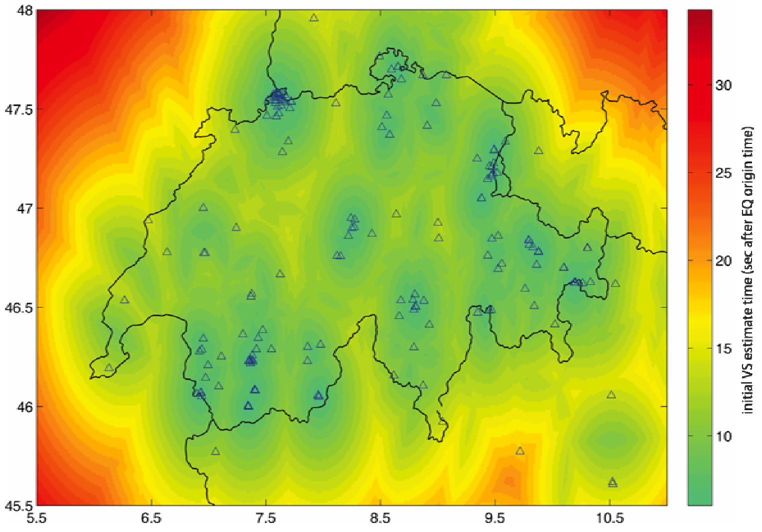


Fig. 11 Approximate initial VS estimate alert times given the current station installations in Switzerland, a triggering criteria of 4 stations, an assumed 3 second telemetry delay and 1 second processing time.

EEW capability is also in progress in the Gulf of Corinth area where a prototype hybrid seismological network has been designed and installed by NKUA. It is planned for single station (on-site) and regional based early warnings in an evolutionary way.

b) The Real-Time "Shake Map" Technology 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 activating 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, Bucharest, Cairo, Istanbul and Naples.

During the SAFER years UniCal has further developed the ElarmS methodologies, finalizing the generation of the alert maps. On October 10, 2007, real-time testing of the ElarmS-RT (ElarmS Real Time) system began in California. On October 30, 2007, there was a M=5.6 earthquake (Alum Rocks), with the resulting alert maps successfully predicting the ground motion at sites not yet affected, enhancing the potentially available lead time. In the SAFER project Elarms has been applied and tested in several regions, including Italy (INGV), Iceland (IMO) and Switzerland (ETHZ).

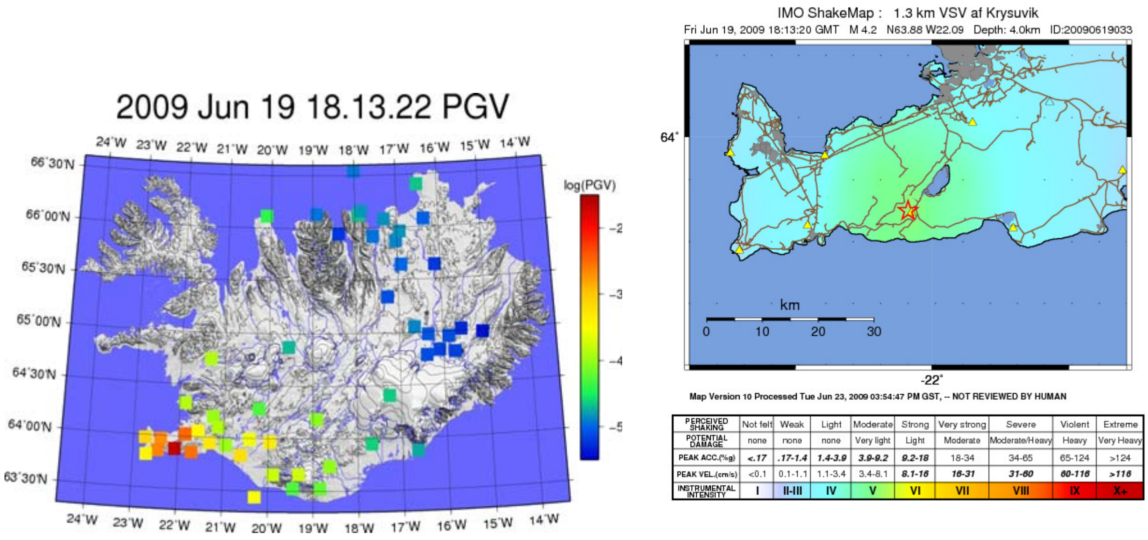
The capability of generation of Shake maps in real time in Europe was improved through the development or the improvement of novel shake map generating software and, in most cases, through the installation and testing of the USGS-ShakeMap package.

The installation of the USGS-ShakeMap package has given the capability of producing in real time shake maps over the whole Italian territory, in Iceland and in the Istanbul area.

In Italy, the USGS-Shake map package has been installed by INGV to produce shake maps over all the national territory, following the standard ShakeMap procedure. For each earthquake the shake maps are determined (automatically) using two distinct procedures. The first one immediately uses the (automatic) location, while the second adopts the manual location. The maps published on the external web site (INGV) are generally available within 15 minutes

In Iceland the initial plan for implementing ShakeMap involved the phase-log data, transmitted in real-time from the seismic stations of the South Iceland Lowlands

(SIL) network to the data center at the IMO. The SIL software does an excellent job in detecting and characterizing micro-earthquakes. However it is not optimized for reliable determination of magnitude for moderate and large events. IMO therefore decided to develop new tools, designed to reliably detect and process events in the magnitude range from M1.5 to M7 and to prepare the necessary data for the generation of alert maps and shake maps (Fig. 12). This new tool includes a range of band pass filters appropriate for different magnitude ranges. Such a real-time analysis tool has been constructed and implemented at all 55 stations of the SIL network. For major events in Iceland, the shake map is available 35 seconds after the alert map, or roughly 2 minutes after origin time of the earthquake and it can immediately be accessed at a website. When information on the fault dimension becomes available – for example from the results of the automatic near-real-time relative-location of aftershocks, the fault parameters can be incorporated to improve the shake map. This has been done for the shake map of 29 May, 2008 M6.3 earthquake near the town of Selfoss in the South Iceland Seismic Zone. The shake map shows rather good agreement with felt intensity reports.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 12 (Left) Alert map showing PGV values, generated by an M4.2 event on June 19, 2009, when all stations of the SIL network had been equipped with the early warning alert process. The squares, representing station locations, are colour coded according to PGV, shown on the scale to the right. The maximum PGV, (>1 cm/s) is observed on Reykjanes peninsula. The alert map, available in 1.5 minutes, clearly shows that the event origin is on Reykjanes peninsula and the felt shaking is confined to the peninsula and vicinity. (Right) Location and magnitude of the event were automatically determined by the process and a shake map generated.

In Istanbul, the USGS ShakeMap was installed on the KOERI server and it is operational for rapid response purposes (Fig. 13). The ShakeMap tool enables to determine ground shaking intensity maps, ground motion parameters (PGA, Sa, Sd), damage and casualty maps with epicenter and magnitude information. KOERI has created a ShakeMap archive for past important earthquakes in Turkey.

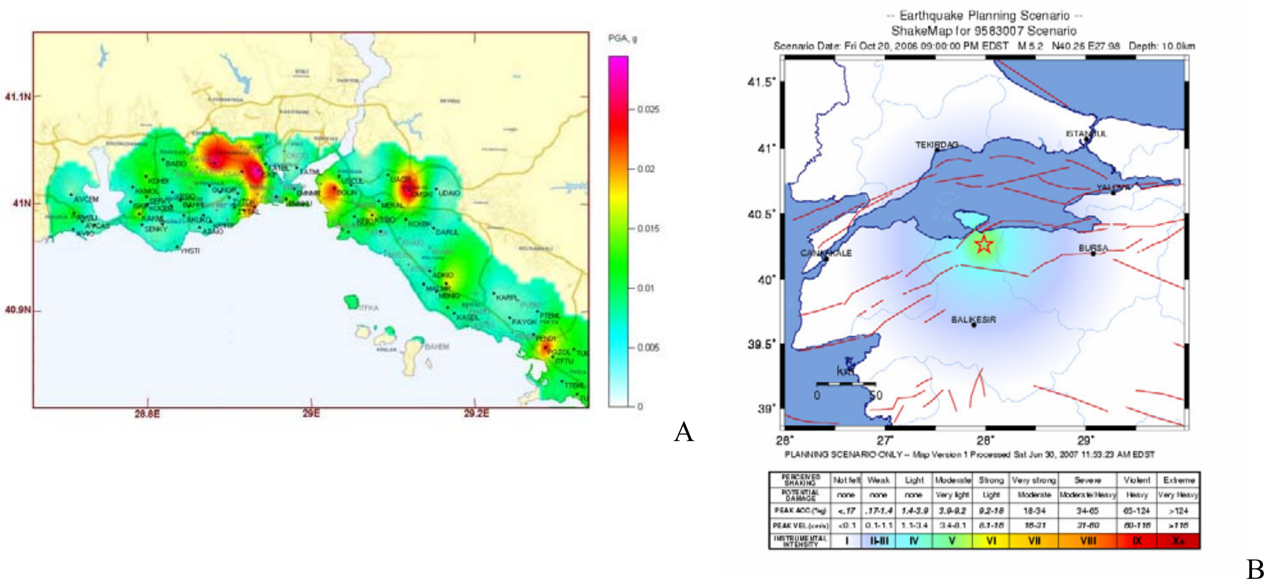


Fig. 13 October 20, 2006 Bandirma (Md=5.2) earthquake (a) PGA map based on the data recorded by the IERRS . (b) PGA-PGV-Intensity maps as generated using the USGS ShakeMap tool.

The USGS shake map software, installed and modified by NIEP for the Bucharest area, was found not to produce realistic results. This is due to the great thickness of soft sediments in the Bucharest area and to the peculiarity in the attenuation relationships for the 60-200 km deep Vrancea earthquakes. NIEP then decided to implement a dense centralized accelerometric network in the Bucharest area and developed a methodology to produce on site shake maps which update in real time the alert maps produced used the regional Vrancea EEW network.

A new technique for ground-shaking map calculation (GRSMap) was developed by AMRA. The technique takes advantage of the characteristics of the Irpinia seismic network (ISNet) installed in the Campania-Lucania region in southern Italy, namely the spatial density of the seismic stations and their high dynamic range. GRSMap uses a weighting scheme of recorded and estimated data aimed at locally correcting the estimated ground motion value to account for finite-fault effects, such as directivity and radiation patterns. In particular, GRSMap triangulates the area of interest by using seismic stations as vertices of the triangles whose centres represent additional virtual stations. Hence the new grid, composed of recording stations and triangulated points, contains more densely spaced nodes that can be used to estimate the peak ground motion values by using the attenuation relationship at any point of the region covered by the network. This procedure results in a more accurate strong-ground motion prediction with respect to the estimates obtained by using standard attenuation relationships.

GFZ has derived intensity prediction equations for the test sites Istanbul, Naples, Bucharest and Cairo. Additionally, there have been efforts towards deriving relations between recorded ground motion (PGA or PGV) and intensity. Intensity prediction equations (IPE) were derived based on the available data for each city. A physically based functional form and a weighted regression scheme based on the characteristics of the area and on the available data was used to derive relations and the associated regression errors as well as prediction errors associated with a new intensity estimate. Different equations were produced to account for the characteristics of each test site.

