REAKT FINAL REPORT

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4.1 Final publishable summary report

Executive summary

REAKT (Strategies and tools for **R**eal time **Ea**rthquake **R**is**k** Reduc**t**ion) is a CP-IP project funded by the European Commission in the context of Framework Program 7 under the Theme Environment (including climate change) in response to the call "Towards real-time earthquake risk reduction".

The main objective of REAKT was to improve significantly the efficiency and reliability of methodologies of real time mitigation of earthquake risk and their capability of protecting structures, infrastructures and people.

REAKT improved the quality of all the information coming from earthquake forecast, early warning and real time vulnerability assessment, finding the best procedures to use all this information in a fully probabilistic framework, including realistic uncertainties estimations. The major scientific advances reached in the project are reported in 90 scientific publications and 2 books in press. A general overview can be found in the website of the project (www.reaktproject.eu).

A number of strategic applications are the real core of REAKT as they provide the opportunity to implement and test scientific products and results achieved in the project, as well as to develop a better understanding of what the end-users expect by applying Earthquake Early Warning (EEW), Operational earthquake forecasting (OEF) and real time time-dependent vulnerability assessment to reduce earthquake related risk at the respective sites.

The applications include i) nuclear (Switzerland), hydroelectric (Iceland) and coal (Portugal) power plants; ii) cable stayed (Greece) and suspension bridges (Turkey); iii) electric power (Iceland) and gas distribution (Portugal, Turkey) networks; iv) oil refineries (Portugal); v) industrial and touristic harbours (Greece, Portugal); vi) railways (Italy);vii) public schools (Italy) and hospitals (Greece).

The applications were segregated into feasibility studies, prototype implementation and implementation efforts, based on the maturity expected to be reached in each application within the project timeline .

Thanks to the strong involvement of different types of end users, a comprehensive view of the conditions favouring or hindering the application of short term earthquake forecasting and early warning methodologies was produced, identifying scientific and regulatory problems to be addressed in future research.

REAKT was strongly multi-disciplinary, calling upon expertise in seismology, structural and geotechnical engineering, statistics, sociology and governance.

The REAKT Project was carried out between September 2011 and December 2014 by a Consortium formed by 23 institutes from 10 European countries (Germany, Italy, Greece, Romania, Switzerland, France, Iceland ,Turkey, Portugal, UK) and one each from Japan, Taiwan ,U.S.A, Barbados, Trinidad and Tobago. The Consortium includes universities, governmental and non-governmental research institutes and one professional organization. The Consortium was led by Paolo Gasparini, AMRA scarl, Naples, Italy assisted by a Project Management team formed by Stefan Wiemer, ETH Zurich, Switzerland Jochen Zschau, GFZ, Potsdam, Germany and Alfonso Rossi Filangieri, Amra Scarl, Naples, Italy.

Summary description of project context and main objectives

1. INTRODUCTION TO THE REAKT PROJECT

REAKT (Strategies and tools for Real time Earthquake Risk Reduction) is a CP-IP project funded by the European Commission in the context of Framework Program 7 under the Theme Environment (including climate change) in response to the call "Towards real-time earthquake risk reduction".

The project has been designed to respond to the growing concern for the increase of seismic risk in a growing world. The continuous expansion of population and the growth of lifeline systems complexity make our world increasingly exposed to seismic risk. The world's urban areas are becoming hot spots of global risk change, because of the continuous increase of population and of complexity of lifeline systems (see f.i. Bilham, 2009).

Most of the European cities probably will not be affected by a dramatic increase of population. Nonetheless they will face increasing levels of risk because of the growing industrialisation and networking of infrastructures, lifelines and economies. The networking involves other continents as a result of the economic and social globalization.

In many cities exposed to high earthquake hazard, a substantial proportion of the population still lives in buildings that do not meet modern earthquake-resistant standards. As a consequence, a primary target for Europe must be the decrease of both human and financial/infrastructural potential losses caused by earthquakes. Preventive actions, such as retrofitting of structures, are essential, but they are not sufficient and cannot be applied easily on a large scale. Real-time actions focussing on decreasing the physical vulnerability and exposure of populations are a viable way to reduce earthquake risk. These actions require the development and the use of probabilistic forecasting, (characterized by high probability gain and very low absolute probability values), of early warning, rapid loss and damage evaluation considering the evolution of vulnerability and risk with time.

The main objective of REAKT was to improve significantly the efficiency and reliability of methodologies of real time mitigation of earthquake risk and their capability of protecting structures, infrastructures and people.

This objective can be achieved in Europe since its territory is covered by many high quality seismic and accelerometers networks, managed by national and European agencies particularly fit for short term forecast. Several local network have been also specifically designed for seismic early warning .

REAKT aimed at improving the quality of all the information coming from earthquake forecast, early warning and real time vulnerability assessment and at finding the best procedures to use jointly all this information. To be used effectively for decision making in real time this information must be combined in a fully probabilistic framework, including realistic uncertainties estimations.

A number of strategic applications are the real core of REAKT as they provide the opportunity to implement and test scientific products and results achieved in the project, as well as to develop a better understanding of what the end-users expect by applying Earthquake Early Warning (EEW), Operational earthquake forecasting (OEF) and real time time-dependent vulnerability assessment to reduce earthquake related risk at the respective sites.

The applications include i) nuclear (Switzerland), hydroelectric (Iceland) and coal (Portugal) power plants; ii) cable stayed (Greece) and suspension bridges (Turkey); iii) electric power (Iceland) and gas distribution (Portugal, Turkey) networks; iv) oil refineries (Portugal); v) industrial and touristic

harbours (Greece, Portugal); vi) railways (Italy);vii) public schools (Italy) and hospitals (Greece). The applications were segregated into feasibility studies, prototype implementation and implementation efforts, based on the maturity expected to be reached in each application within the project timeline .

Thanks to the strong involvement of different types of end users, a comprehensive view of the conditions favouring or hindering the application of short term earthquake forecasting and early warning methodologies was produced, identifying scientific and regulatory problems to be addressed in future research.

REAKT is strongly multi-disciplinary, calling upon expertise in seismology, structural and geotechnical engineering, statistics, sociology and governance.

REAKT has provided a common field where most of the European and extra-European research groups active in the fields of earthquake forecasting, early warning and real-time vulnerability systems worked together, comparing and discussing their results, setting the scene for an effective integration of methods applied to the various temporal scales of relevance for hazard and risk mitigation.

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2. OBJECTIVES

The main objective of REAKT was to improve significantly the efficiency and reliability of methodologies of real time mitigation of earthquake risk and their capability of protecting structures, infrastructures and people.

The main specific objectives have been:

1. **a better understanding of physical processes underlying seismicity changes on a time scale from minutes to months;**
2. **the development, calibration and testing of models of probabilistic earthquake forecasting and the investigation of its potential for operational earthquake forecasting;**
3. **Improvement of performances of early warning systems;**
4. **Evaluation of methods of citizen based alerts: Flashsourcing, twitter quake detection, testimonies;**
5. **The development of time-dependent fragility functions for buildings, selected infrastructures, and utility systems;**
6. **the development of real time loss estimation models over the lifetime of structures and systems due to foreshocks, main shocks and their subsequent aftershock sequences.**
7. **the construction of a detailed methodology for optimal decision making associated with an earthquake early warning system (EEWS), with operational earthquake forecasting**

(OEF) and with real time vulnerability and loss assessment in order to facilitate the selection of risk reduction measures by end users;

8. the study of the content and way of delivering public communication, recognizing the value of a degree of self organization in community decision making;

9. the application of real time risk reduction systems to different targets (trains, industries, hospitals, bridges, schools, etc.).

Main S&T results/foregrounds

1. FROM WHERE REAKT STARTED

When REAKT was conceived the practical application of short-term forecasts, early warning methods, time dependent vulnerability estimates and rapid loss assessment for earthquake risk reduction **was still in its infancy. No widespread consensus existed in the informed technical community on how to best move on** .

Attempts to reduce in real time earthquake risk were pursued mainly in California and Japan through two independent approaches*:*

- the development of probabilistic forecasting methods applied to the detection of changes of seismic activity and its possible use to drive actions aimed at the reduction of exposure to earthquakes;
- the application of early warning methods to automatically drive safety measures (stop fast trains, switch off dangerous components of industries, nuclear power plants, etc.) or to give short timely alerts to schools, hospitals, etc. Early warning methods were massively implemented in Japan.

Projects of implementations existed in Taiwan, California, Turkey, Mexico and a few other countries (see Allen et al, 2009). REAKT got the legacy of the EC FP6 SAFER (Seismic Early Warning for Europe), the first coordinated European Project on earthquake early warning (EEW) (www.saferproject.net) and extended it to include short term operational forecasting and rapid response (Zschau et al., 2009).

Operational forecasting

Operational earthquake forecasting (OEF) is the production of authoritative information about the time dependence of seismic hazard to help communities to prepare for potentially destructive earthquakes. It is based on statistical and physics based models of earthquake interactions. Such models use a region's earthquake history to estimate temporal changes in the probabilities of future earthquakes (Gerstenberger et al, 2005, Jordan et al, 2010, Jordan and Jones, 2010).

OEF has the objective to indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions. Probabilistic forecasts of future seismicity likewise can serve as important prior information for EEWS, helping to reduce warning times and decrease uncertainties.

The study of earthquake predictability and OEF related research has in the past decades been impeded by the lack of an adequate experimental infrastructure, the capability to conduct scientific prediction experiments under rigorous, controlled conditions and evaluate them using accepted criteria specified in advance (Jordan, 2006). To remedy this deficiency, an international Collaboratory for the Study of Earthquake Predictability (CSEP, www.cseptesting.org) has been formed. It is structured into four testing centers in the US, Japan, New Zealand and Switzerland that served a variety of testing regions around the world. The CSEP EU Testing Center (http://www.cseptesting.org/centers/eth) represents the European node of the Collaboratory for the Study of Earthquake Predictability (CSEP).

Earthquake Early Warning and rapid alert

Earthquake early warning (EEW) systems use information extracted from the early arriving P-waves to estimate the maximum shaking expected from an ongoing event and send this information to regions farther away from the earthquake source (or epicentral) region prior to the arrival of the damaging ground motion. **Such systems allow for mitigating actions to be taken**

before strong shaking and can significantly shorten the time necessary for emergency response and the recovery of critical facilities such as roads, hospitals and communication lines. (Gasparini et al, 2007). Regions in the immediate vicinity of the earthquake epicenter (the blind zone of an early warning system) have very small S-P times, and, therefore, little or no warning time. The available warning time for a location is longer with increasing distance from the epicentral region. Thus, EEW systems can be most effective for providing warning for large earthquakes originating at some distance from a site.

Extending the window of observation from seconds before to tens of minutes after the earthquake occurrence, data from high technology, densely spaced early warning networks can be channeled to earthquake control centers where reliable shake and damage maps can be computed and made available for post-event emergencies and rescue actions.(Allen et al, 2009, 2010, Erdik et al, 2010)

EEWS systems are extensively applied in Japan as a method for effective risk reduction. They have been applied since 1982 to shut off power to the Shinkanzen fast trains. The satisfactory performance of the system led the Government of Japan to develop a nation-wide EEWS. It started to give information to the public in 2007. In two years it issued 15 warnings to the public, anticipating strong ground motion. Only one was a false alarm. After the catastrophic M 8.1 earthquake on 19th of September 1985 hit Mexico City, an EEWS was established to protect the city. The system started to provide public warnings in 1993. Up to 2009 it provided 13 public warnings.