The Vrancea region is characterized by the occurrence of large intermediate depth earthquakes showing an anisotropic attenuation distribution. This is accounted for by introducing a site correction function which is obtained by fitting residuals between observed intensities and the isotropic part of the IPE to a spatial function of longitude and latitude. Relations are derived using the Joyner-Boore attenuation equations, rupture and epicentral distances, which fit well the observed intensity distribution.

IPE for the Campania region were derived accounting for the uncertainties in earthquake source parameters through a Monte Carlo approach. For each studied event, source parameters were defined with associated uncertainty bounds, and one million regressions were performed sampling source parameters within these uncertainty bounds. Results were compared to the outcome of a standard regression scheme performed for Joyner-Boore equations and epicentral distances. Results show that the regression errors for the Monte Carlo approach and the standard regression are very similar, indicating that the uncertainty in source parameters can be neglected in comparison to the variability in the intensity data set.

For the Cairo area, magnitude information about previous earthquakes is inhomogeneous and for some events available only in terms of Ms. To obtain a homogeneous dataset, Ms has been converted into Mw using two different empirical relations, and two regressions have been performed. The obtained relations are similar and reproduce well the observed intensity field of the 1992 Cairo earthquake (which was not included in the regressions).

c) Complex Earthquake Features Within Minutes

Earthquake Early Warning requires that information on the earthquake is being made available within a few seconds. It has been shown before that this is now achievable for measured ground motion, earthquake location and “Early P-wave Magnitude”. However, this can not be achieved at present for more complex features of an earthquake, like focal mechanism, slip distribution and other details of the rupture process. To a certain extent this shortcoming holds also for the determination of the magnitude, because the “Early P-wave Magnitude”, obtained within seconds, is only a first rough estimate of the earthquake size based on empirical correlations and not on a thorough understanding of the underlying physical earthquake process. All the above parameters, however, are needed as accurately as possible to obtain a good estimate of the ground motion also in between the seismic stations (where it is not measured) and consequently on the specific distribution of the seismic damage to be expected.

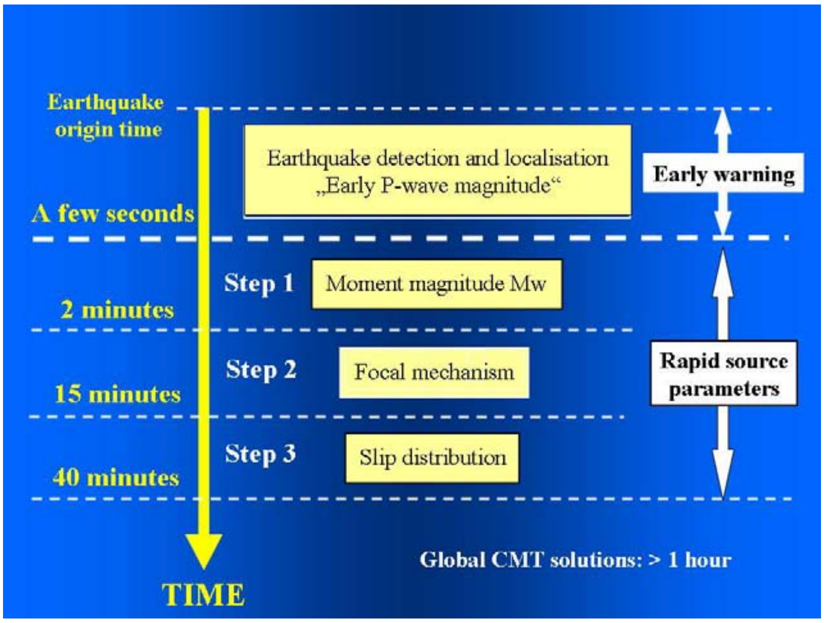
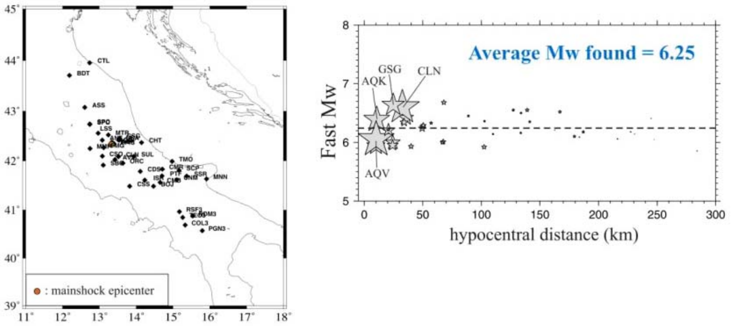


Fig. 14 Source parameters are now available within minutes

SAFER has been successful in reducing the time necessary for determining the physics based magnitude (moment magnitude) by a factor of 10 to 20: from 30 to 60 minutes down to 2.5 to 3 minutes! It has also developed the capability of calculating the focal mechanism and other details of the rupture process of an earthquake from near-field observations, as well as from teleseismic records within 15 to 20 minutes (Fig. 14). This is an important progress, as it has direct application to tsunami early warning and to rapid seismic damage prediction for which, different from seismic early warning, a delay time of a few minutes can be tolerated.

CNRS has in fact developed a new method (MWSYNTH) for rapid determination of moment magnitude using near field records (Fig. 15). The method was initially validated for moment magnitudes ranging from 3.9 to 7.7, stations at epicentral distance < 100 km, and shallow sources (hypocentral depth < 50 km). Input data are strong-motion records. The method is now extended to larger magnitudes (up to Mw 9), greater epicentral distances (up to 320 km), and deeper earthquakes (down to 200 km depth). This extension will be particularly important for cases involving subduction zones. To cover the full range of magnitudes and distances, a time window of 120 s ,starting from the earthquake origin time, is used, meaning that the moment magnitude can be computed 2.5 to 3 minutes after an earthquake occurs.

a) Application of the MWSYNTH method to the L'Aquila (Abruzzo) Earthquake of April 6, 2009 (01H32 UTC)



b) Application of the MWNEAR method to the L'Aquila (Abruzzo) Earthquake of April 6, 2009 (01H32 UTC)

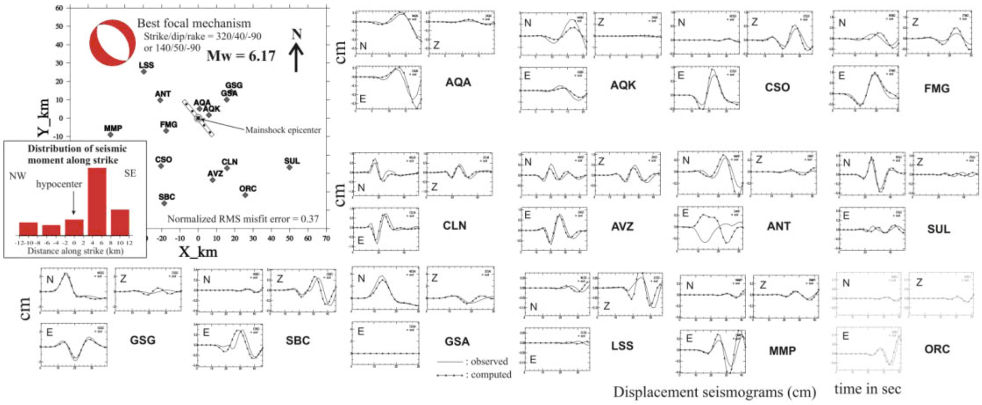


Fig. 15 Application of the MWSYNTH (a) and FMNEAR (b) methods to the l'Aquila earthquake. In (a) the map shows the location of the strong motion stations employed in the determination of the moment magnitude. In (b) the map shows the distribution of strong motion stations used to determine the focal mechanism and the distribution of seismic moment. The resulting focal mechanism is shown in red (normal faulting). Insert in the lower-left corner of the map displays the distribution of seismic moment along strike, showing a clear dominant directivity towards the SE.

An alternative and integrative method using teleseismic body waves and theoretical Green's functions deconvolution provides in 15-20 minutes the focal mechanism, and the apparent source time functions which give insight into rupture complexity and directivity. Finally CNRS developed a method for rapid focal mechanism determination using near-field records. The method, called FMNEAR, is under final validation and tuning for earthquakes ranging in magnitude from 3 to 8.3. It is based on the waveform modelling of strong-motion records integrated to displacement and automatically band pass filtered. For magnitude smaller than 5.5, the rupture is represented by a point source, but for larger magnitudes a finite 1D dimension source model is used which distributes seismic moment along the strike of the fault. The focal mechanism and the linear seismic moment distribution are inverted at the same time using a fast and optimized grid search combined with a simulated annealing algorithm. On a common up-to-date PC the focal mechanism can be computed within 15 to 20 minutes after origin time using six seismic stations.

d) "Seismic Ground Shaking Potential" Versus "Tsunami Generation Potential"

The moment magnitude (M_w) is the parameter generally utilized to describe the size of an earthquake. It is derived from the low frequency asymptote of the displacement spectra and it is a measure of the final static displacement of an earthquake. The energy magnitude (M_e) is derived from velocity power spectra and it is a measure of the part of energy radiated as elastic waves from an earthquake. Because they measure different physical properties of an earthquake, there is no *a priori* reason that they should be numerically equal for any given seismic event. The former is well suited for characterising the tsunami generation potential of an earthquake, but it does not well describe the ground shaking potential, more relevant for the damage associated with an earthquake. The energy magnitude reflects the ground shaking potential associated with an earthquake much better. Unfortunately, the energy-magnitude is not widely used in seismology and methods for its rapid estimation were not in place before SAFER! Now, at the end of the SAFER project, a new method exists, capable of providing the energy magnitude for any earthquake worldwide within only a few minutes.

GFZ developed a new procedure to calculate M_e and applied it to recent significant earthquakes in order to test (offline) its performance also for events occurring in remote areas after the deployment of new broadband stations worldwide (Fig. 16). The importance of implementing such procedure in rapid response systems is shown using as example a pair of recent great earthquakes occurred in the Kuril Islands arc. These two events have very similar M_w and location (the difference is about 100 km). However, our rapid determinations of M_e gave a value of 8.3 for the event occurred on 13 January 2007 ($M_w = 8.1$), whereas for the event occurred on 15 November 2006 ($M_w = 8.3$) gave a value of 7.8. Indeed, the latter event generated a tsunami with maximum measured wave height of 176 cm (also a person was injured at Waikiki). The maximum intensity values was about VI degree of MM in some localities of Russia. The shaking was only slightly felt in Japan. A much smaller tsunami was generated by the former event (the maximum measured wave height was 37 cm), whereas the shaking was much more severe. This pair of earthquakes clearly show the importance of using rapid determinations of M_e jointly with M_W in order to better discriminate between the tsunami and the shaking potential of large earthquakes.

The new procedure allows for a fast first estimate of the shaking potential of an earthquake that can be compared to the tsunami generation potential as inferable from the moment magnitude. The method makes use of data from the global seismic network and does not require local networks. Disaster management may be supported by this kind of information in their decision whether to prepare for a tsunami and/or for direct damage due to ground motion.

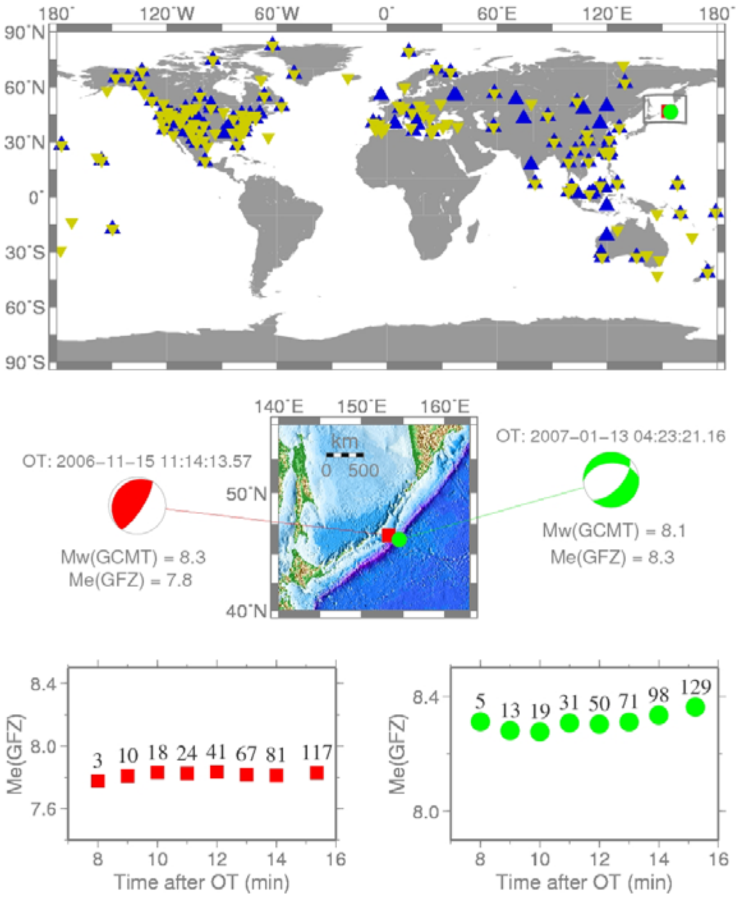


Fig.16 Map showing the location of the two Kuril island earthquakes and the stations used to calculate Me(GFZ). The blue triangles represent the stations used for the earthquake of 15 November 2006, and the yellow triangles for the event of 13 January 2007. The box delimitates the area shown enlarged in the middle together with the GCMT fault plane solutions. In the lower diagrams Me(GFZ) values at different times after OT have been plotted for the 2006-11-15 (left) and the 2007-01-13 event (right), respectively. The number above each symbol represents the number of stations used at different times after OT.

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.

This system, termed the Self-Organising Seismic Early Warning Information Network (SOSEWIN), is characterised by the following features:

- Each seismological sensing unit or Sensing Node (SN) is comprised of low-cost "off-the-shelf" components, with each unit initially costing several hundred Euros, in contrast to 1,000's to 10,000's for standard seismological stations;
- Each SN undertakes its own, on-site seismological data processing, preliminary analysis, archiving, and communication of data as well as early warning messages. Moreover, each SN will also have the capacity to measure other environmental parameters (e.g. noise, temperature etc.);
- The reduced sensitivity of the SNs compared to standard instruments (due to the use of lower-cost components) is compensated by the network's density, which in the future is expected to number 100's to 1000's of units over areas served currently by the order of 10's of standard stations;
- The SOSEWIN is a decentralised, self-organising ad-hoc wireless mesh network.

The development of the SOSEWIN focused on two points. The first was the design of the low-cost SNs themselves, while the second is its self-organising, decentralised character. The originality of both these aspects of the SOSEWIN distinguishes this network from more traditional types. Since the SOSEWIN is concerned only with larger, potentially damaging events, the lower sensitivity expected from the SNs compared to standard commercial instruments is not a significant concern. Moreover, it must be immediately stated that SOSEWIN is not meant to replace existing seismological networks, but to compliment them.

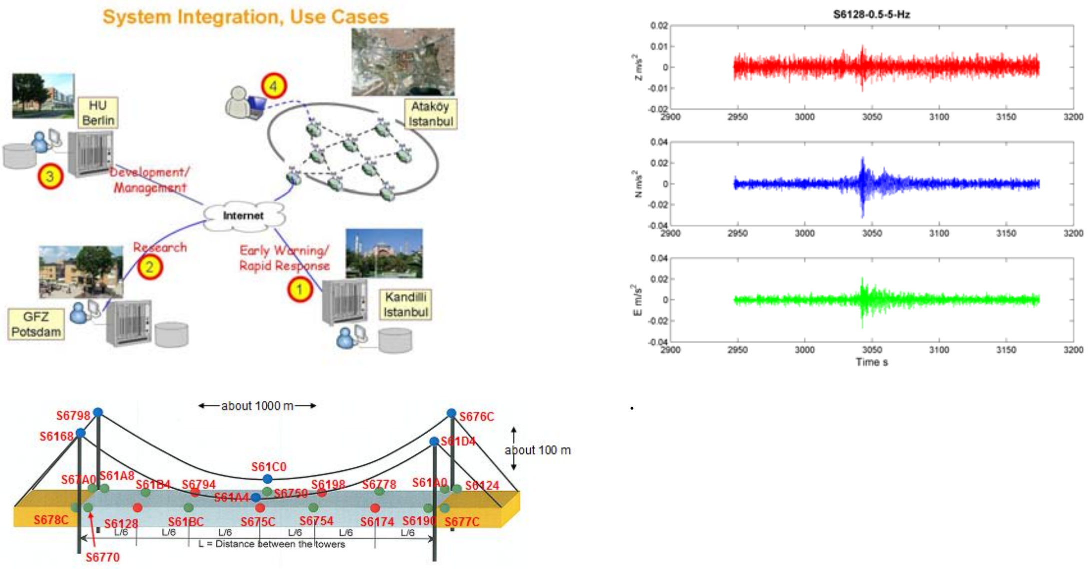


Fig. 17 The SOSEWIN prototype is providing real-time earthquake information to the partner institutes KOERI, UBER, and GFZ, in Turkey and Germany. In addition SOSEWIN has been tested for infrastructure monitoring in Istanbul at the Fatih Sultan Mehmet Suspension Bridge.

The sensing node prototype is comprised of two main units:

- An embedded PC that can be purchased off-the-shelf. It is practically a 486er embedded PC with a 266 MHz CPU and offers one slot for a CompactFlash card, which acts as the hard disk, and two Mini PCI slots for two WLAN Mini PCI cards for the communication needs. This serves as a wireless mesh network node and computing unit.
- The digitizer board, which controls the sensors , samples the resulting sensor data by analogue-digital-converters and provides them, together with GPS readings, to the embedded PC.

The digitizer board is powered and connected via USB connection. Figure 17 gives an overview of the architecture of the low cost sensor node prototype.

During the development of the sensing nodes (SNs) of the SOSEWIN low cost sensor network, GFZ, KOERI and UBER noticed that the hardware selected allows to calculate different parameters during an event and leave the selection of the "best" parameter suitable for Early Warning and Real Time Shake Maps to the end-user. The SNs are developed with the primary goal of performing real-time seismological analysis for EEW. Considering the early warning requirement of issuing ground motion estimates as quickly as possible, and the fact that SNs are comprised of low-cost components, the general scheme designed for real-time processing involves the local, relatively simple, rapid, and robust analysis of data. In addition, during the different stages of the seismological analysis (i.e. idle monitoring status, event detection, event characterization, and summary of the recorded ground motion during the event) the SN will issue within the SOSEWIN a variety of short messages (i.e. few hundreds of bytes) containing both seismological and engineering parameters.

During the idle monitoring stages, messages will be regularly transmitted by the SN to its corresponding LN (minimizes traffic). These messages consist of average values for the acceleration recorded, allowing on-site environmental seismic noise characterization, together with parameters indicating the health of the instrument.

The most important seismological processing in case of an earthquake is the detection of the initial P-waves. The procedure for triggering adopted within SOSEWIN relies on the ratio between the average recorded absolute vertical ground motion component over a short time average window and that for a longer time average window. The search for the best parameters was done with real recordings made by the KOERI rapid response network of recent events in the Marmara region

Immediately after triggering, the SN transmits the P-wave trigger time together with parameters that allow some indication of the severity of the ground motion, namely the peak ground motion parameters (namely peak ground acceleration, peak ground velocity, and peak ground displacement) for the vertical component of ground motion. In addition, the cumulative absolute velocity, the Arias intensity, and the predominant period are calculated and included in these messages. From the moment of the trigger, all of these parameters will be continuously determined.

At the same time, the S-wave trigger will be activated. In practice, this involves the algorithm starting to check the ground motion on the horizontal components for the identification of the incoming S-waves. S-waves are identified, similarly to the P-wave, when a predefined value of the signal-to-noise ratio for S-waves is exceeded. At this point, the event characterisation stage is started with the computation and transmission of the S-waves trigger time, together with ground motion parameters continuously determined for the three component of ground motion.

The final actions involve the computation of the acceleration response spectra for some significant periods (i.e. 0.1 sec, 1 sec, and 3 sec), and generating event files containing the summary of the peak ground motion values recorded during the event (PGA, PGV and PVD). Finally, this information is incorporated into files that are produced in a format appropriate for the USGS tool ShakeMap. Finally, while real-time event location is not included in the current version of the seismological analysis carried out by the SOSEWIN, this is intended to be incorporated in the near future. This will also involve having such estimates being continuously updated as more stations are triggered.

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 Bosporus 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 configurated at present is still conventional, SOSEWIN has opened a novel avenue for seismic early warning that is extremely promising.

With a collaborative work of KOERI, UBER and GFZ, 20 nodes were installed in July 2008 in Atakoy district for testing purpose in early warning and rapid response. The system recorded 2 earthquakes with M>4.0 so far. It is intended to expand this network by integrating with existing Early Warning and Rapid Response networks. In 2008, the SOSEWIN system was temporarily installed to the Fatih Sultan Mehmet Suspension Bridge for structural monitoring purpose. A joint poster was presented at AGU 2008, and a joint paper submitted to the Bulletin of Earthquake Engineering.

f) Near Real-Time Detection of the Onset of Foreshock Activity and Real - Time Aftershocks Hazard Assessment

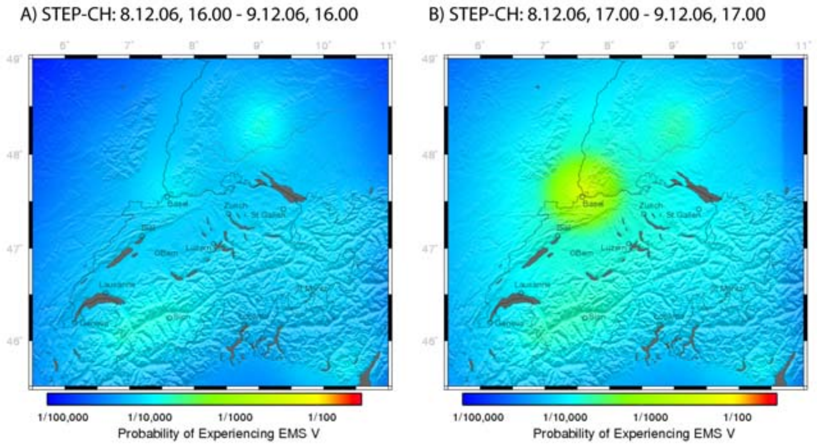
The timely forecasting of the time evolution of a seismic sequence is a major seismological problem. The practical importance of having a quantitative probabilistic tool providing updated forecasts was evident during the recent L'Aquila (Central Italy) earthquake sequence which culminated in the destructive Mw6.3 event of April 6,2009.

This problem was faced in SAFER, the reliability of existing tools was investigated in several contexts and novel tools were developed.