Following the pioneering experiences in Japan, Mexico and Taiwan, and prototype experimentations in USA and Europe, during the last two decades there was a worldwide development of several early warning systems, based on different technological and methodological approaches. Most of systems developed so far are conceived as either “regional” (network-based) or “on-site” (stand-alone) systems. On site EEWS are used to protect some nuclear power plants (e.g. Ignalina in Ukraina) and other industries. The recent implementation in of nation-wide, high dynamic range, dense accelerometer arrays makes now available, potentially in real-time, unsaturated waveforms of moderate to large magnitude earthquakes recorded at very short epicentral distances (<10-20 km). This would allow for a drastic increase of the early warning lead-time, e.g. the time between the alert notification and the arrival time of potentially destructive waves at a given target site.

Recent advanced and innovative technological developments have been carried out in the framework of the FP6 SAFER Project. GFZ and the Humboldt University of Berlin developed an innovative, self-organizing wireless mesh information network made up of low-cost sensors, which is named the Self-Organizing Seismic Early Warning Information Network (SOSEWIN), with the aim of setting up earthquake early warning systems for mega cities. A prototype of the system was installed in Istanbul, Turkey, in July, 2008 (Fleming et al., 2009). Recently, a further prototype of the SOSEWIN system, named GFZ-WISE (Picozzi et al., 2010) has been developed for performing dense 2D seismic ambient-noise array measurements in urban areas (Parolai et al., 2005; Picozzi et al, 2009). Results of the tests performed indicate an excellent performance of the innovative instruments when used in seismic site effect surveys.

Three earthquake early warning systems were available at the beginning of the REAKT project. The PRESTo/ERGO system, the Virtual Seismology (VS) platform and the ElarmS system. The first two were developed respectively in Italy by Amra/University of Napoli Federico II and in Switzerland by ETH Zurich, in the frame of the SAFER project, the latter was developed and used by Caltech in California

During last decade, KOERI of Bogazici University has deployed 200 strong motion recorders in Istanbul in the form of a dense array, 100 of which are utilized for post-earthquake rapid response information generation through very fast data acquisition, analysis and elaboration (Sesetyan at.al.,

2010). The rapid response information is automatically obtained within few minutes after the earthquake and it provides with distribution of ground shaking intensity (Shake Maps), physical damage and casualties (Loss Maps) obtained on the basis of the state-of-the-art methodologies incorporated in the ELER software (Erdik et al., 2010) developed within the EU FP6 NERIES Project. 10 strong motion stations located at the closest points to the Main Marmara Fault were used for EEW Alarm generation (Alcik et al, GRL, 2009; Boese et al., 2008).
It is now well-known that felt earthquakes generate strong and immediate increase of traffic on websites providing rapid earthquake information, increases caused by eyewitnesses rushing to find out information about the shaking they have just been through. EMSC routinely maps within 5 minutes of its occurrence, the area where an earthquake was felt by statistically processing the IP locations of eyewitnesses causing the surge (Bossu et al., 2008, 2010). This is known as a *felt map*. Recently it has been demonstrated the capacity to instantly detect and map widespread damage through the loss of Internet connexions they generate. Additional ground motion measurements can be obtained through citizen-operated network of embedded laptop motion sensors (Cochran etal., 2009). Social networks such as *Facebook* and *Twitter* with more than 500 millions users worldwide are a way to engage with the Citizens and promote their participation in such initiatives (Bossu et al., 2010).

Time dependent vulnerability

Vulnerability and risk assessment of structures was usually performed based on the as-built, or pristine condition of structures (NIBS, HAZUS, 2004). Estimation methods relied on determination of the earthquake hazard parameters, structural modeling and analysis for the determination of the structural response, and correlation of structural response with expected structural and non-structural damage. Currently available analytical procedures were evaluated within numerous publications and EU research projects (e.g. FP6 NERIES Project, Erdik et al., 2010a; Hancilar et al., 2010). To this end, simplified multi-degree-of-freedom procedures, either in terms of displacement (e.g. D-BELA, Crowley et al., 2004) or in terms of simplified pushover analysis (e.g. SP-BELA, Borzi et al., 2008) within an uncertainty framework can be used. Aging, deterioration effects and cumulative damages due to past earthquakes are usually neglected. These parameters, however, are important for the real risk assessment of all kinds of structures. For example, according to the American Society of Civil Engineers (ASCE) over half of the nearly 600 000 bridges in USA are approaching the end of their design life and nearly a quarter need significant retrofitting or replacement (ASCE, 2009). The same is true for all other elements of the built environment. It is obvious that the seismic vulnerability of “aged” structures is increased compared to the initial ones.
Although physical vulnerability changes with time, it is usually considered to be almost stationary. **Despite a long list of efforts that have been led by many engineering communities for the inclusion of time as a parameter of the vulnerability, there is no widespread use of time-dependent vulnerability functions in the natural risk assessment scientific community.** Some recent studies have addressed the issue of the seismic response of buildings to repeated ground motion (Fragiacomo et al., 2004; Li, 2006; Jalayer et al., 2009). Cumulative damages of foreshocks, main shocks and aftershocks, may decrease considerably the resistance of the damaged structures to withstand future shaking, and avoid collapse (Francin et al. 2009). Although they account for a degradation of the physical vulnerability over a seismic sequence, these studies have not led to the definition of fully time-dependent vulnerability.

Decision making in a real time framework

Decision-making in real time for earthquakes deals with two major time scales. Short-term forecasts rely on information on a time scale of days, with high probability gain but very low (typically less than 1%) absolute probability of occurrence of a damaging event in short time scale. In contrast early warning may have lead times of tens of seconds to a few minutes, but a much higher reliability.

One major problem is to decide on the nature and utility of providing information directly to citizens on such short scales (days or minutes). This problem is raised by the fear that a warning of an imminent earthquake may result in panic. Social scientists have long studied this issue and found it is not a major source of concern (Quarantelli, 1956, Goltz, 2002). The experience from many public alerts in Japan and Mexico also provide no evidence suggesting that carefully issued warnings result in panic if the public has a prior education on the risks involved and the actions to take. In fact issuing of public EEW alerts in Japan was preceded and accompanied by a long, intensive broad public education campaign enacted by the Japan Meteorological Agency about the purpose and limitation of EEW in Japan and the proper actions to be taken (Kamigaichi et al.2009).

A general framework for deciding whether or not to apply an automatic early warning system was developed using cost – benefit analysis in the FP6 SAFER Project (Iervolino et al, 2009). Then general method can be applied with different constraints to each particular end user need.

Real-time seismic risk assessment could have been used to assess the risk to the population at any given time, based on the forecasted seismicity. Recently, a novel approach was proposed (vanStiphout et al., 2010) that combines real-time probabilistic forecasting based on the site-specific time-dependent seismic hazard (e.g., Gerstenberger et al., 2005; Marzocchi and Lombardi, 2009) with information on the fragilities and exposure at risk. To add a quantitative baseline for risk decision making, cost-benefit analysis (CBA, e.g. Marzocchi and Woo, 2009) is then used to translate this probabilistic forecast to a Boolean indicator - take or not take an action - which then can be used by decision-makers as an important input during an ongoing seismic swarm, or in the aftermath of damaging event when the buildings are potentially weakened and rapid decisions about their usability are needed. The CBA thus confirms the decision of 'no evacuation' taken by the Italian civil protection in the hours and days preceding the Mw 6.3 mainshock occurred at L'Aquila in 2009.

The method introduced by REAKT partners ETHZ and INGV (van Stiphout et al. ,2010) suggests that the current generation of forecasting models is not good enough to warrant evacuation as a mitigation action. This result is to us a strong motivation to propose a 2nd generation of earthquake forecasting models with a higher probability gain over the background probability,

2. MAIN HIGHLIGHTS OF THE REAKT PROJECT

The focus of the REAKT project was the development of operational methodologies of real time seismology and the demonstration of their effectiveness when applied to different targets. A part of the activity was however dedicated to better understand basic principles of earthquake generation and damage production needed to improve the capacity of forecasting the size of an event and the expected damage in a given site. An important part of the project was dedicated to elaborate principles and procedures of rapid decision making under uncertainties.

In the following pages, a short overview of the main achievements of REAKT is given. The details of each achievement can be found in the quoted references. A comprehensive description of all the results of the project is given in the deliverables archived in the project website (www.reaktproject.eu).

The highlights described in this report follow the logic structure of the projects: from progress in the knowledge of the earthquake generation process (HL 1-4), to short term forecasting (HL 5-6) to progresses in early warning methodologies (HL 7-11), to time dependent vulnerability assessment (HL 12-14), to procedures of decision making (HL 15-16) finally to applications (HL 17-23) and capacity building (HL 24).

I. NEAR FAULTS OBSERVATORIES ARE STRENGTHENED AND NEW METHODS REDUCE UNCERTAINTIES FOR EVALUATION OF CLUSTERED MICROSEISMICITY.

A proper evaluation of the short term probabilities of occurrence of a large earthquake during a seismic swarm relies on a reliable understanding of the underlying mechanical process. Is it simply self-triggering, through static or dynamic Coulomb stress interaction between seismic ruptures? Or is it forced by fault creep, or alternatively by pore pressure migration?

To help answering these questions REAKT improved the multi-parameters instrumentation existing in the Near Fault Observatories (NFO) of Corinth, Marmara sea and Valais, installing strain-meters, electromagnetic and geochemical stations. As the solution of the problem requires the analysis of long time series, the signals from the new installed instrumentations gave a minor contribution during the three years duration of the project.

It was thus essential to infer as much as possible from the micro-seismicity alone.

The earthquake source size is commonly determined analyzing seismic records in the spectral domain (inversion of corner frequency assuming an omega-square source model) after inversion of the attenuation parameters. This was carefully done for the three newly instrumented NFOs of Valais, Corinth, Marmara as well as for Irpinia (e.g., Edwards et al. 2013, Zollo et al. 2014). For these NFOs, the resulting stress drop shows scale-independent values of 1 MPa (0.1-10 Mpa range) for Valais, Irpinia and Marmara. For Corinth, stress drops are higher, and present a slight increase with source dimension, from 0.3 MPa for M=1, to 30 MPa for M=3 (Matrullo et al. 2014); some multiplets show the same trend, with a 10 fold increase in stress drop values (Godano et al., 2014).

A new developed method of reduction of source size uncertainties for dense clusters using a new two steps Bayesian probabilistic spectral inversion (Godano et al. 2014) was applied to a persistent multiplet in Corinth (Figure 1). It shows a complex spatial structure with a mostly connective rupture zone. The statistical properties of the spatial distribution of cumulative slip indicate the constraints on the mechanical loading of the cluster (Dublanchet et al. 2014).