Several research groups in SAFER focussed their activity on the developments of statistical and physics-based models for time-dependent earthquake forecasting, the performance evaluation of clustered seismicity models with statistical test procedures and the implementation of the corresponding software for retrospective and on-line (prospective) experiments. The results of the three retrospective forecast experiments from the 1992 Landers (California), the 1997 Colforito (Italy) and the 2008 Selfoss

(Iceland) events have indicated that purely statistical forecast models, in particular the Epidemic Type Aftershock Sequence (ETAS) models, provide currently the most powerful approach to forecasting aftershock seismicity. Physics-based forecast models are generating results comparable in data consistency to the pure statistical forecast model if additional stochastic elements are integrated. This has been shown by introducing uncertainties in the stress calculations based on the use of different finite fault source models. This result is promising for the future, but requires for implementing this type of models for prospective experiments that additional information such as finite fault source models and structural information (including uncertainties) is introduced.

The results of these retrospective tests have been essential for planning and implementing the Robust Aftershock Forecasting Tool (RAFT, Fig. 18). Different versions of RAFT are available, ranging from one operational on-line (RAFT-CH), another operational in near-real time with a delayed data stream from the seismic network, and a third one operational in off-line automated and manual state (FORMA, RAFT-Italy, EQW). The latter is still preliminary and needs further work for the final connection to the data stream from the seismic networks.


A) STEP-CH: 8.12.06, 16.00 - 9.12.06, 16.00

B) STEP-CH: 8.12.06, 17.00 - 9.12.06, 17.00

C) No site amplification

D) Site amplification included

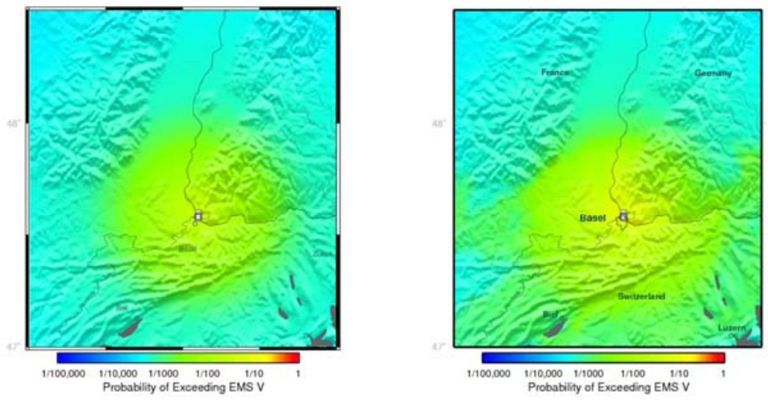


Fig. 18 An application of RAFT: Snapshot of the Short Term Earthquake Probability model for Switzerland A) from 8.12.2006, 16.00 to 9.12.2006, 16.00, B) from 8.12.2006, 17.00 to 9.12.2006, 17.00 showing the Probability of Experiencing EMS V. C) Zoom to the Basel area for the period 8.12.2006, 17.00 to 9.12.2006, 17.00 without and D) with site amplification included.

A novel approach was used by NOA, who investigated the potentiality of Poisson Hidden Markov models and provided an automated system FORMA (**Fo**reshock-**M**ainshock-**A**ftershock) for seismic sequence characterisation. FORMA uses the seismic activity rate and the so-called seismic b value to discriminate in near real-time between different types of earthquake sequences including the seismic background, foreshock-, aftershock- and swarm like activity. The system was applied to data recorded by the Greek National Seismic Network with a focus on the earthquake sequence in 2008.

The Poisson Hidden Markov Models concept was applied with success for a retrospective analysis of the seismic activity occurred in the region of Killini, Ionian Sea, Greece, from 1990 till 2006. It was found that the method has better performance than traditional analyses since the transition from one seismicity state to another does not only depend on the total number of events involved but also on the current state of the system. Therefore, this method recognizes significant changes of seismicity as soon as they start, which is of particular importance for real-time recognition of foreshock activities and other seismicity changes.

Both FORMA and Poisson Hidden Markov Model algorithms constitute a promising tool for the identification of the state of seismicity and the detection of seismicity changes, for discrimination of swarms from foreshocks, for the forecast of the mainshock from foreshocks and for the early recognition of aftershocks patterns.

The achieved results confirm that time-dependent probabilistic aftershock hazard assessment is feasible. Several tools have been developed up to a pre-operational level, and even beyond. They have been tested extensively and a broad community consensus on their applicability was established. It is now up to national networks to decide if and how to implement the tools we have developed. The recent L'Aquila event demonstrated clearly the usefulness and need for aftershock forecasting.

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. AMRA 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 (Fig. 19). 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 that the consequences of a false alarm.

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 used to test the potential of hybrid EEWSs. It was 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.

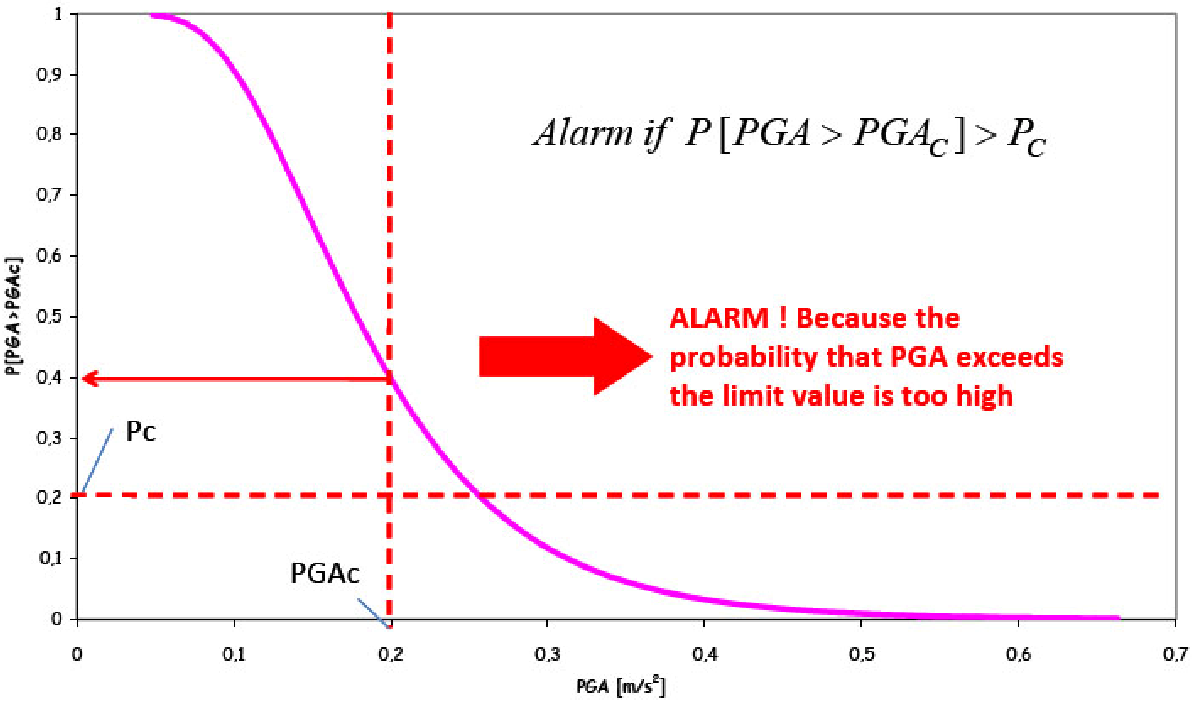


Fig. 19 An alarm should be issued when the expected PGA is higher than the critical value indicated by a cost-benefit analysis

5. IMPROVING EARLY WARNING CAPABILITIES IN FIVE 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, about 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 M6. 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.

a) Athens

Before the beginning of the SAFER project, no efforts were made for developing EEW at Athens and in Greece in general. Within SAFER such an effort started in two main directions.

The first one aimed at developing a prototype hybrid seismological network, i.e. an integration of regional and on-site systems. The network infrastructure is installed around the Gulf of Corinth (Fig. 20), one of the most seismically active areas in Europe and one of the major threats for the metropolitan area of Athens. The EEW network consists of the NKUA Seismological Laboratory seismometers (CORNET and ATHNET) and accelerometers networks (RASMON). Each seismometric station is equipped with a mini-pc running local acquisition software (RTPD). Data are transmitted to the central Station located at NKUA main acquisition RTPD node. RTPD to RTPD connectivity is performed through a 2 way robust error corrected transmission protocol. By running a single station (on-site) algorithm as a client to the local RTPD at each site on site EW alerts can be implemented. These alerts can be forwarded to the central EW application server either through the same communication or through a separate one. The transmitted data to the central acquisition server permit the implementation of network based EW algorithms. The distance among stations range from 5 to 30 km. Sites with real time data transmission to the central site at NKUA are connected with off line seismographs and dial-up accelerographs in order to provide a dense network in the covered area. NIED provided NKUA with its early warning system code, already in use in Japan, in order to be implemented in the real-time transmission system.

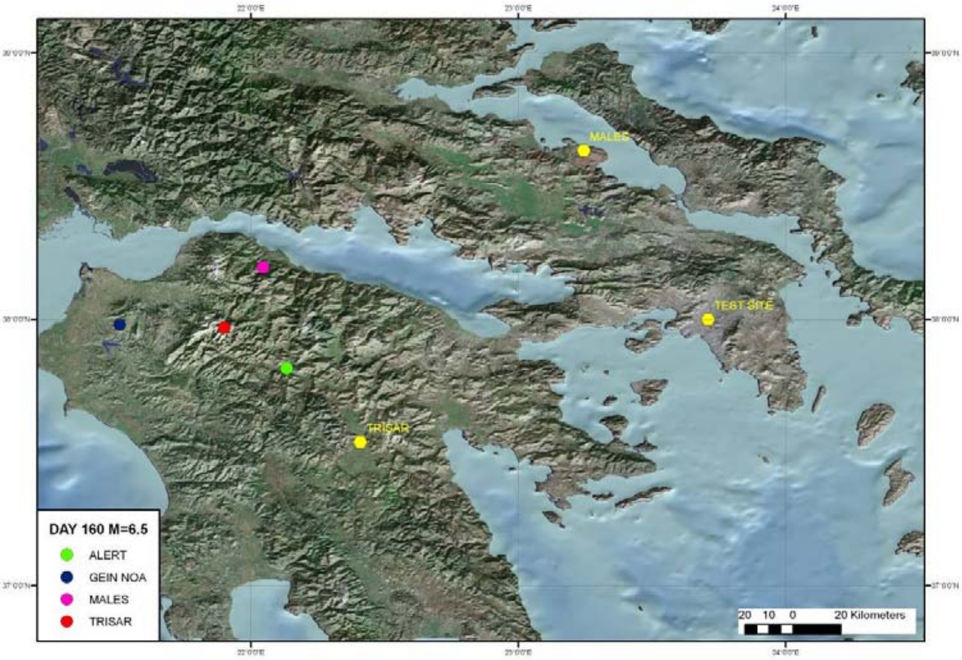


Fig. 20 Seismic network used for array processing of the June 6, 2008 Andravida Mw=6.4 earthquake, using the software implemented by NORSAR and NKUA.

The second effort was focused on the problem of online characterization of the evolution of an on-going seismic activity, in particular on detecting a possible transition from background seismicity to foreshock activity in near real-time. In the SAFER project, the automated system **FORMA** (**FO**reshock-**M**ainshock-**A**ftershock) for the discrimination among different seismic activity patterns in near real-time has been designed. It incorporates all the data bases, including the possibility of real time updating with data from monitoring stations, and the software ***EQStat*** with statistical tools for the elaboration and selection of several data sets (e.g. selection of target area, time windows and earthquake data sets; completeness analysis and declustering of the catalogue; calculation of seismicity rates ***r***; calculation of ***b***-value; testing for significant changes of the parameters ***r*** and ***b,*** etc.).

FORMA incorporates also an algorithm to estimate the probability of change of seismic activity at any given time, (e.g. background/foreshock, background/swarm foreshock/aftershock, aftershock/background) on the basis of the statistically significant change of two diagnostic parameters: seismicity rate ***r*** and ***b***-value. Finally an alert decision matrix gives the near real-time identification of an ongoing foreshock activity having a high probability to foreshadow a forthcoming stronger mainshock.

b) Bucharest

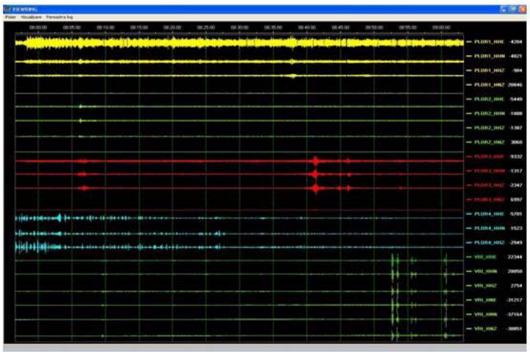
The Vrancea seismogenic zone in Romania is a peculiar source of seismic hazard, representing a major concern for several European countries, such as Bulgaria, Serbia, Republic of Moldavia etc. Earthquakes in the Carpathian-Pannonian region are confined to the crust, except the Vrancea zone, where earthquakes with focal depths down to 200 km occur. For example, the M_W =7.7 earthquake of November 10,1940 was produced by a rupture at 140 km, the M_W =7.4 event of March 4,1977 occurred at a depth of 110 km, the M_W =7.1 earthquake of August 30,1986 at 134 km of depth and M_W =6.9 May 30,1990 event at 85 km of depth. The depth interval between 110 km and 130 km remains not ruptured since 1802 when it produced the strongest historical earthquake (M_W =7.9 - 8.0) in this part of Central Europe. This depth interval is a natural candidate for the next strong Vrancea event.

Bucharest is located at 150-170 km distance from the Vrancea zone. In spite of this distance, the city suffered severe damages from the high energy Vrancea intermediate-depth earthquakes. For example, the March 4, 1977 event (M_W =7.4) produced the collapse of 36 buildings with 8-12 levels, and seriously damaged more than 150 old buildings. The strong accelerations produced in Bucharest by the Vrancea earthquakes are predominantly due to the thick sedimentary formations underlying the city. The fundamental phenomenon responsible for the amplification of seismic motion over soft sediments is the trapping of seismic waves due to the impedance contrast between sediments and underlying bedrock. Non linear site amplification is quite general in the Bucharest area.

EEW capability existed already in Romania when SAFER started. It was based on the data collected by a regional network implemented in the Vrancea area. During the SAFER years additional accelerometric stations were installed in the Bucharest city area for real time determination of ground shaking.

The main progress brought by SAFER to the early warning and disaster management capability of the city concerns the rapid magnitude determination of Vrancea earthquakes, the optimization of the seismic network to improve EEW efficiency, the development of a new azimuth dependent attenuation law to fit the geology of the region, the integration, in an early warning approach, of alert-, shake- and damage maps.

An automatic procedure was developed and used to test different methods to rapidly evaluate earthquake magnitude from the first seconds of the P wave. A method to rapidly estimate magnitude in 4-5 seconds from the detection of the P wave in the epicenter area was obtained (Fig. 21). The software developed by NIEP was tested during the Vrancea earthquake on April 25, 2009 when the magnitude(M_w =5.7) of the earthquake was accurately computed within the first 5 seconds.



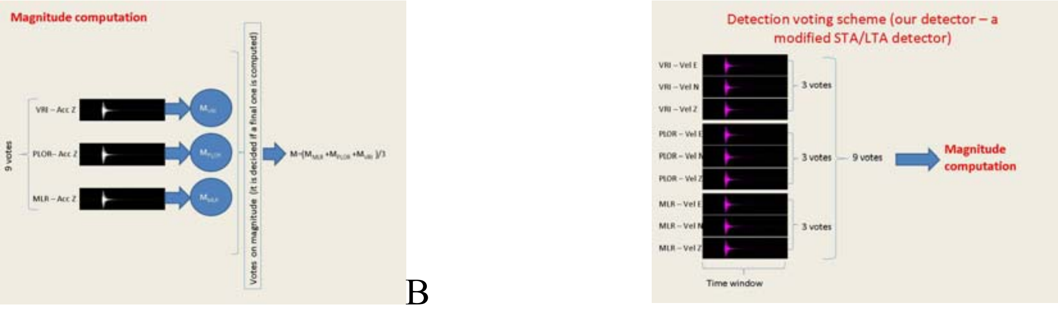
- data packing delay depends on data source. E.g. if the digitizer sends data at every second, the transmission is optimized in order to minimize the delay.

-K2, Q330 and SeedLink support; unlimited number of channels (tested 279).

-modular design, you can add your new code and new algorithms

-possibility to process offline data (mseed2ring module)

A



B

C

Fig. 21 The procedure developed at NIEP for real time estimate of magnitude. (a) waveforms are organized in data packages (b and c) a voting procedure is enforced for selection of magnitude.

The integration of alert-, shake- and damage maps is performed automatically for the Bucharest area. It allows the real time generation of reliable shake maps in the city area. The procedure starts with the rapid determination of the magnitude of the earthquake from the P-waves recorded at the Vrancea network. The system generates a preliminary shake map (alert map) for Bucharest within 4-5 seconds, using pre-defined attenuation and site response laws. This alert map is improved and converted step by step to a measured shake map as the real-time data from accelerometers installed in the Bucharest area become available. The improvements account for the prominent nonlinear site effects due to the thick sedimentary layer underlying the city. In order to make rapid damage assessment possible, these data can be combined in the EEW-System with vulnerability information. For this purpose, existing tools for damage and loss assessment were tested and further improved for application to Bucharest. The final models are amenable to provide loss assessment for the city of Bucharest in real time.

c) Cairo

With a total population of 16 million Cairo can be considered as one of the largest megacities in the world. Cairo is located in a basin-like feature of topography, where it is surrounded by high mountains from the eastern side; low relief at the central part, and high mountains on the western side. Although Cairo has experienced some historical earthquakes that destroyed many of historical and archaeological structures (e.g. the 7th of August 1847), most of the buildings and lifelines, especially in the rural communities within Cairo, don't follow an anti-earthquake design code. Structures are built on very soft and soft sediments which greatly affect the ground motion and the response of the overlying structures. A M_b5.9 event occurred on October 12, 1992 causing 561 deaths, 9832 injured and an economic damage of more than 35 million US$ (Fig. 22). In the aftermath of this earthquake, the Egyptian Government supported the National Research Institute of Astronomy and Geophysics (NRIAG) to install and operate the digital Egyptian National Seismic Network (ENSN) and strong motion instruments all over the Egyptian territory. Most of these stations transmit the real time data via satellite to the Helwan main centre. The main centre produces GIS maps for the decision-makers and civil defense authority. However, no seismic early warning capability existed, because real-time and/or near real-time early warning technology had not been implemented, and various types of input data that are crucial for early warning had not been gathered so far. With SAFER the real-time shake map technology has been installed in Cairo and its performance, after being optimized for major earthquakes in the past, is currently being tested online in connection with the seismic monitoring system. The input parameters for the shake-maps include new information acquired during the project, including a magnitude calibrated intensity attenuation relation, microtremor measurements for characterising site dependent ground motion amplification and vulnerability composition models for all the considered 43 districts of Greater Cairo. These in conjunction with a specific Dynamic Decision support Module (DDSM) developed within SAFER, enable to simulate possible earthquake damage scenarios in the future, and together with the seismic monitoring system and the implemented shake map technology, provide the basis for an operational earthquake early warning and rapid response system.

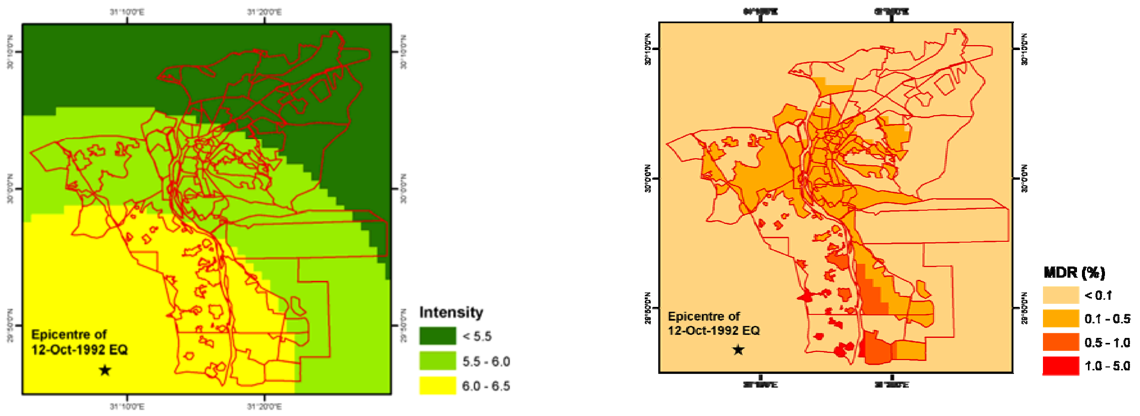


Fig. 22 Calculated intensity map (left) and damage map (right) for the earthquake of 12th October, 1992. (MDR mean damage ratio).

d) Istanbul

The seismic hazard for the mega-city Istanbul is extremely high. Destructive earthquakes over the past 2000 years have hit Istanbul about once every century. Observations of past earthquakes in the 20th century show a westwards migration of epicentres along the North Anatolian Fault Zone which had reached an area only some hundred kilometres east of Istanbul where two strong earthquakes in 1999 in Kocaeli (Mw=7.4) and Duzce (Mw=7.1) occurred. Approximately 1000 people in the Istanbul suburb of Avcilar were killed and the damage to buildings and structures was rather serious, though the epicentre of the Kocaeli earthquake was more than 110 km away.

An extension of the North Anatolian Fault passes just 25 km south of Istanbul. This region to the immediate south has been identified as a seismic gap where the probability of a large earthquake in the near future is high. A large earthquake in this area would affect between one third to a half of the total Turkish industrial activity that is concentrated in the Marmara provinces near Istanbul.

Moreover, the drastic increase of the city's population from 1 to more than 10 million people since 1950 runs parallel with an even more drastic increase in its vulnerability. In addition to overcrowding, faulty land use planning and construction, inadequate infrastructure, as well as environmental degradation, loss of vegetation, and a high percentage of informal settlements are some major reasons for this increased vulnerability.

The catastrophic events in 1999 have raised public awareness of seismic risk within the Marmara region, and Istanbul in particular. In cooperation with governmental institutions, the Kandilli Observatory of the Bogazici University in Istanbul (KOERI), which is our Turkish partner in the SAFER project, has therefore designed and installed the earthquake information system IERREWS (Istanbul Earthquake Rapid Response and Early Warning System).

The Istanbul test site has several strong motion networks. Each of them has its own algorithms. Istanbul Earthquake Early Warning (IEEWS) has 10 strong motion stations located as close as possible to the fault zone. Continuous on-line data from these stations provide early warning for potentially disastrous earthquakes via digital radio modem.