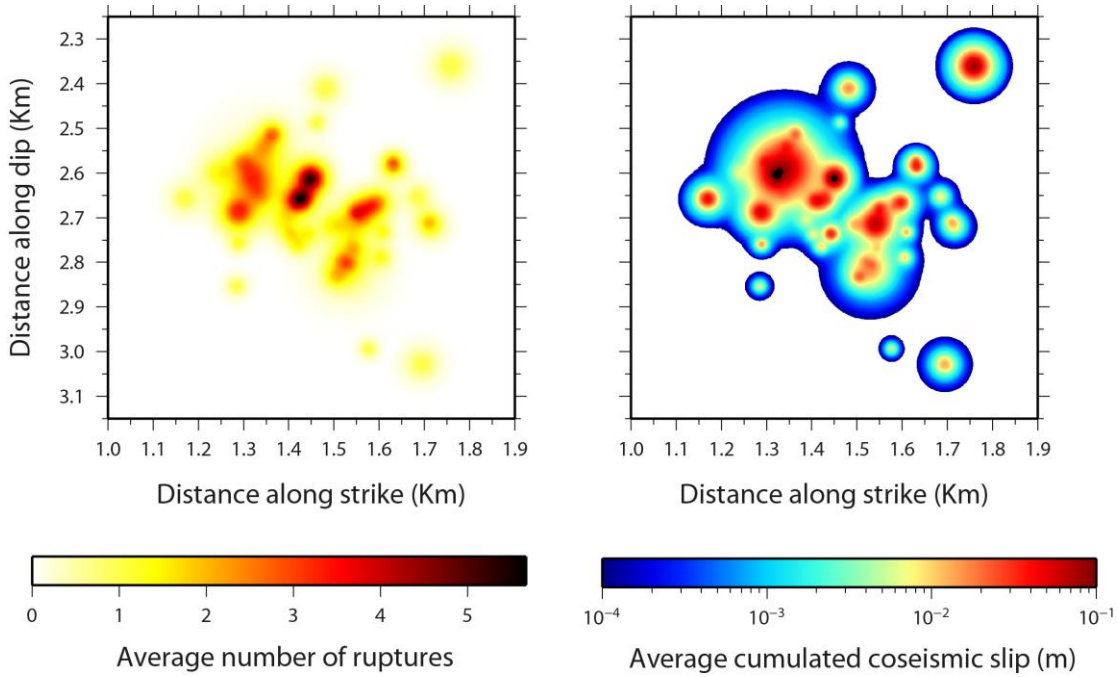

Figure 1 Fine structure of a persistent multiplet in Corinth from a Bayesian inversion. *(from Godano et al. 2014)*

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II. EVIDENCE FOR LOCKED AND CREEPING SECTIONS OF THE MAIN MARMARA FAULT APPEARS TO HAVE LOCKED SECTIONS AND CREEPING SECTIONS

The seismicity of the North Anatolian fault under the Marmara sea (Main Marmara Fault, MMF) has been analyzed in details to provide insights about the loading state and evolution of this major regional seismic gap. The last destructive earthquake on it occurred in 1755, leading to high probabilities of a similar event in the coming decades, owing to the 2 cm/year of accumulating slip deficit inferred from geodesy.

The principal issue for the seismic hazard assessment is thus to know whether the MMF is totally or partly locked. Locked segments are the expected places of the large coseismic slip, while continuously creeping segments may slow down, reduce, or even stop the seismic rupture – thus reducing the local shaking hazard.

A new, more complete seismic catalogue has been produced for the period 2007-2012, using advanced methods with high resolution location and a variety of source studies.

This study shows a heterogeneous distribution, along the MMF, of (1) the seismicity rate and clustering mode, (2) the slip rate inferred from seismic moment rate release, (3) repeater source distribution, and (4) b values, provide indirect but collectively strong evidence in favour of a locked Kumburgaz segment, surrounded to the west by a creeping Central segment, and to the east by a partially locked Cinarcik segment. (Figure 2)

As a consequence for the medium term hazard (decades), the seismic rupture of the locked segment alone (45 km long, 12 km deep) would produce an M~7.3 earthquake. This heterogeneous fault model should help defining the appropriate friction of numerical rupture models for simulating dynamic propagation, improving the first scenarios of dynamic ruptures developed by Aochi (2014). Also, the simple geometry and the very low activity along the threatening Kumburgaz segment are the signature of very little stress heterogeneities along the fault plane. Therefore it is a good candidate for supershear rupture [Bouchon and Karabulut , 2008] if the event was initiated at the transition between the Central and the Kumburgaz basins.

These results also provide some clues for guiding future research on short term earthquake forecast (days to months) based on the monitoring of seismicity. Indeed, seismic space-time clustering at the edge of the locked Kumburgaz segment should deserve particular attention. More specifically, if repeating foreshocks were expected to develop as a nucleation phase similar to that of the 1999 Izmit earthquake [Bouchon et al., 2011], they should emerge at depth below or at the boundaries of the segment.

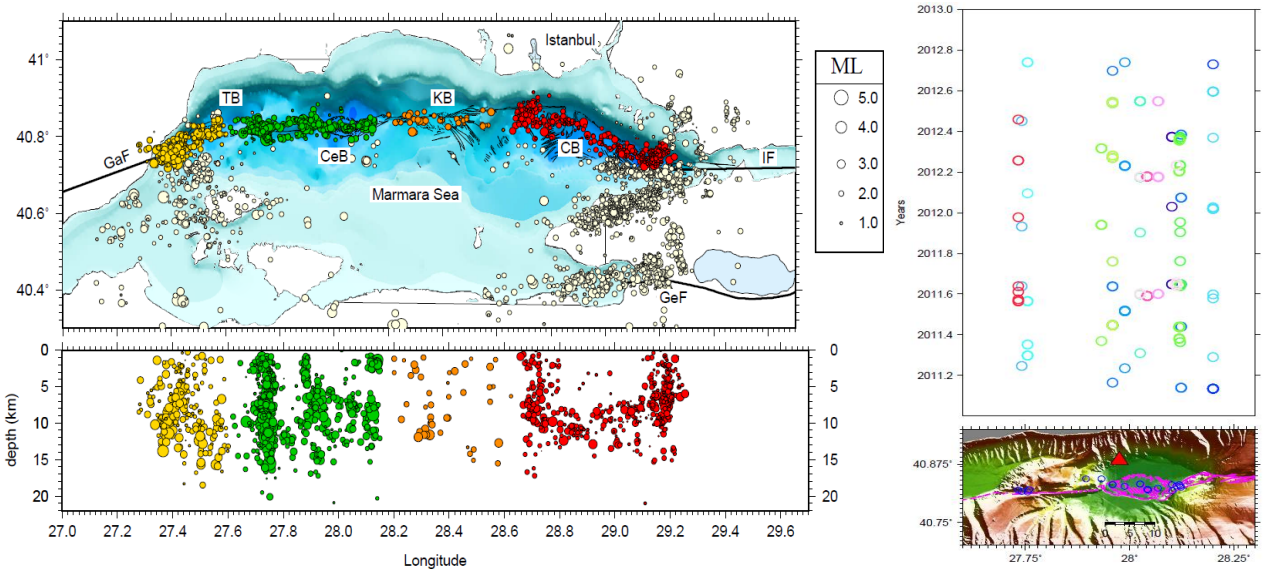

Figure 2. Left: map and vertical section of the 2007-2011 relocated seismicity in Marmara sea The colours correspond to the four main fault segments along the Main Marmara Fault. Right: time-longitude plot of the seismic repeaters (identified by colors) of the Central segment.

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III. EVIDENCE AND ROLE OF FLUIDS FROM MICRO-SEISMICITY CLUSTERING IN THE CORINTH NEAR FAULT OBSERVATORY

Detailed analysis of high rate of micro-seismicity in the Corinth area has shown that creep transients are probably not the dominant driving process of the micro-seismicity (Lambotte et al.2014) and has confirmed and characterized the role of fluids in the triggering. The seismic clusters, 1 to 10-15 km in size, lasting weeks to months, can provide daily seismicity rates of hundreds of detected events. The largest ones show clear migration of hypocenters, at the rate of 1 to 100 m/day, and diffusivities of 0.01 to 1 m^2/s, typical of pore pressure diffusion in crustal rocks, as was first shown for the 2001, 2002, and 2004 swarms (Pacchiani and Lyon-Caen, 2010; Bernard et al., 2006; Bourouis and Cornet, 2010). The REAKT project, accurately relocated hypocenters, and investigated further the space-time characteristics of the 2004, 2009 and 2013 major swarms.

For the 2004 swarm, the accurate relocation of the events reveals an internal diffusion process within these small faults, again with typical diffusivity values for crustal rocks. Interestingly, the diffusivity increases with the size of the fault, suggesting more permeable volumes for larger faults, and appear larger near the center of the seismic layer, suggesting a higher damage there (Figure 3)

This 2004 swarm however also provide some indirect evidence for an accompanying creep. A complex interplay between pore pressure and creep instabilities thus seems to have lead the 2004 swarm activity.

The 2013 swarm, lasting 2 months, activated the root of the old Pirgaki fault around 8-9 km in depth, 5 km south the main active zone of the rift axis (Kapetanidis et al., 2014), with many felt events (Mmax=3.7). It presented two well separated propagation phases, each over 2 km, again with typical crustal pore pressure diffusivities of 0.1 m^2/s.

No strain transient could be detected during these large swarms on the borehole strainmeters, located within 15 to 20 km away (Canitano et al, 2013a&b), which sets an upper limit equivalent to M~5 to the aseismic strain source. The source of high pressure fluids may be a fractured reservoir just beneath the microseismic layer, as suggested by tomographhic images (Gautier et al., 2006), fed from below by the dehydratation of the African subducting plate, at 50 km in depth (Bourouis and Cornet, 2009).

The detailed space-time analysis of all these swarms in Corinth is thus revealing some major permeable channels, through and along the dominant fault system. The new incoming data will allow us to progressively complete this picture, quantifying the permeability and pore pressures, as well as creep. This will be necessary for any attempt for predicting the evolution of such transients, and for evaluating their contribution to the short term probability of a large earthquake.

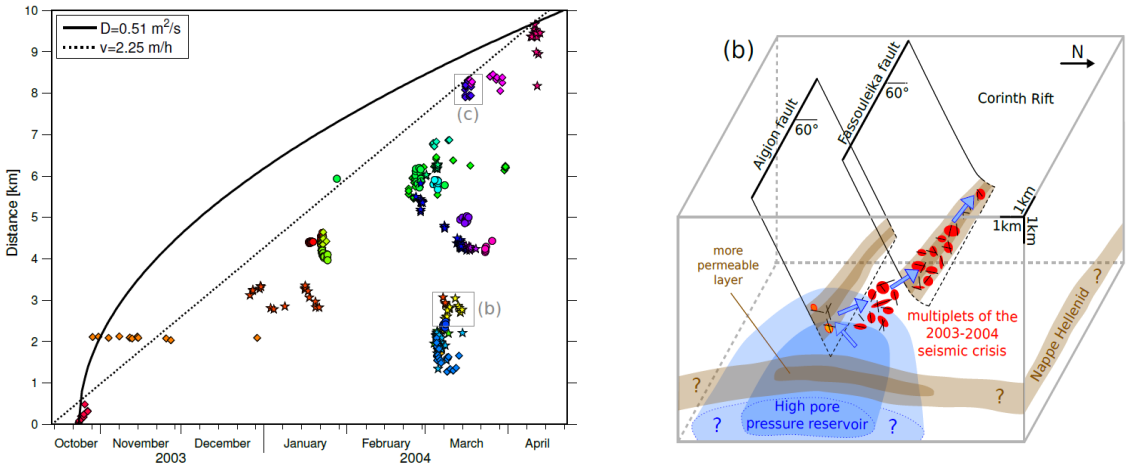

Figure 3 Migration of the 2004 swarm. left: distance (km, Eastward) versus time of epicenters. Colors are for distinct multiplets. right: sketch of the swarm activity. Red are for the multiplets. Blue arrow is inferred fluid migration.

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IV. NEW EVIDENCE FOR CREEP TRANSIENTS IN SEISMOGENIC SUBDUCTION INTERPLATE CONTACT

The detection and quantification of transient creep (or slow slip event, SSE) on large areas of seismogenic faults is expected to improve our understanding and modeling of seismic swarms, and more specifically for foreshocks and for the nucleation phase of large earthquakes (Bouchon et al., 2013). In the Near-fault Observatories studied in REAKT (Valais, Irpinia, Marmara, Corinth), up to now only Corinth provided evidence for such events, accompanying intense seismic swarms in 2002 and 2004. This lead us to focus on subduction areas, more prone for SSEs, with two approaches: one, indirect, with seismic catalogues, the other directly with high resolution geodetic measurements.

For the seismicity analysis, a probabilistic method has been developed to detect swarms that are likely caused by a transient increase in background rate, hence in aseismic stress loading. The detection is declared when the average earthquake productivities, depending on magnitude, distance, and time delay, after having been adjusted for the region, are too low to explain the observed level of activity (Marsan et al., 2012, 2013). This method was in particular applied to the japanese subduction in the region of the M9, 2011 Tohoku earthquake (Figure 4). Nine swarms were found for the 1990–2011 period, the last one being the 2-months foreshock swarm of the Tohoku shock, and the related seismicity rate increased by factors of tens to hundreds. The 2-days short term precursory sequence, however, appeared as a typical mainshock aftershock sequence of the M=7.6 foreshock. One anomalous swarm, out of the 9 detected, was thus followed by the M9 Tohoku earthquake, which represents a huge probability gain for such a rare event. When located on the subduction contact, their most likely cause is the occurrence of an SSE.

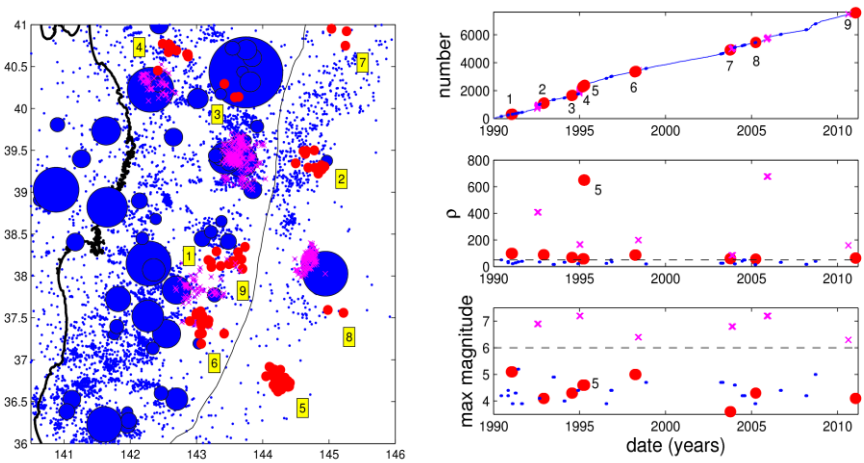

Figure 4. Seismicity and swarms in eastern Tohoku. Left: seismicity map of eastern Honshu. Blue dots: regular seismicity. Red dots: anomalous swarms. Number in yellow square: identifier of cluster of swarm. Pink: anomalous swarms with mainshock. Right: clusters of anomalous swarms. Top right, cumulative number of all events; middle right, factor in seismicity rate increase; bottom right , Mmax of the cluster. Pink crosses are for strong aftershock sequences.

In the northern Chile subduction zone, we succeeded into directly detect and characterize a sequence of SSEs, precursory to the M=8.2, April 1rst, 2014 Iquique earthquake (Boudin et al., 2014). This earthquake, which ruptured a small fraction of the 800 km long seismic gap, was preceded by a unusually strong sequence of moderate to large foreshocks (up to M=6.7), starting in January 2014. The area was densely monitored by seismological and geodetic (GPS) stations from

the IPOC array, which allows to resolve in great detail the precursory sequence (Ruiz et al., 2014; Schurr et al., 2014; Kato et al., 2014), raising a strong controversy on weak evidence for aseismic slip for GPS records.

We analyzed the records of our two-component longbase hydrostatic tiltmeter, located in the Santa Rosa mine near Iquique. We corrected them for tide, atmospheric pressure effects, and a small secular trend, and removed the coseismic steps from the foreshocks. The residual signal shows two well resolved tilt anomalies of about 50 nradians, the first one starting with the January foreshock sequence (Fig. 5 right). With the additional constraints from the reported small GPS displacements, the sources of the tilt appears to be located near the main asperity of the largest aftershock (April 2nd, M=7.6), beneath the coast line.

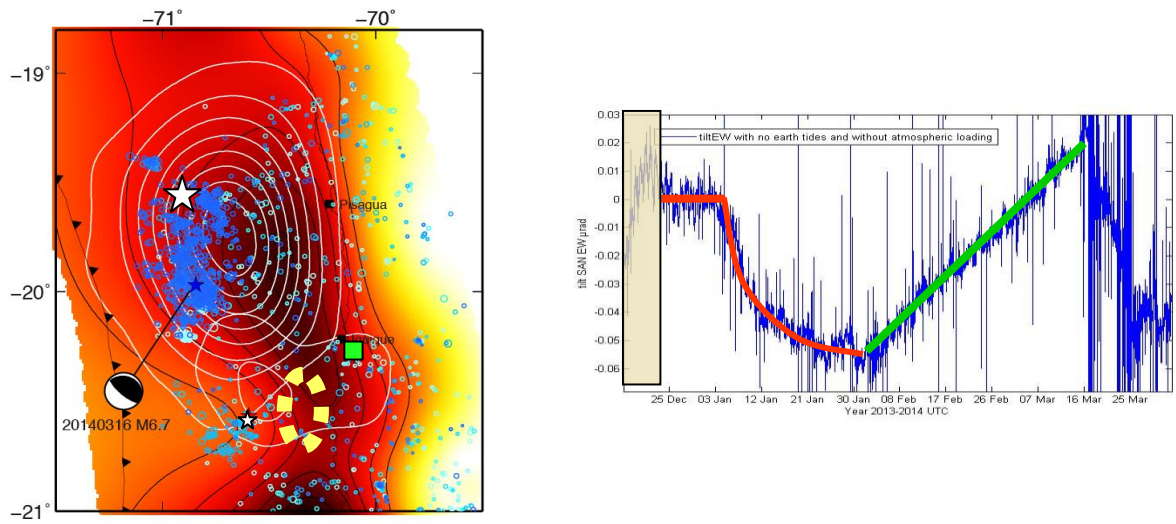

Figure 5 . The 2104 Pisagua (Chile) precursors. Left: (Modified from Schurr et al 2014). Background colors (yellow-red-black): increasing coupling from GPS. Blue dots: foreshocks. White stars:hypocenter of mainshock and main aftershock. Green square : Santa Rosa tiltmeter. Yellow dotted ellipse: approximate area of precursory SSE sequence. White contours are the main shock (north) and main aftershocks (south) iso-values of coseismic slip. Right: 3 months of the corrected precursory tilt of the East component. Red: fit to the first SSE; green: fit to the second SSE.

Our tilt records also allowed us to exclude the existence of the large slow slip event in the March 16 foreshock zone proposed by Ruiz et al. (2014. However, due to the large distance of the tiltmeter site to the mainshock epicenter, one cannot rule out a nucleation phase with an equivalent moment magnitude less than about 6.8. In conclusion, our tiltmeter observation clearly revealed that the Iquique 2014 foreshock sequence consisted of a cascade of cross-triggered seismic and aseismic slip events, migrating on the weakly coupled interplate surface inferred from GPS.

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V. A MODULAR CODE FOR OPERATIONAL EARTHQUAKE FORECASTING (OEF)

Just after the Mw 6.2 earthquake that hit severely L'Aquila, on April 6 2009, the Civil Protection nominated an International Commission on Earthquake Forecasting (ICEF) that paved the way to the development of the Operational Earthquake Forecasting (OEF), defined as the "procedures for gathering and disseminating authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes". Although no time frame is explicitly mentioned in the OEF definition, the time variability of seismic hazard is particularly evident in the short-term, i.e., in time windows of days/weeks; the short-term space-time earthquake clustering is indeed the most significant feature of the earthquake occurrence process.

REAKT contributed to establish the first OEF system for the Italian territory that fully accomplished the ICEF's requirements. The OEF_Italy system is planned to provide the authoritative scientific information required by OEF.

The philosophy of OEF_Italy system rests on few basic concepts: transparency, reproducibility and testability. The authoritativeness of a source is usually assigned by the interested stakeholders. Of course, delivering robust and credible information is of paramount importance to become authoritative source for a wide range of potentially interested stakeholders like laypeople. According to the recommendations reported in Jordan et al. (2011), authoritative information should be based only on earthquake forecasting/prediction models that are under evaluation by independent experts, like, for example, in the Collaboratory for the Study of Earthquake Predictability experiments (Jordan, 2006; Zechar et al., 2010). These experiments are running in Italy, California, Japan, part of China, New Zealand, Western Pacific, and over the whole globe. Their main goal is to evaluate the performance of each earthquake forecasting model comparing the forecasts with the real seismicity in purely forward experiments (Schorlemmer et al., 2007). CSEP is continuously improving and strengthening the models evaluation phase and increasing the class of models put under test. We think that CSEP represents the most advanced framework to objectively test the models' forecasting capability. Such an evaluation is important to justify and explain how forecasts for operational purposes are obtained. For now OEF_Italy considers three different models that are all based on the description of space-time earthquake clustering (Lombardi and Marzocchi, 2010; Falcone et al., 2010; Woessner et al., 2010).

In the OEF_Italy system, the scientific information derives from the best forecasting model. The definition of the best model is particularly important in operational science and it deserves careful

discussion (Marzocchi and Zechar, 2011). Intuitively it may be argued that the best model is simply the best performing model in a test experiment. Actually, this is not necessarily true. In recent papers, Marzocchi et al (2012), Rhoades (2013), and Taroni et al (2014) showed that ensemble models are preferable to any single model, because their forecasting capabilities are usually superior (and never significantly worse) to the capabilities of the best single model available. This approach has many similarities with successful forecasting schemes in other fields (see Silver, 2012, for a discussion on this topic). Ensemble models are usually obtained through a weighted average of all models and the weights are related to the past forecasting models' performance. Using an ensemble model, we may also estimate the epistemic uncertainty which is represented by the variability of forecasts among the models.

In summary, this philosophy of work allows the OEF_Italy system to: i) be fully transparent and the results are reproducible by anyone; ii) be open to any modelers who want to contribute, provided that the model is under test in at least one CSEP experiment; iii) minimize scientific controversies, because the use of ensemble models based on objective statistical evaluation of the models performance reduces significantly the subjectivity that is implicit when choosing the model to be used.