The Istanbul Earthquake Rapid Response System (IERRS) has 100 strong motion stations placed in quasi-free field locations (basement of small buildings) in the populated areas of the city, within an area of approximately 50x30km, to constitute a network that will enable early damage assessment and rapid response information after a damaging earthquake.

Aside from the IEEWS and IERRS, the Self-Organizing Seismic Early Warning Information Network (SOSEWIN) has been installed in June 2008, in the Atakoy district of Istanbul (Fig. 23). The network includes 18 Sensing Nodes (SN) and 2 Leading Nodes (LN). It is the purpose to integrate the SOSEWIN system with the existing IEEWS and IERRS in future.

Fig. 23 SOSEWIN prototype installation in Istanbul. In the district east of the international airport of Istanbul 20 SNs are installed, two of them are connected to the Internet with DSL lines. This internet connection is used to data transfer for the involved partner institutes in Turkey and Germany.

There are also several structural health monitoring strong motion instruments installed in critical structures in Istanbul. Some of them are : Historical Structures of Hagia Sophia Museum, Fatih Mosque, Suleymaniye Mosque, Critical structures of Fatih Sultan Mehmet Bridge and Bosphorus Bridge. Each of these networks has its own algorithm. The SAFER Project initiated the parameter optimization in the Istanbul Earthquake Early Warning System IEEWS (Fig. 24). The existing IEEWS utilizes band-pass filtered PGA and CAV values. A new parameter called Bracketed Cumulative Average Velocity (BCAV) has been proposed to be used in the IEEWS. As a new approach the specific window-based BCAV namely BCAV-W is planned to be used in IEEWS. In order to improve the capability of IEEWS, τ_c and Pd methods have been studied. The empirical relationships between τ_c and M_w, and between Pd and PGV for the Marmara Region were derived.

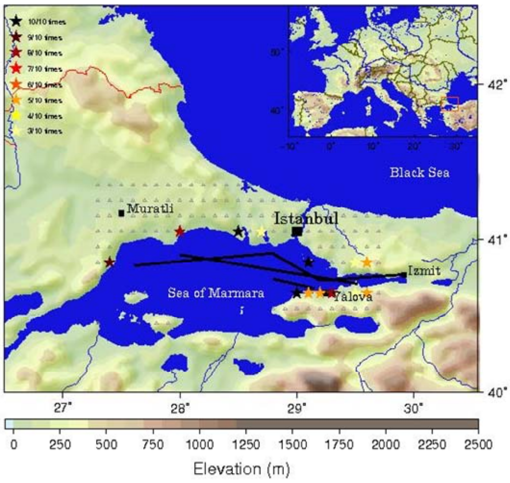


Fig. 24 Using the Turkish megacity Istanbul as target city, sets of optimum locations of seismic EW-stations are computed using a genetic algorithm. The grid of possible locations of the seismic stations is indicated by grey triangles. The stars show cost-optimized locations of a network of seismic stations in case that 10 stations located on land are considered.

For the Istanbul Earthquake Rapid Response System (IERRS), the SAFER project initiated the installation of the USGS ShakeMap in the KOERI server, and this is operational since December 2006. The existing IERRS gives ground motion parameters (PGA, Sa, Sd), damage and casualty maps with information from stations without taking into account epicenter and magnitude information. The installation of ShakeMap enabled the derivation of ground shaking intensity maps, ground motion parameters (PGA, Sa, Sd), damage and casualty maps with epicenter and magnitude information including information from stations.

The SAFER project also initiated a work on site response consistency for IERRS stations. The predominant frequency of each station site has been determined by analyzing the records from past events and these have been associated with site response characteristics of each station location.

e) Naples

With about 6 million inhabitants and a large number of industrial plants, the Campanian region (southern Italy) is highly exposed to the seismic risk, related to a moderate to large magnitude earthquake originating from active fault systems in the Apenninic belt. The 1980, M=6.9 Irpinia earthquake was the most recent destructive earthquake in the region having caused more than 3000 causalities, huge and widespread damages to buildings and infrastructure on the whole regional territory. Considering an earthquake warning window ranging from tens of seconds before to hundreds of seconds after an earthquake, several public infrastructures and buildings of strategic relevance (hospitals, gas pipelines, railways, railroads, ...) can be considered as potential target-sites for the application of EEW in the Campania region.

A few years before SAFER, the Civil Protection of Regione Campania started a feasibility study of EEW for earthquakes located in the Apennine region close to Naples. It was based on the existence of a high quality densely spaced seismic network around the Irpinia fault zone. The network covers an area of about 100 km × 70 km over the active seismic faults system that generated the 1980, $M_S = 6.9$, Irpinia earthquake. It constitutes the core infrastructure for a regional Earthquake Early-Warning System (EEWS) that remains under further development today. The EEW system is primarily aimed at providing an alert to selected target sites in the Campania Region upon the occurrence of moderate to large earthquakes ($M_S > 4$), and to promptly compute regional ground-shaking maps. The network is currently composed of 27 seismic stations and five Local Control Centers (LCC) data storage and processing sites. All of the stations are equipped with a strong-motion accelerometer (Guralp CMG-5T) and a three-component velocity meter (Geotech S-13J), with a natural period of one second, thus ensuring a high dynamic recording range. Five stations feature a broad band velocity meter (Nanometrics Trillium, 0.025–50Hz), to record regional and teleseismic events and to provide useful data for analysis of ambient seismic noise, which is aimed at obtaining a shear-wave velocity model of the region. Due to the source-to-target distances for a target located in the city of Naples, the expected warning time (26-30 sec) can be sufficient to operate the automatic shut-down or disconnection of local plants and to control and protect sensitive target infrastructures as gas pipelines, viaducts, the railway network, operating rooms in hospitals, high-risk industrial installations and relevant databank servers.

During the SAFER years, and through the SAFER project, an intensive activity was dedicated to the development of an automatic fast procedure of earthquake location, magnitude determination and expected ground acceleration at a given site, which includes and continuously updates the uncertainties of each parameter. The earthquake location is determined using P-wave arrival times, whereas the earthquake magnitude is determined using the P-wave peak amplitude (P_d) in an evolutionary approach where location and magnitude values evolve with time as new data from more distant stations and from later wave arrivals become available. The real time and evolutionary algorithms for magnitude estimation at the Campania Region EWS is based on a magnitude predictive model and a Bayesian formulation. It is aimed at evaluating the conditional probability density function of the magnitude as a function of ground motion quantities measured on the early part of the acquired signals. A prototype EEW system (PRESTo) and the identification of criteria for directing engineering applications and automatic decision making were the final SAFER result. For the first time, the whole approach, from the evolutionary method for rapid earthquake parameter determination to real-time engineering applications, follows a strictly probabilistic pattern.

PRESTo is the acronym for *PRobabilistic and Evolutionary early warning SysTem*, a new software platform on which the Earthquake Early Warning System (EEWS) is built. PRESTo is an integrated software tool that continuously processes the live streams of 3-component acceleration records from the seismic stations When an energetic event is detected at a minimum number of two stations, the system promptly performs the first P-picking location. Peak ground displacement measurements (PD) in a narrow time window after the observed P and predicted S-signals are used to estimate the earthquake magnitude and predict a peak ground motion parameter at distant target sites. As the radiated waves propagate through, alarm messages, containing the evolutionary estimates of the above parameters along with their uncertainties, can thus reach, through dedicated communication lines or the Internet, the vulnerable structures in the region before the arrival of destructive waves, thus enabling the automatic activation of safety procedures. An empirical attenuation model at regional scale is used to predict the peak accelerations at target structures. For earthquakes originating within the seismic network, a first alarm can be delivered within 4-6 seconds from the origin time and a stable, low error location and magnitude estimate is achieved within 10 seconds after the origin time. PRESTo can easily be configured and tailored to different networks, by providing the seismic stations details, velocity model, coefficients of the regression laws, and by tuning the parameters controlling the data analyses algorithms and the alarms dissemination.

Performance tests of the Campania Earthquake Early Warning systems are reported in Fig. 25.

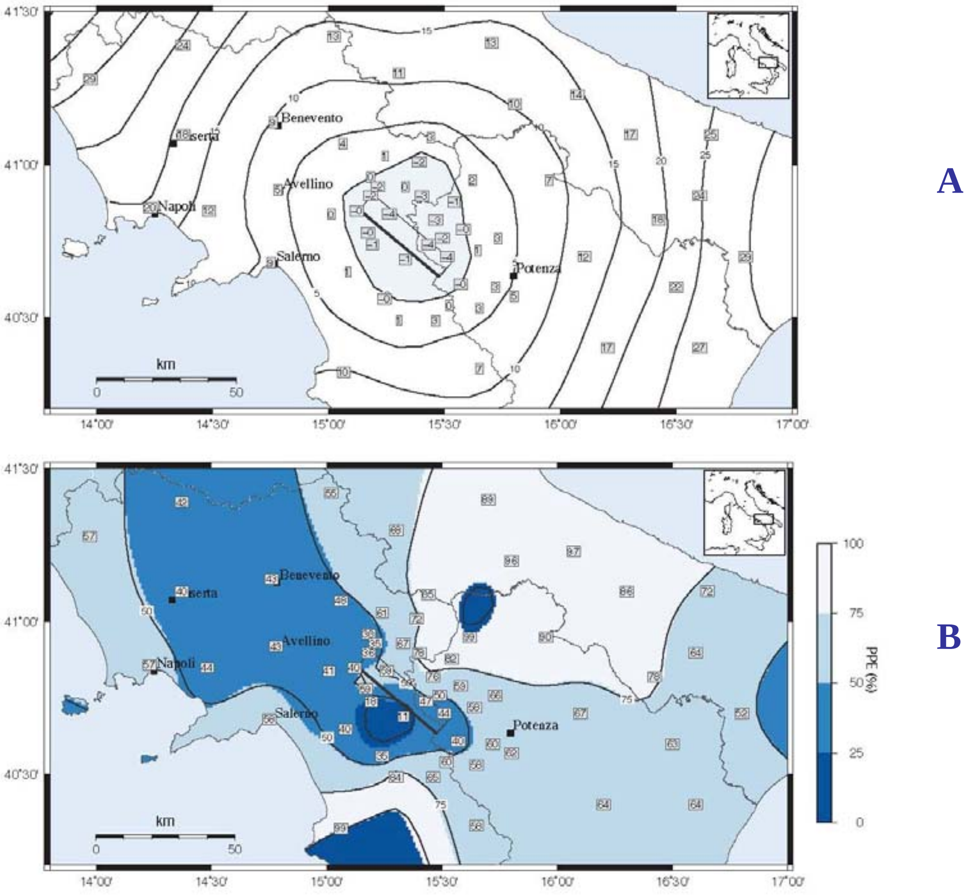


Fig. 25 Performance tests of the Earthquake Early Warning Network of Campania in terms of (a) lead times (b) probability that the prediction error (PE=log(PGVtrue) – log(PGVesti)) is within 1-sigma interval of the standard error on the Ground Motion Prediction Equation. High values of PPE means high performance of the system in terms of prediction of ground shaking level at the target.

Other SAFER products include advanced methods for the real-time production of shake maps. In addition, the capability of real-time risk assessment for Naples has been improved with an off line test of the SELENA method.
A feasibility study of the application of earthquake early warning systems to different infrastructures and facilities has been carried out for the Campania region (southern Italy). Solutions for redundant and robust communication technologies have been identified for a test site in Naples.