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VI. SHORT TERM EARTHQUAKE OCCURRENCE MODELS BASED ON INFORMATION ABOUT PRE-EXIXTING FAULT STRUCTURES AND STRESS STATE FOR SHORT AND INTERMEDIATE TERM FORECASTS

There are two main approaches to earthquake forecasting, the ETAS (Epidemic Type Aftershock Sequence, e.g. Ogata, 1988; Ogata and Zhuang, 2006) and STEP (Gerstenberger et al., 2005) models that are purely statistical methods. In contrast, the Coulomb method is an only physics based approach that calculates the static stress changes due to earthquake slip in the nearby region. REAKT has worked out a new method for forecasting aftershock rates that combines the statistical STEP approach with the spatial constraints provided by the Coulomb stress changes.

Once performed sensitivity tests it was seen that incorporating the physical constraints from Coulomb stress changes can increase the forecasting power of a statistical model but that good data are required if prospective forecasts are to be implemented in practice. In particular, despite lack of dependence of the new hybrid model on the magnitude of the stress change, the performance of the model strongly depends on the quality of the slip distribution. Finally, a modified version of the hybrid model has been developed in which the generic Coulomb redistribution parameter (93% of rate in positively stressed regions) is replaced with a variable value based on observation in the learning period. This variant generally outperforms the STEP model, even when the Coulomb stress pattern is poorly constrained. If confirmed by further research, this suggests that it may be possible to develop a robust Coulomb/STEP model that is relatively insensitive to data quality.

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VII. EVIDENCE FOR A DIFFERENCE IN RUPTURE INITIATION BETWEEN SMALL AND LARGE EARTHQUAKES

The process of earthquake rupture nucleation and propagation has been investigated through laboratory experiments and theoretical modeling, but a limited number of observations exist at the scale of earthquake fault zones. Whether the magnitude of the earthquake can be predicted while the rupture is ongoing represents an unsolved question.

The evolutionary approach applied to the source parameter estimation is based on the progressive expansion of the P-wave time window and of the distance range until the expected arrival of the S-waves (Colombelli et al., GRL 2012). The ground motion records of the 2011 Mw 9.0 Tohoku-Oki earthquake have been first analyzed, in order to investigate the suitability of existing regression laws between early warning parameters and magnitude for such large events (Figure 6). The application of this methodology has shown that the two Early Warning parameters have the potential to reproduce the rupture process of the ongoing earthquakes, but wider time/distance observation ranges have to be considered when dealing with large events.

The Analysis of a larger data set of Japanese earthquakes in the magnitude range 4<M<9, has shown that the evolution of P-wave peak displacement with time is informative regarding the early stage of the rupture process and can be used as a proxy for the final size of the rupture.

In fact a rapid initial increase of the peak displacement was evident for small events and a slower growth for large earthquakes. **Our results indicate that earthquakes occurring in a region with a large critical slip distance have a greater likelihood of growing into a large rupture than those originating in a region with a smaller slip-weakening distance.** (Figure 7,8).

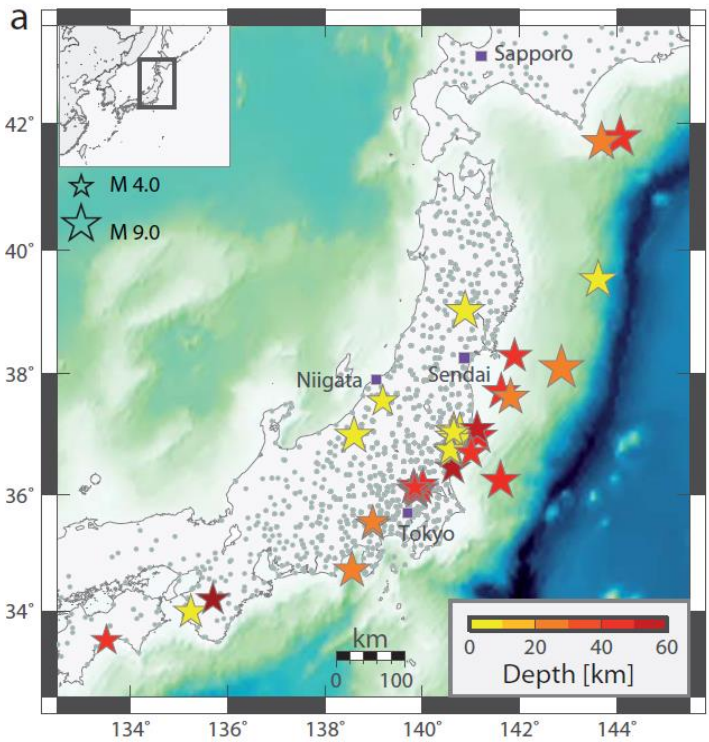

Figure 6 The map shows the distribution of stations used in this study (small green circles) and the epicentral locations of the 43 selected events (coloured stars). The size of the star is proportional to the magnitude, and the colour represents the source depth. The black bar at the bottom right denotes a 100 km length.

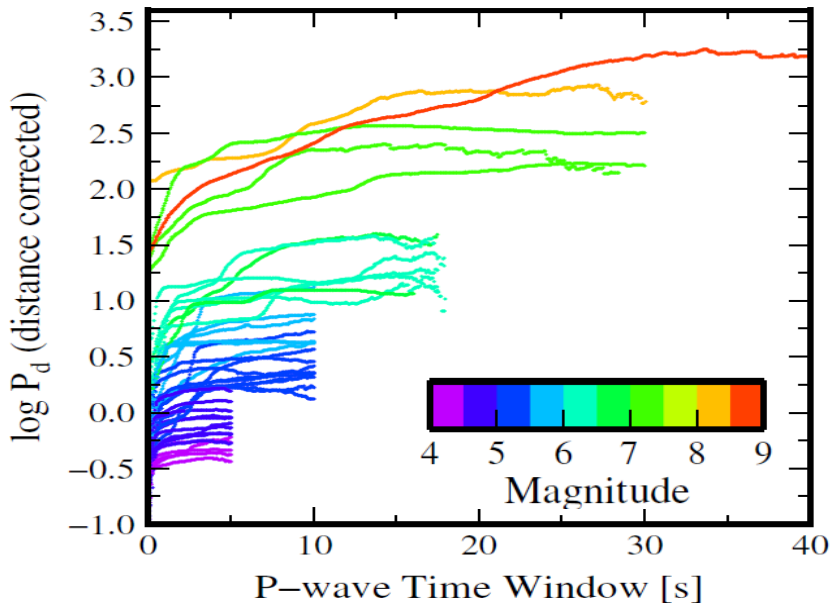

Figure 7. Average logarithm of the Pd vs. PTW (LPW) curve for each analysed event. The y-axis represents the average logarithm of Pd, obtained by using all the available data at each time point, after correcting individual values for the distance effect

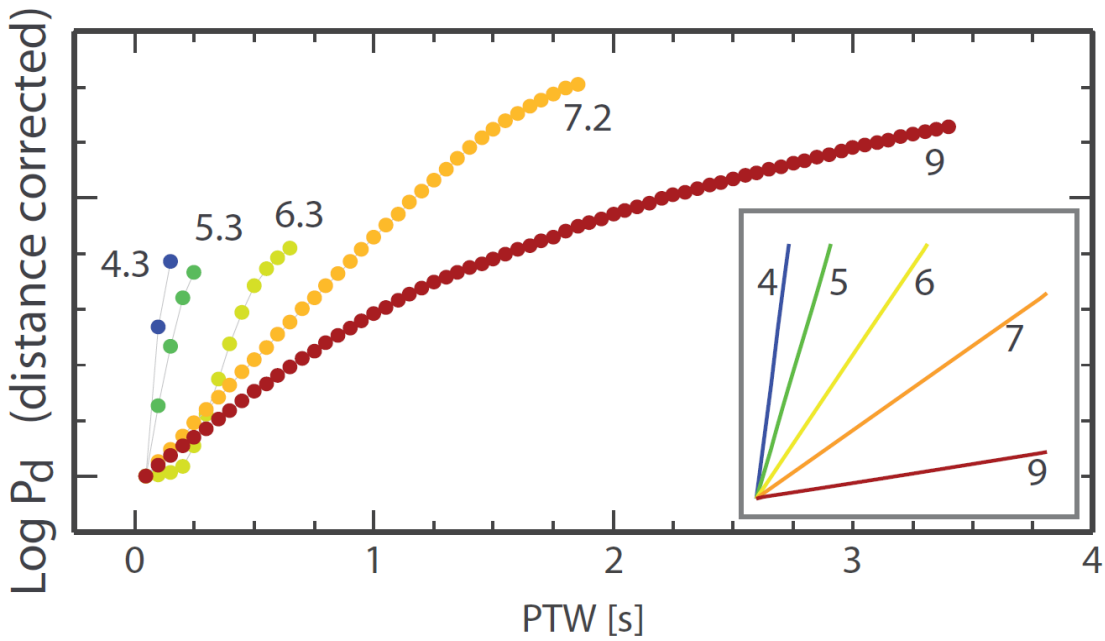

Figure 8. Magnification of the LPW curve until time T1 for representative events. A common initial value has been assigned to compare the shape of the curves. The insert box shows the expected initial slope of the LPW curve for different magnitudes given the observed trend of B1 with magnitude

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VIII. REAL-TIME IMAGING OF THE EARTHQUAKE RUPTURE USING HIGH-RATE GPS AND STRONG MOTION DATA

By combining the complementary advantages of conventional inversion and back-projection methods, we have developed an Iterative Deconvolution and Stacking (IDS) approach for imaging earthquake rupture processes with near-field complete waveform data. This new approach does not need any manual adjustment of physical (empirical) constraints, such as restricting the rupture time and duration, smoothing the spatiotemporal slip distribution, etc., and therefore has the ability to image complex multiple ruptures automatically. The advantages of the IDS method over traditional linear or non-linear optimization algorithms are demonstrated by the case studies of the 2011 Tohoku earthquake (Figure 9). For such a large earthquake, the IDS method is considerably more stable and efficient than previous inversion methods. Additionally, the robustness of this method is demonstrated by comprehensive synthetic tests, indicating its potential contribution to tsunami and earthquake early warning and rapid response systems. It is also shown that the IDS method can be used for teleseismic waveform inversions. For the earthquakes discussed here, the IDS method can provide, without tuning any physical or empirical constraints, teleseismic rupture models consistent with those derived from the near-field GPS and strong-motion data.

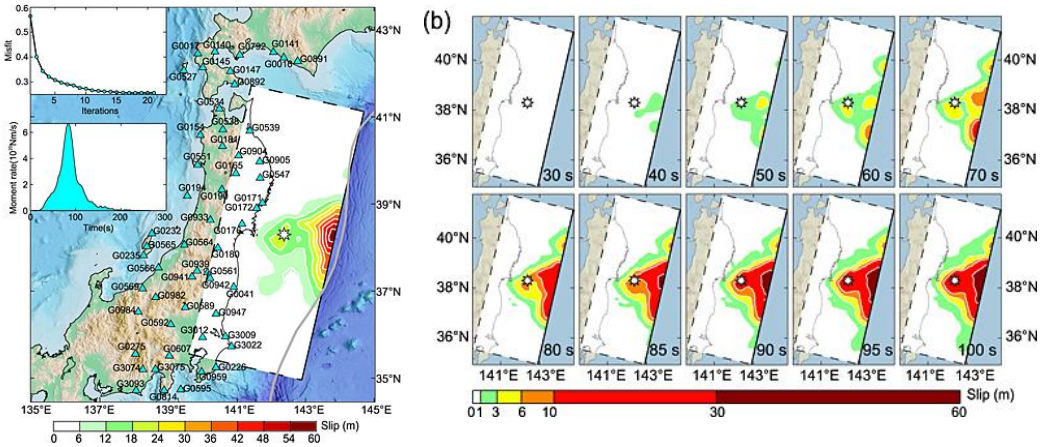

Figure 9. IDS source imaging results for the Tohoku earthquake using the high-rate GPS data. (a) The misfit curve of the iterations (upper left) and the source time function (lower right), GPS stations (cyan triangles), and the surface projection of fault slip distribution. (b) Snapshots of the temporal variations of the fault slip distribution projected to the surface. Stars in (a) and (b) denote the epicentre.

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IX. MOBILE NETWORK FOR EARLY WARNING/RAPID RESPONSE

In order to investigate the most suitable communications typology for sending real-time strong motion data acquired by a cluster of GFZ-WSU, the new development of the SOSEWIN system was installed in an urban environment, namely the Steglitzer Kreisel building (119 meters high, 30 floors) in the district of Steglitz, Berlin. 16 GFZ-WSU equipped with MEMS were installed in this building every 2nd floor until the roof. In order to provide synchronized timing for the stations, an indoor GPS system was used. The following communication typologies were investigated for sending the data to the GFZ, located at a distance of about 20 km:

VSAT - Very Small Aperture Terminal (VSAT) systems that are satellite-based data communication systems.

WLAN - A wireless local area network (WLAN) link between the test site and the data management was established using directional antennas.

UMTS - The Universal Mobile Telecommunications System (UMTS), a third generation mobile cellular system.

The acquisition and transmission of data was performed for about one month. Although all three systems were found to be suitable for sending the real-time data from the test-site to the data center, for the purposes of the REAKT task 4.3, a combination of WIFI and UMTS offered the best compromise between flexibility and costs since a SOSEWIN type deployment can easily implement these communication typologies, while the relatively limited cost for transmission make them suitable for application before, during, and after a disaster.

In a subsequent step, a new multi-parameter real-time sensor network for early warning has been designed and different sensor combinations were tested, with the aim of exploiting the potential for different applications worldwide. Different sensors and sensor types have been identified which will allow the simultaneous monitoring and analysis of ground shaking (broadband seismometers, geophones or acceleration), deformation and displacement (GPS), optical sensors (camera picture streaming) and meteo- and hydro-monitoring (weather stations, tide gauge, pore pressure).Different means of analysis are under development and implementation, depending on the required lead time, either directly using the calculation capability of each single node that make up the self-organising network, or in the early warning centre. The sensors may be used in both permanent installations in high-risk areas, or as a temporary network during a task force mission following an event. While the technology used in the SOSEWIN -nodes enabled a more or less pure acquisition unit, the new hardware has greater computing performance (~1.7 GHz quad core processor, 2 GB RAM) and is capable of more sophisticated data processing and analyses steps directly on the nodes themselves in early warning systems.

Finally, a Webinterface for configuration, network information, monitoring the status of the acquisition and station location was developed, as well as software for on-site forecasting for damage level based on empirical relationships, and on-site real time forecasting of building motion using simplified structural models (Figure10).

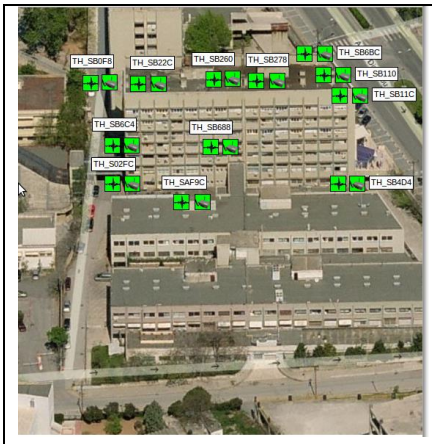	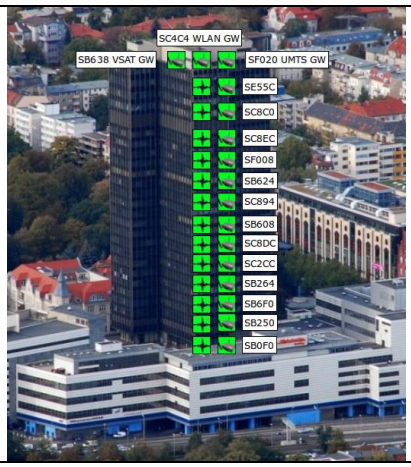	
Installation at test sites	Testing Communication	Development of a new Multi-Hazard SOSEWIN system

Figure 10. Several installation of SOSEWIN equipped with MEMS (the basis of the technological development carried out in WP4) have been performed within WP 7 "Strategic applications and capacity building" of REAKT. This includes the monitoring of the AHEPA hospital in Thessaloniki, Greece, a school in Naples, Italy, and in the Atakoy district and the IGDAS buildings in Istanbul, Turkey.

References

Parolai S., Bindi D., Boxberger T., Milkereit C., Fleming K., Pittore M., 2014. Suggestions for and perspectives of On Site Early Warning and rapid damage forecasting using single stations, SRL, submitted.

X. Citizen based alert: Flashsourcing, Twitter Quake Detection, Testimonies

EMSC has 3 main results in the course of the REAKT project. It has first implemented a citizen based alert for felt earthquakes which merges 2 complementary methods flashsourcing (real-time website traffic analysis) and Twitter earthquake detection performed by the USGS, which jointly detect felt earthquakes over the whole planet. The flashsourcing method has been extended to detect and map damaged area through the concomitant loss of Internet sessions.

The second result is the development of a prototype real time mapping system of earthquake's effects merging flashsourced and crowdsourced information (macroseismic data, geo-located pictures) as a decision support tool for the EMSC seismologist on call.

Finally, EMSC has promoted the deployment of citizen operated seismic networks in Europe (in collaboration with the Quake Catcher Network experiment in the US) with currently 2 networks in operation in Greece (Patrai and Thessaloniki), one being tested in Western Indies which have already produced a couple of dozens of seismic records (Figure 11, 12)

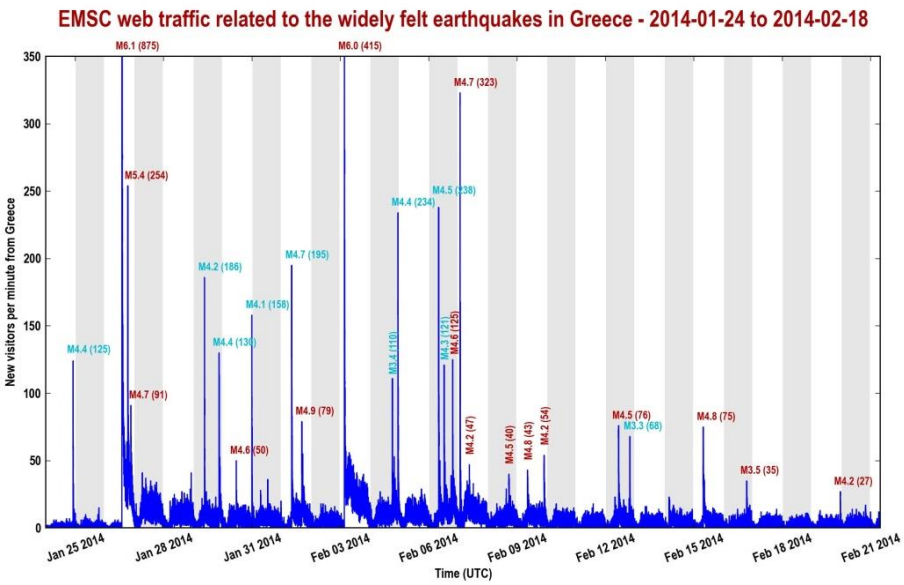

Figure 11. ESMC website traffic during the seismic crisis in Cephalonia (Greece). One can see on the top of the day and night variations peaks related to felt earthquakes. These peaks are caused by the massive affluence on EMSC website of eyewitnesses looking for earthquake information

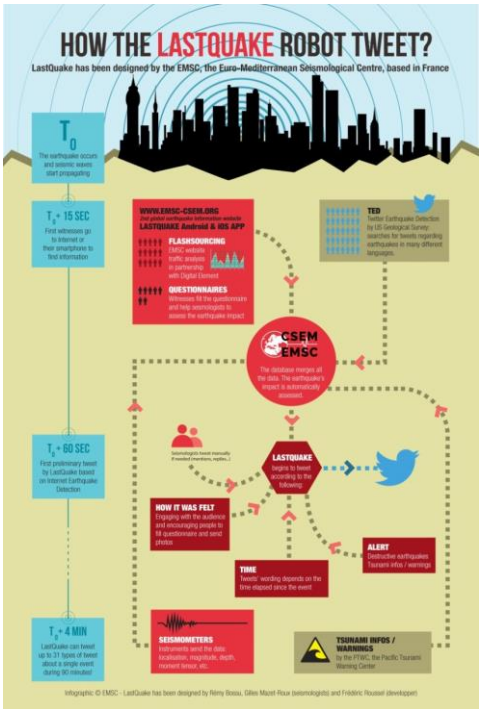

Figure 12. Schematic representation of the LastQuake QuakeBot, i.e. a program which automatically publishes earthquake information on Twitter. LastQuake is based on merging different source of information to automatically identify felt earthquakes and offer timely public information

References

R. Bossu, R. Steed, G. Mazet-Roux, F. Roussel and Caroline Etivant. The key role of eyewitnesses in rapid impact assessment of global earthquakes (in press)

R. Bossu and P. S. Earle, 2011. On the use of the Internet to collect earthquake information. Annals Geophysics, Vol. 54 (6), 2011, pp. 672

XI. REDUCING THE BLIND ZONE – FASTER, MORE RELIABLE EEW ALERTS

The ETH team, in collaboration with Caltech, have developed an innovative framework for Earthquake Early Warning that promises to seamlessly combine single-station and network methods (Meier et al, 2014). We use a filter bank approach to decompose in realtime earthquake signals across the frequency band (see Fig 13). By matching the amplitudes in our observed frequency bands with the most similar amplitudes contained in comprehensive near-field database of earthquake ground motions, we are able to estimate event magnitude and distance from a single station from only 0.5s after first signal detection, and very clearly distinguish between large and small events (see Fig 14). Our fully probabilistic approach allows us to 1) easily combine multiple stations and optimally use all available network information by using the full duration of all available time series and 2) assimilate other information such as Baysean priors (e.g. previous seismicity), not yet arrived data, and other independent Earthquake Early Warning estimates. By developing this approach, in a typically dense network, we can reduce first EEW estimates by between 2-5s compared to a 4 station network approach, substantially reducing the blind zone.