6. SAFER AND THE BROADER COMMUNITY

One of the most important outcomes of the SAFER project has been to provide information to the wider public by a programme of outreach activities. One of the main instrument for this has been the Project Web-site (http://www.saferproject.net) which is active since the beginning of the project and is receiving an average of about

3000 visit per month. SAFER has raised the attention of the public and the media to the potentiality and the implementation of EEW systems and stimulated the collaboration among seismologists' and seismic engineers' community.

a) SAFER and the Scientific Community

The SAFER achievements were and will continue to be presented to several international meetings of geophysics, seismology and seismic engineering. Special sessions on earthquake early warning systems were organized by SAFER at international scientific conferences (Fall Meeting of the American Geophysical Union, San Francisco, December 2007, 31st General Assembly of the European Seismological Commission, Crete, Greece, September, 2008; General Assembly of the European Geosciences Union in April, 2009).

More and more frequently, in several non European contexts SAFER is addressed as an unique European group of researchers active at the frontier of EEW knowledge. For instance, the participation of SAFER representatives to present the results achieved in Europe was specifically asked by the organisers of the 2n International Workshop on Earthquake Early Warning held in Kyoto, April 2009.

The contributions by SAFER have a relevant part on special issues of Geophysical Research Letters (Allen et al., 2008), of Seismological Research Letters (Allen et al., in press), of Journal of Soil Dynamics and Earthquake Engineering (Iervolino et al., in press) and of an incoming Springer book on EEW.

In the European context several SAFER ha collaborated closely with the NERIES project mostly on the themes of implementation of Shake maps and the development of tools for forecasting the time sequence o aftershocks.

An interchange of information is occurring also with other European projects dealing with EEW and tsunami early warning, particularly with the TRANSFER project, through the participation to project meetings.

b) SAFER and the Media

A burst of interest of TVs and newspapers towards the SAFER project achievements occurred after the publication of some results of the project as early as 2006 and the presentations at the American Geophysical Union Fall meeting in San Francisco in December 2007. Many newspapers all over the world (U.S.A., Mexico, Spain, Italy, Germany, etc.) stressed out the scientific and technological effort that was in progress in Europe through SAFER. Some of them (e.g. San Francisco Chronicle, El Pays) rated the effort in Europe second, directly after Japan. The interest continued in the following years with several TV networks from Germany, Italy, France and United States and high diffusion newspapers and magazines published interviews with the coordinators of SAFER. In this way the project became a main contributor in diffusing among the people the concept of Earthquake Early Warning and its potentiality. Moreover it started to make many people especially in Europe aware that a few seconds or tens of seconds of warning time are not at all useless but they do count. It has started to make people conscious of how many things can be done in a few seconds to reduce the risk and to save life.

c) SAFER and the End Users

The obvious end users of EEW systems are the Civil Protections and the various emergency management agencies. Other end users are dangerous industries and managers of life – lines and industries. The experience in Japan is showing that privates and the general public can be also involved as end users.

The involvement of such a wide range of users requires *ad hoc* well planned national policies and cannot be a goal of a scientific project as SAFER alone.

However, SAFER has started discussions with Civil Protections and emergency management agencies by inviting representatives of these organizations to each of the annual meetings. Representatives of Naples, Bucharest, Athens and Istanbul organizations attended the meetings and a half a day round table discussion, respectively.

7. THE EUROPEAN VALUE OF THE SAFER PROJECT

The European Union and the different countries with high seismic risk have issued specific laws and regulations to mitigate risk. These laws generally define the seismic hazard in all the European and national territories and provide the rules to be followed for the constructions in seismic zones. High seismic hazard regions of Europe are characterized by a very high percentage of old buildings, infrastructures and life-lines. The key point for efficient risk reduction in these cases is to find the sustainable combination of structural actions (construction codes for new buildings and retrofit actions for the old ones) and real time risk reduction actions. Warning systems fit the purposes of the latter. They require a close collaboration between earthquake engineering and seismology.

The results of SAFER have shown that EEW systems and know how ready to be implemented exist in several European countries . In order to do this, current European regulations for the protection of infrastructures against earthquakes must be modified to include design criteria (performance based) for structural control systems (EWS based).

The results of SAFER well meet the EU priorities concerning “Global Change and Ecosystems” because they do *“improve the capacity and power of real time seismology to deliver timely integrated information in order to enable actions to be taken immediately before destructive shocks occur and to provide information and warning in the subsequent phases of the event.”* They have contributed to the preparedness for, and the mitigation of the negative consequences of potentially catastrophic seismic events, particularly in large towns and highly populated areas of Europe.

SAFER has 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, show that SAFER is quite visible and well considered even in countries like Japan, who are the traditional leaders in this field.

SAFER has 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 project has also attracted more than 30 young researchers, an European young community able to continue and forward the research in this field.

8. A VISION FOR THE FUTURE

The SAFER Steering Committee delivered to the European Commission a document where the role of Earthquake Early Warning methods in building a safer Europe was outlined, the problems for a rapid application of the method in Europe were identified and the research needed to further develop the method was indicated.
The main parts of this vision paper are hereafter reported as an overview of the advantages and problems for the EEW implementation in Europe and as a glance to the future based on the SAFER experience.

The concept of "early warning" was introduced by Dr. J.F. Cooper in 1868 who proposed locating mechanical devices at locations between 10 to 100 miles from San Francisco. When triggered by critical ground motion, these devices would send an electrical signal to a bell ringing system in the town hall. Unfortunately, this idea was not realized. The first practical application of an "early warning" strategy was developed by the United States and former Soviet Union during the Cold War as a countermeasure to the threat posed by intercontinental ballistic missiles. The system was originally centered around radar networks, and later improved by the integration of satellite-based early warning systems, the latter focusing on detecting a missile's launch. The objective of these systems was to alert target areas as soon as a missile or its launch was detected. Within this context, the term "lead time" was defined as the time elapsing between the detection of the missile and its estimated impact at the target. Consequently, the early warning was meant to be given just after the launch had been seen by satellites, or the missile detected by radar.

Over the last few decades, the meaning of early warning (EW) has greatly expanded. It is now used with small, but significant, variations for various types of hazard, from epidemiological to economical, social, and of course, all types of natural and environmental phenomena. In fact, within some of these contexts, including natural hazards such as floods and volcanic eruptions, the warning is not given after the onset of the catastrophic event itself, but beforehand, based on the occurrence of some precursor that can trigger the said event (for example, intensive rainfall for floods, and earthquakes and/or ground deformation for volcanic eruptions).

The case of earthquake early warning (EEW) is very similar to the missile early warning example. An EEW system is based on the fact that most of the radiated energy is contained in the lower velocity wave phases, termed S- and surface waves, that travel at about 3-5 km/s or less. These waves arrive at a location with a delay or lead time with respect to the smaller amplitude but higher velocity P-waves that travel at about 6-7 km/s. The alert is given after an earthquake's P-waves are detected by a network of seismometers, the warning being transmitted by much more rapid telecommunication techniques.

However, EEW is not limited to simply issuing alarms, but incorporates the implementation of many actions that contribute to the protection of persons, transport and energy lifelines, industries, and other critical infrastructures, seconds to minutes after the first detection of an earthquake. Another point that must be emphasised is that EEW is not concerned with earthquake prediction as such, although it will be able to estimate the impact such events would have, based on their early detection and analysis of the initial signals.

"Early warning systems": Why are they needed?

Ever increasing urban populations, especially the larger cities, are becoming hotspots of global risk change. This urban explosion takes place predominantly in the developing world, where the population of large cities doubles every 15 years, while that of informal settlements doubles every 7 years. There are expected to be around 420 million people residing in cities with a population of 2 million or greater by 2015, of which 350 million will be in developing countries. For the case of Europe, because of its increasingly urban nature, high level of industrialisation and ever greater networking of infrastructures, lifelines and economies, its cities also face increasing levels of risk, again making them hotspots of risk change. It may therefore be said that the developing world faces increased risk that would lead to greater loss of human life, while Europe's risk is of increasing financial and infrastructure losses. Hence, Europe must focus on both aspects because of its own immediate interests (the physical safety of its population and protection of their livelihoods) and as a result of globalisation (economic and social) and the resulting greater integration of economic partners, meaning that negative events around the world increasingly cannot be considered in isolation.

The importance of EW in general has been highlighted in a number of international documents at various governmental levels. Within the context of the United Nations, EW was emphasised within the Hyogo Framework for Action, where it was identified as one of the five priorities for action. In addition, a report requested by the then UN Secretary General, Kofi Annan, provides a global assessment of the EW capabilities, gaps and opportunities, while three international conferences dealing with EW, all under the auspices of the United Nations, have continued to emphasise the importance and necessity of EW systems.

Earthquake hazard cannot be reduced, but, risk, the probability of damage occurring, can be. This is due to risk being a function of not only hazard, but also of vulnerability. While earthquake hazard is more or less constant with time, vulnerability is currently increasing exponentially. Hence, having the capacity for mitigating actions to be undertaken in a timely manner has the potential of drastically reducing the negative consequences of an earthquake. This requirement raises many scientific and technical challenges. For example, in the high-risk areas of Europe, the lead times are of the order of only 10's of seconds. Such a short time window means that many actions, particularly those associated with industrial processes, would need a high degree of automation, raising legal issues regarding liability in the event of false or missed alarms.

Within today's EU, large areas of Italy, Greece, Cyprus, Slovenia, Romania and Bulgaria experience the highest levels of seismicity, while parts of Portugal, Spain, France, Germany, Austria and the Czech Republic have significant risk. There are also areas of equally high, and possibly higher, risk in countries bordering the EU, for example the rest of the Balkan Peninsula and Turkey, whose scientists and engineers are already in several research partnerships with institutions in the EU. Ongoing assessments of seismic risk in normally quiet areas such as Austria, Switzerland and Germany has revealed that current building stock, not all of which is designed to consider seismic events, may require retrofitting to cope with the possibility of even moderate earthquakes.

Although parts of Europe, the US and Japan have populations that are exposed to similar levels of high earthquake hazard, the relative vulnerability of the European population is some 10 times greater than in Japan, and 100 times that of the US, a result of a lower level of spending in earthquake mitigation, including Europe's weaker EEW capacity.

The protection of critical infrastructure is one of the priorities of the EU, since the well-being of its citizens, as well as their security and economy, depends upon a broad interconnected social, economic and political infrastructure, and the services that are provided. The destruction or disruption of portions of this infrastructure could entail the loss of lives, the loss of property, and a collapse of public confidence and moral. In order to counteract these potential vulnerabilities, the European Council requested in 2004 the development of a European Programme for Critical Infrastructure Protection (EPCIP). Since then, comprehensive preparatory work has been undertaken, which has included the organisation of relevant seminars and the publication of a Green Paper, where the question was posed as to whether EPCIP should be based on an all-hazards approach, an all-hazards approach with a terrorism priority, or a terrorism-hazards approach.

A vast majority of member states (twenty) expressed their support for the adoption of an all-hazards approach for the EPCIP, while recognizing that terrorism should be the priority. This is consistent with the Hyogo Framework, where it was stated that an "*integrated, multi-hazard approach to disaster risk reduction should be factored into policies, planning and programming related to sustainable development, relief, rehabilitation, and recovery activities*". The Green Paper defines prevention as the range of deliberate, critical tasks and activities necessary to build, sustain, and improve the operational capability to prevent, protect against, respond to, and recover from an incident. Prevention involves efforts to identify threats, determine vulnerabilities and identify and obtain the required resources. The EW can therefore contribute to the goals of the EPCIP.