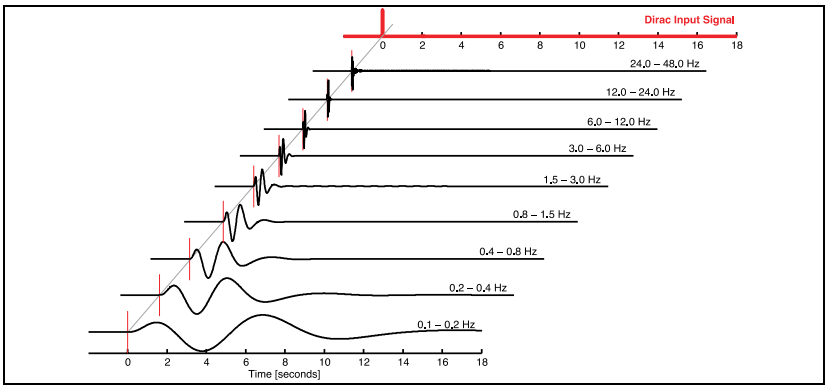

Figure 13-. Effect of the filter bank applied to a Delta function

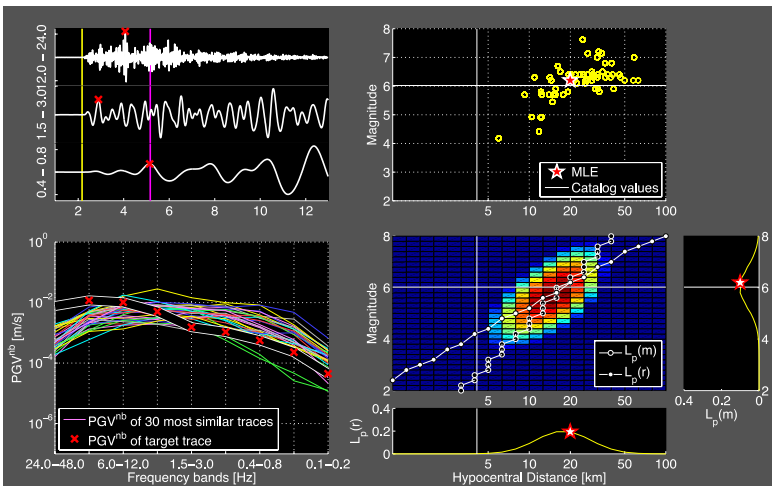

Figure 14. Summary of our approach, as applied to 1.5s of data from 2014 M6.0 Napa Valley Earthquake at 5km distance: a) raw time series and sample filters; b) peak amplitudes for filter bank, and 30 most similar records extracted from the database; c) spread of magnitude and distance for the 30 most similar records; d) bivariate Gaussian density function, and magnitude and distance likelihood profiles.

References

Meier M.-A., T.H. Heaton , J. F. Clinton, 2014, Offline Performance of the Filter Bank EEW Algorithm in the 2014 M6.0 South Napa Earthquake, Poster presentation, AGU Fall meeting, San Francisco, USA

XII. TIME DEPENDENT FRAGILITY CURVES CONSIDERING DETERIORATION MECHANISMS

The methodological framework for the derivation of the time and state dependent fragility curves for the elements at risk of different types of structures have been defined in detail. Fragility curves have been derived for the intact and degraded structures. The deterioration mechanisms that are taken into account are aging (namely corrosion effects) for the case of reinforced concrete (RC) buildings, bridges and shallow tunnels, while cumulative earthquake damage effects have been considered in the case of RC and masonry buildings and deep tunnels. Soil-structure interaction has been also investigated for RC buildings, wharves, and tunnels.

Some innovative results are that:

- A significant increase in the seismic fragility of the RC bridges has been observed over time due to corrosion of reinforcement bars. The work indicates that a refinement of the proposed European bridge fragility curves is essential considering aging as well as state dependent characteristics to apply reliable risk mitigation schemes.
- State-dependent fragility curves considering cumulative earthquake damage derived for RC buildings and Mansonry buildings confirm the importance of the history of earthquake loading to the effective fragility of the structure.
- A numerical model to derive analytical fragility curves for shallow and deep tunnels has been developed by using a nonlinear constitutive law both for the tunnel lining and surrounding ground.

XIII. TIME-VARIANT LOSS ESTIMATION DURING DIFFERENT PARTS OF THE EARTHQUAKE CYCLE

The project has also contributed to the development of methodology and tools to undertake time-variant loss estimation during different parts of the earthquake cycle: well before the earthquake, during foreshock sequences, during the main earthquake, and during aftershock sequence.

Concerning the loss estimation for risk assessment in the long term, history-dependent models for both hazard and vulnerability allow to incorporate time-variant information about the seismic risk; e.g., seismic history of construction site and degree of structural degradation. This allows, to evaluate the absolute failure probability, yet also conditional to different knowledge levels about the seismic history of the structure. The developed Life-cycle reliability analysis of deteriorating structures potentially accounts for both progressive aging and damage accumulation due to earthquake shocks

An approach based on stochastic processes has been developed for the loss estimation in emergency management and quantitative assessment of aftershock risk

This approach allows the building tagging to regulate occupancy in the post-event emergency phase and may represent a basis for handy tools enabling risk-informed tagging by stakeholders and decision makers (Fig.15)

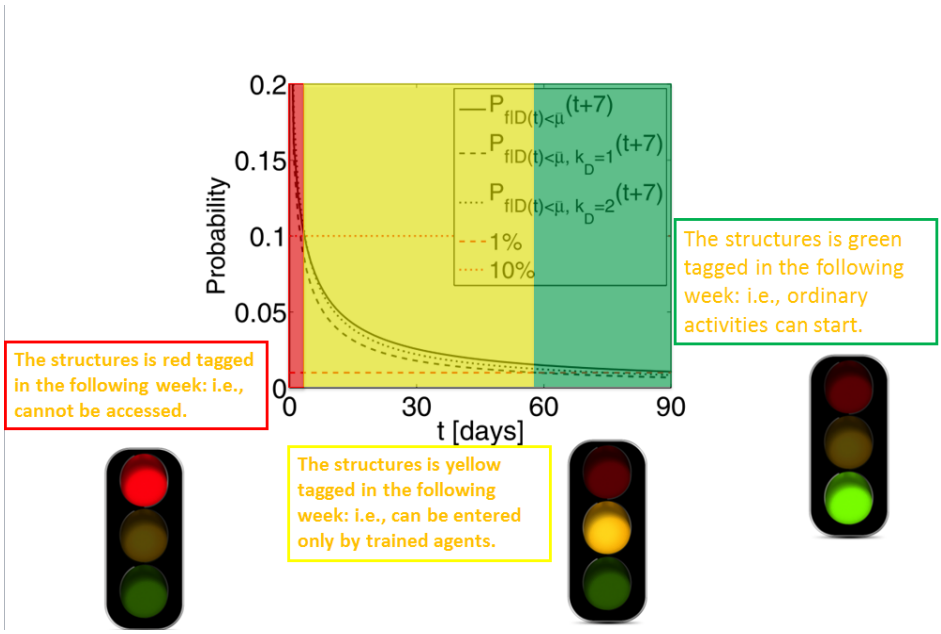

Figure 15- Example of building tagging for accepted thresholds of risk during an aftershock sequence. Seismic risk in the following 7 days conditional to different information on the structural history.

References:

Iervolino I., Giorgio M. and Polidoro B. (2014a) Sequence-based probabilistic seismic hazard analysis. Bulletin of the Seismological Society of America. DOI: 10.1785/0120130207

Iervolino I., Giorgio M. and Polidoro B. (2014b) Reliability of structures to earthquake clusters. Bulletin of earthquake engineering. DOI 10.1007/s10518-014-9679-9

Iervolino I., Giorgio M. and Chioccarelli E. (2013a) Closed-form aftershock reliability of damage-cumulating elastic-perfectly-plastic systems. Earthquake Engineering and Structural Dynamics, 43:613–625.

Iervolino I., Giorgio M. and Chioccarelli E. (2013b) Gamma degradation model for earthquake-resistant structures. Structural Safety, 45: 48-58.

XIV. DEVELOPMENT OF REAL TIME LOSS ESTIMATION MODELS FOR RISK ASSESSMENT THROUGH AN EEWS.

As the ultimate goal of an EEWS is to reduce losses due to earthquakes, the performance of the system should then be evaluated in terms of potential avoided losses. The idea behind this work is that the tuning of the system (i.e. how to set the alert threshold) should be made by using some sort of loss model, either – as the title suggests – in real time, or before the setting up of the system as an evaluation tool.

The loss models used for EEWS are different than traditional loss models because not all the losses are affected by the mitigation action, and thus only those losses that can be mitigated need to be estimated

The main issues are recalled here, in the format of a short workflow (See Figure 16) to be followed for loss estimations for EEWS:

1. Total losses: a first step is to list the types of losses that can occur if no actions are taken. Only a short and quick inventory is needed at this stage, i.e. no full assessment.
2. List of actions: then the envisaged actions should be listed; for example after a brainstorming session. In many cases, only one type of action will be retained, but sometimes, several actions might be possible (e.g. alarm to evacuate a building and another automated action).
3. Avoided and induced losses: for each action, a tree diagram, should be created in order to list: a) the potential avoided losses by the action and b) the potential losses induced by the action (mainly in case of a false alarm).
4. Decision framework: at this stage, it should be decided whether to use a loss balance (or cost-benefit analysis) or a multi-criteria analysis. As stated previously, in the first case, each item should be monetized whereas in the second case, more simple units can be kept.
5. Loss evaluation: depending on the chosen framework, the various losses identified at stage n°3 should be evaluated. One of the main difficulties at this stage is that losses avoided are a function of the hazard hence a table or a graph with ground motion on the x-axis should be the result.
6. Optional – Sensitivity analysis: Generally, such an evaluation involves a large number of hypotheses, involving potentially very large uncertainties. It is highly recommended to perform a sensitivity analysis for the main parameters in order to assess if the decision is altered by a change in the hypotheses.

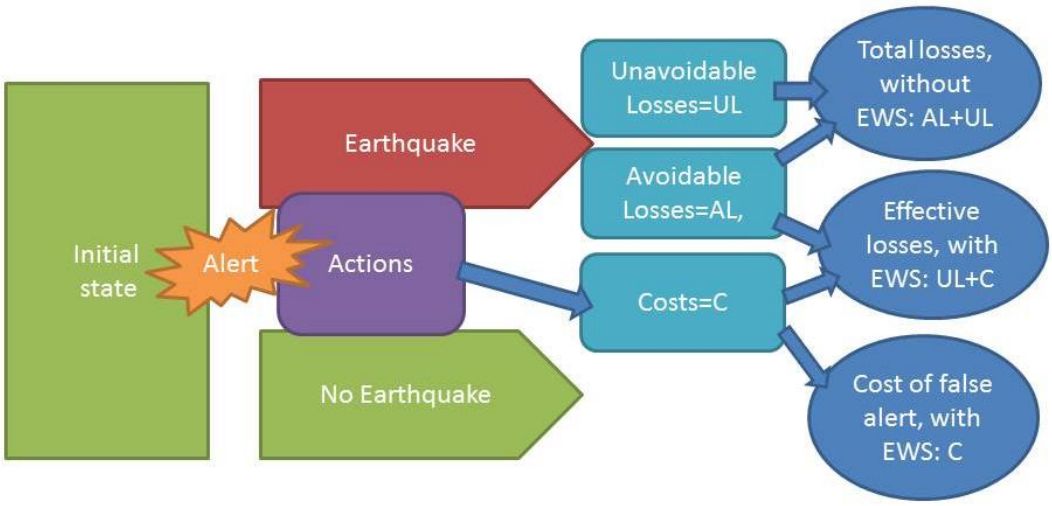

Figure 16 Scheme representing the various components of a loss estimation for EEWS

XV. FRAMEWORK FOR PARTICIPATORY DECISION MAKING USING EEW AND OEF METHODS

Operational Earthquake Forecasting requires decisions made in the course of a few days or even less whereas Earthquake Early Warning requires decision made in tens of seconds. Although the time scale is largely different both are strongly dependent on participation of different actors if they must be applied to protect large public.