More recently, a communication, while focusing on tsunami risks, clearly recognizes the need for further work on EW systems in Europe. In this document, it is stated that: *"while focusing this specific effort on the tsunami warning system, the Commission remains committed to a multi-hazard approach since the proposals will strengthen the existing early warning systems in Europe in a more general perspective"*. Considering a more practical implication of this statement, it is quite conceivable, in fact necessary, for EW systems tailored to different hazards should share some commonalities (e.g. their communications capacities).

However, a problem linked to the implementation of policies that would achieve the goals set by the Green Paper or the Communication mentioned above is that areas of high earthquake hazard often cross national borders, which raises the issue of the common difficulties associated with international activities. It is therefore essential that civil protection authorities develop complementary procedures to respond to an earthquake that has caused damage over a wide area. Such procedures would in part be facilitated by the European Civil Protection Agency. However, one cannot understate the value of direct contact between the authorities of neighbouring countries.

How will an EEW system increase European society's safety and resilience?

- Warning the general population of impending danger, in a manner appropriate for the society in question.
- Protecting critical structures, and allowing them to remain operational (e.g. hospitals, air traffic control).
- helping civil protect authorities to obtain timely alerts for more rapid and efficient mobilization and adaptable response. This would include aftershock forecasting.
- minimizing earthquake-induced secondary effects (e.g. fires, industrial accidents) as well as the impact of aftershocks and triggered events (e.g. landslides and tsunamis).
- increasing the safety of the population, particularly in schools and public places.
- EEW contributes to the protection of transport systems and lifelines.
- Allowing economic and social facilities to "return to normal" as soon as possible.

An important goal of an EEW system is to warn a population that a potentially dangerous earthquake has occurred. The problem then is to decide on what manner such an alert should take. Obviously, having a working EEW system would be much less efficient if the population for whom it is established are not aware of their own part. Therefore any EEW system would need to be tailored to suit a given society, with an emphasis being on so-called people-centred EW.

As it has been mentioned several times in this document that the protection of infrastructure is a major task of EEW. Critical infrastructures consist of those physical and information technology facilities, networks, services and assets that, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments. Critical infrastructures extend across many sectors of the economy, including banking and finance, transport and distribution, energy, utilities, health, food supply and communications, as well as key government services. Indeed, it is not only the protection of critical infrastructures that is a goal of EEW systems, but also allowing them to remain operational during a post-earthquake period. It is obvious that some infrastructures, such as hospitals, would in fact be even more necessary during such a period, and therefore should receive particular attention in developing actions that will ensure their operational status.

Coupled with this would be the need for other critical (although not possibly life threatening in their absence) infrastructures to resume their activities as soon as possible. Business and industries are obvious examples, in that the economic activities of the affected region would be under particular strain. Likewise, schools should have the capability of resuming, not least because the population in general, which would most likely be experiencing significant physical hardship, would need some semblance of their normal lives to ease their now considerable burdens.

In some well documented cases, the largest proportion of fatalities, casualties and economic losses may result from secondary events triggered by an earthquake, e.g. tsunamis (Lisbon, 1755, Sumatra, 2004), fires (Tokyo, 1923; San Francisco, 1906), industrial accidents (Izmit, 1999) and landslides (Neapolitan Earthquake, 1857, El Salvadore, 2003) and both tsunamis and landslides (Okushiri, 1993). These kinds of secondary effects will become more important, owing to the increasing interconnection and complexity of modern societies. As was discussed before, EEW systems will include the capability of lessening the consequences of these secondary events. Gas pipelines would be cut off to reduce the likelihood of fire, while the examples given above dealing with trains and bridges would lessen the likelihood of derailments and additional traffic casualties in the event of bridge or tunnel failures. Of particular importance would be the integration of EEW systems with those dealing with tsunami and landslide hazard.

EEW techniques are being developed where an earthquake's characteristics, namely its epicentre, focal depth and magnitude, are determined with a high degree of accuracy even before the earthquake has finished. Such information is of crucial importance in the generation of near real-time scenarios of the expected geographic distribution of damage. Techniques of this type, known under the general term *shake maps*, have proved to be very useful for the timely mobilization of the civil protection groups and rescue teams. There are currently available products that generate such maps that are then made available on-line with special products made available to specific end users such as the media.

EEW would also play a crucial role after an event, with respect to aftershock detection, Aftershocks always occur following a substantial earthquake, and are a source of considerable hardship, not only in disturbing an already traumatise population, but in restricting rescue operations, and in inflicting additional damage to the weakened built environment. Therefore, part of EEW is the development of methodologies to obtain some predictive capacity for aftershock behaviour, allowing a greater degree of flexibility for rescue operations and to keep the general public informed.

While EEW is not only on its own an invaluable contribution to disaster mitigation efforts, it should form an indispensable component of longer-term risk reduction and development strategies. A recent essay in the international science journal *Nature* emphasised the need for governments and the appropriate agencies to invest much more in prevention (including EW) during the period between disasters, recognising that funding for such actions is difficult to obtain if a disastrous event has not occurred for some time, despite the cost efficiency of preventative measures.

Within Europe, there is significant variation in the current status of EEW, with only 10% of possibly affected cities having some form of EEW and even here, the capacity of the current systems varies. The fact that many cities with a significant seismic hazard have no means of EEW at all demonstrates a pressing need for the establishment of EEW systems in the cities most at risk, and an expansion in those where such a system exists. For example, in Greece, the metropolitan region of Athens, which is surrounded by many active seismogenic zones at distances of up to 250 km, and which was hit by devastating earthquakes in 1981 and 1999, although included as a test-area in the above mentioned SAFER project, still not yet an operational EEW.

One problem is that the lead times available, a function of the nature of the area's seismicity, varies significantly and is one factor that cannot be improved upon, regardless of the technology available. For example, lead times for Bucharest would generally be of the order of 30 seconds, owing to the distance to the Vancea region, where the vast majority of Romanian earthquakes occur. However, for Istanbul, such times are only of the order of 10 seconds owing to the proximity of the Marmara Sea fault.

Aftershock activity after strong earthquakes have many times proved destructive. Therefore, monitoring and real-time alerts regarding aftershocks are of great social importance since many decisions of the civil protection depends upon the nature of these events. The main issues that should be met by an effective EEW include identifying in near real-time conditions such as the migration of aftershock epicentres, the determination of the area, size and number of the expected aftershocks, including their temporal variability, and the rapid discrimination at high confidence level between swarms-fore shocks-aftershocks.

Aftershocks not only contribute significantly to the damage inflicted on the built environment and lifelines, but they also, quite simply, are a major source of distress to the population who could well be living under extreme hardships, not only physically but especially emotionally.

A vision for the future

Improvements

- Extensive cost-benefit analysis of each potential tool.
- Identification and resolution of legal problems (e.g. liability in the event of false or missed alarms).
- Education and training, both for mitigation and response.
- Detection and processing within 1 second of the first seismic wave arrivals.
- Development of rapid active and semi-active controls for structures (1-2 second response).
- Rapid and accurate impact assessment (minutes to hours after an event).

New directions and goals

- Diffusion of information, “end-to-end EW”.
- Specialized IT and decision making support systems.
- Integration of sensors, communications and decision making systems, following European and international standards.
- People-centred EEW.
- Mobile sensor networks for aftershock EEW, allowing continuous real-time hazard assessment.
- Integration into programs of eco-sustainable development.

- Creation of a European cross-border network of EEW systems (system of systems).

- Integration with other EW systems (all-hazard systems).

The European Union must have the objective of reducing the individual vulnerability of the population of Europe to a level comparable to that of Japan and the US. EEW has the potential of significantly contributing to this goal, as demonstrated in Japan.

EEW systems would benefit from advances in communication technology, of which Europe is at the forefront, while Europe’s communication network would have the potential of benefiting from the establishment of national and international EEW networks.

ANNEXES

a) Partners and Involved Researchers

GFZ
GFZ-Potsdam, German Research Center for Geoscience - Germany (COORDINATOR)

Jochen Zschau, Coordinator
Claus Milkereit, WP Leader
Kevin Fleming, Project Manager
Frank Roth
Stefano Parolai
Monika Sobiesiak
Helmut Grosser
Rongjiang Wang
Gottfried Grünthal
Dietrich Stromeyer
Mathilde Sörensen
Bogdan Enescu
Sebastian Hainzl
Domenico Di Giacomo
Matteo Picozzi

AMRA
AMRA Scarl – Naples, Italy

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Gaetano Manfredi, WP leader
Aldo Zollo, WP Leader
Alfonso Rossi Filangieri, Project Manager
Maria Lancieri
Claudio Martino
Claudio Satriano
Iunio Iervolino
Giovanni Iannaccone
Vincenzo Convertito
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Adrian Grigore
Mihaela Popa
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Richard Allen, Main Scientist

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El Hady, S. M.
El Sayed, K. A.

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KNMI
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Torild van Eck, Main Scientist

CEDIM

Cedim AG, Karlsruhe, Germany

Lothar Stempniewski, Main Scientist
Rüdiger Werp
Tanja Liesch

b) Workpackages and Tasks

WP	TASKS
WP1 **Project Coordination and Management** *Copordinator* *Jochen Zschau* *GFZ-Potsdam*	*Project Coordination and management*
WP2 **Real Time estimation of earthquake source parameters** *Coordinator* *Aldo Zollo* *AMRA Naples*	**Task 2.1** *Real-time methodologies for event detection and location*
	Task 2.2 *Real-time methodologies for magnitude/moment estimates*
	Task 2.3 *Near real-time processing of seismic arrays for earthquake rapid alert*
	Task 2.4 *Implementation and testing of virtual seismologist expert system*
	Task 2.5 *Application of developed techniques to selected European test sites*
WP3 **Real-time** **damage assessment and reduction strategies** *Coordinator* *Gaetano Manfredi* *AMRA, Naples*	**Task 3.1** *Real time damage scenarios*
	Task 3.2 *Induced landslides – Real time slidemap and delayed slide*
	Task 3.3 *Applications for real-time risk reduction: algorithms, interfaces (case studies) for semi-active and active control of infrastructures*
WP4 **Real Time Shake Maps** *Coordinator* *Claus Milkereit*	**Task 4.1** *Implementation of on-line shake map and intensity map generation*
	Task 4.2 *Seismic network optimisation*

GFZ-Potsdam	**Task 4.3** *Parameter optimisation*
	Task 4.4 *Development of a prototype system of low cost seismic sensors and building monitoring devices with real-time reporting and early warning capabilities*
	Task 4.5 *Accounting for site effects in real-time loss estimations*
	Task 4.6 *Implementation of the real-time shake map estimation for the megacity Cairo*
WP5 **Real-time aftershock hazard assessment** *Coordinator* *Stefan Wiemer* *ETH Zuerich*	**Task 5.1** *Building RAFT – the Robust Aftershock Forecasting Tool*
	Task 5.2 *Improving aftershocks hazard assessment by incorporating physical models*
	Task 5.3 *Integrating temporary seismic networks into the real-time aftershock hazard assessment*
	Task 5.4 *An automated system for 3D real-time aftershocks hazard assessment in Greece*
WP6 **Dissemination of Results And End-Users Interface** *Coordinator* *Gerassimos Papadopoulos* *NOA Athen*	**Task 6.1** *Dissemination of results*
	Task 6.2 *Interface with end users*
	Task 6.3 *Dynamic Decision Support Module*
	Task 6.4 *Synergy with other EU funded project*

c) Publications

First Year

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