Four distinctive roles can be defined within the context of decision making: the decision maker (or end user), who is the person or institution in charge of making the final decision on risk reduction (e.g. directors of a specific building); the stakeholders, who are the people impacted by the decision (e.g. workers in a specific building); the analysts, who provide guidance to the decision makers; and experts, who may help with specific aspects of the procedure. While the final decision is made by the decision maker only, it must gain acceptance from all stakeholders. All stakeholders have to be involved within a participatory decision-making process, at least as suppliers of information and opinions.

A procedure already developed for integrated water-basin management has been adapted to EEW.

The principal highlights of the Participatory Decision procedure developed by REAKT can be expressed in terms of the six key conclusions below, which constitute a practical and methodical basis for future implementation.

[1] Decisions should be Rational, Equitable, and Defensible.

OEF and EEW decisions should be made for sound reasons, give due regard to everyone's interest, and be explainable if challenged. These three requirements should underlie all participatory decision-making.

[2] Hierarchy of decision methods allows decision-making to be adaptable.

Decision methods have different domains of applicability. MAUT is appropriate for critical industrial installations, and transport infrastructure. Cost-benefit analysis is practical for other industrial and commercial enterprises, small businesses and residences.

[3] Confidence levels in Cost-Benefit Analysis can guide decision-making.

Uncertainty in estimating the costs and benefits of any OEF action can be taken explicitly into account and used to develop degrees of confidence that the benefits of any particular decision actually exceed the costs.

[4] Individuals can be their own personal decision-makers.

Exposed to a risk, people differ from each other in three crucial ways: the cost to themselves of avoiding the risk; their willingness to pay to avoid the risk; and their psychological locus of control over their risk environment.

[5] Individuals should be nudged to act in their own safety interests.

In a democracy, authorities are reluctant to compel citizens to undertake actions which may involve personal costs. However, authorities may nudge citizens to take voluntary action in the direction of increased personal safety.

[6] Risk analysts should intermediate between scientists and civil protection.

The task of earthquake scientists is to assess the seismological evidence, and evaluate the seismic hazard in probabilistic terms, taking account of the uncertainty. It is then the task of professional

risk analysts to undertake the formal computational decision analysis as a bridge to assist civil protection decision makers.

XVI. A TOOL FOR AUTOMATIC EEW DECISION MAKING

REAKT developed and applied to a demonstration case a tool to evaluate the efficiency of the implementation of an automatic EEW system. The tool is based on a combination of MAUT (Multi-Attribute Utility Theory) and BN (Bayesian Network).

Some tools have been developed in order to facilitate the more challenging steps. The first is the FAST diagram that help for identifying a comprehensive list of risk mitigation actions. The second tool is the Multi-Attribute Utility Theory (MAUT), which is one method for performing multicriteria analysis. This type of analysis allows taking into account different criteria for the assessment of each alternative. The MAUT also provides the ways for eliciting the preferences and for combining the valuation of each criterion in a unique utility function. Overall, MAUT is a robust alternative to the more commonly used CostBenefit Analysis. The third tool introduced in this report is the Bayesian Network (BN), which provides a robust and convenient way for dealing with conditional probabilities.

The combination of MAUT and BN has been tested on a demonstration case: the use of an Earthquake Early Warning System (EEWS) for automatically closing access to a bridge. The 2 main criteria assessed are “Maximize the safety of persons” and “Minimize the economic cost due to false alarms”. The example shows that for different decision-makers, the MAUT give different results, according to their own preferences. One interesting result is that in some cases, the best decision was not to install any EEWS because the costs of False Alarms were comparatively too high with respect to the gains in safety. Although more focused on the applicability to EEWS, short discussions on the applicability of the framework for Operational Earthquake Forecasting are also included. In conclusion the framework and the tools proposed seem applicable to a large number of cases for decision-making in earthquake risk reduction.

In conclusion, the case study showed that the proposed tools (a combination of Bayesian networks and MAUT) were effective in practice for applying the proposed decision making framework. One important aspect with respect to the state of the art is that it allows not only to set up the system but also to evaluate whether an EEWS is appropriate at all for the application.

XVII. END USER VISUAL DISPLAY FOR EARTHQUAKE EARLY WARNING

One of the final products of REAKT was the development of an Earthquake Early Warning Display (EEWD).

The EEWD is capable of: 1) supporting all alerts generated by the main EEW algorithms used in Europe (starting with VS and PRESTo); 2) allowing configuration for regionalisation of shaking parameter predictions - local ground-motion prediction equations (GMPEs), ground-motion to intensity conversion equations (GMICEs), amplification due to local site effects; 3) supporting future developments for configuration according to particular end-user requirements.

In addition to real-time operations, the EEWD supports 1) the recording and replaying of real-time earthquake alerts and 2) playback of manually produced planning scenarios.

The first public release of the software was made available to selected REAKT partners in January 2015 under GPL license: http://www.gnu.org/licenses/gpl.html version 2 or higher. The first public release and its source code are made publicly available on the REAKT website

http://www.reaktproject.eu/index.php?option=com_content&view=article&id=496&Itemid=58, along with some basic documentation about the main features of the EEWD. Future versions of the software will be maintained elsewhere (e.g. GitHub) and ensure community contribution to software development.. A screenshot of the EEWD GUI (Graphical User Interface) is shown in Figure 17.

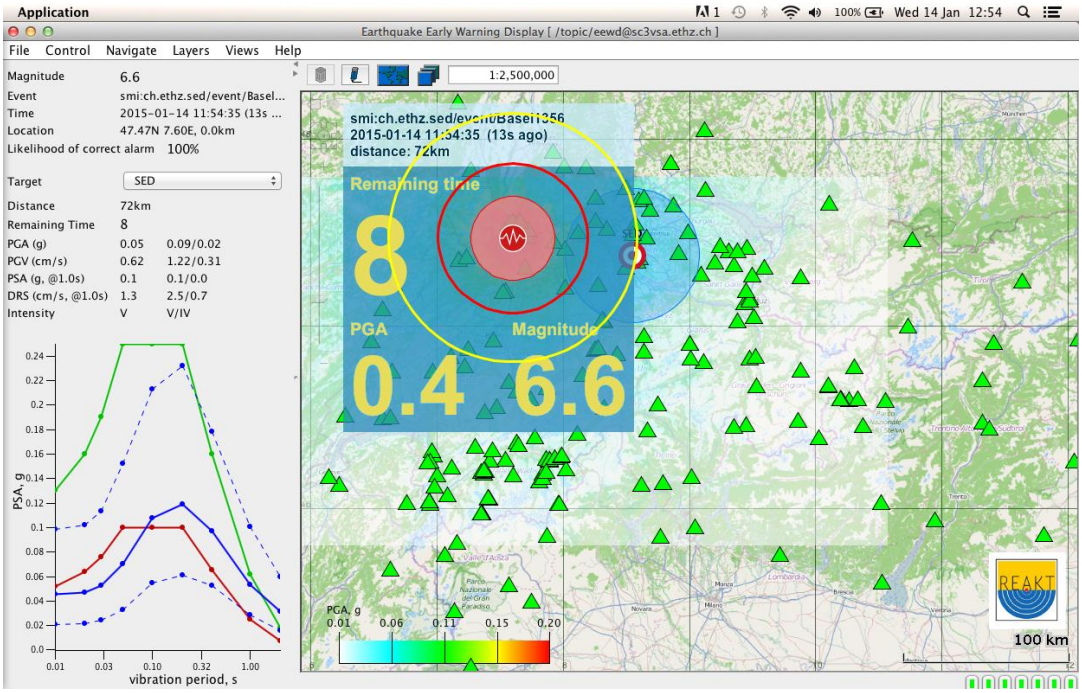

Figure 17 – Basic elements of a GUI aimed at real-time dissemination of earthquake alerts. The EEWD will also show uncertainties, if available, for magnitude, distance and shaking parameters. Magnitude and location uncertainties will be passed to the EEWD by the EEW algorithm in use. Uncertainly in the shaking parameters will be based on the st. err. of the prediction.

XVIII. ON THE USE OF EEW FOR REAL-TIME RISK MITIGATION AT NUCLEAR POWER PLANTS

REAKT implemented a module (VS/SC3) of the Virtual Seismologist algorithm (VS) that since summer 2013 issues messages to Swissnuclear. Using VS(SC3) at the SED implies that all real-time high-quality strong-motion stations (Cauzzi and Clinton, 2013) in Switzerland (in addition to all broadband Swiss stations and a large number of real-time streams that the SED continuously acquires from neighbouring countries) now contribute to the earthquake locations and rapid estimation of magnitude. As a consequence, the detection capabilities of the EEW algorithm are presently consistent with the completeness magnitude of the Swiss national seismic networks, *i.e.* practically zero probability of missing an event with local magnitude $M_L > 2$ in the Swiss region. VS(SC3) messages are transferred to Swissnuclear through the UserDisplay code (UD), a graphical interface that was developed at the California Institute of Technology (Caltech) during Phase II of the ShakeAlert project in California. The UD version delivered to swissnuclear for testing allows the users to play scenarios of the largest historical events in Switzerland (Figure 18).

Figure 18 - Example UD screenshot showing peak ground motion and response spectrum predictions at the site of Mühleberg, based on the location and local magnitude of the 1584 Aigle event. The grey-shaded area around the target is the expected blind zone. The red and yellow circles are the S- and P-wave fronts, respectively.

After having carefully explored the possible (considering the national and international regulatory framework) mitigation actions in response to EEW, along with their costs, benefits and risk variation with time, Swissnuclear concluded that the usefulness of EEW for nuclear power plants in Switzerland is presently associated to preparedness of the operators in the control room provided that the full response spectrum is estimated, as done by the UD customised by SED for Swissnuclear. The most critical consideration that presently prevents operational (*e.g.* resulting into shutdown of primary or secondary systems) EEW at swissnuclear is the still high rate of false alerts. Although expected to decrease to ~ 0 in the future, the probability of false alerts is ~ 10 % based on the statistics presently available derived from the demonstration VS systems in Switzerland and California. This amount of false alarms is still too high compared to the high quality requirements in the nuclear industry and thus, the associated risk and cost of unnecessary downtime are not justifiable with respect to safety and the grid stability. Significant earthquake scenarios including lead-time and blind zone estimates provided by SED (see *e.g.* Figure 19) also contributed to inform the end-user opinion on the use of real-time hazard information.

In Switzerland, alerts associated with strong shaking (e.g. *PGA* larger than 0.1 g and event location outside the blind zone) can be expected to be sent to a power plant only for events with M_W larger than ~ 6. Earthquakes of this size, although rare, are possible in the greater Swiss region.

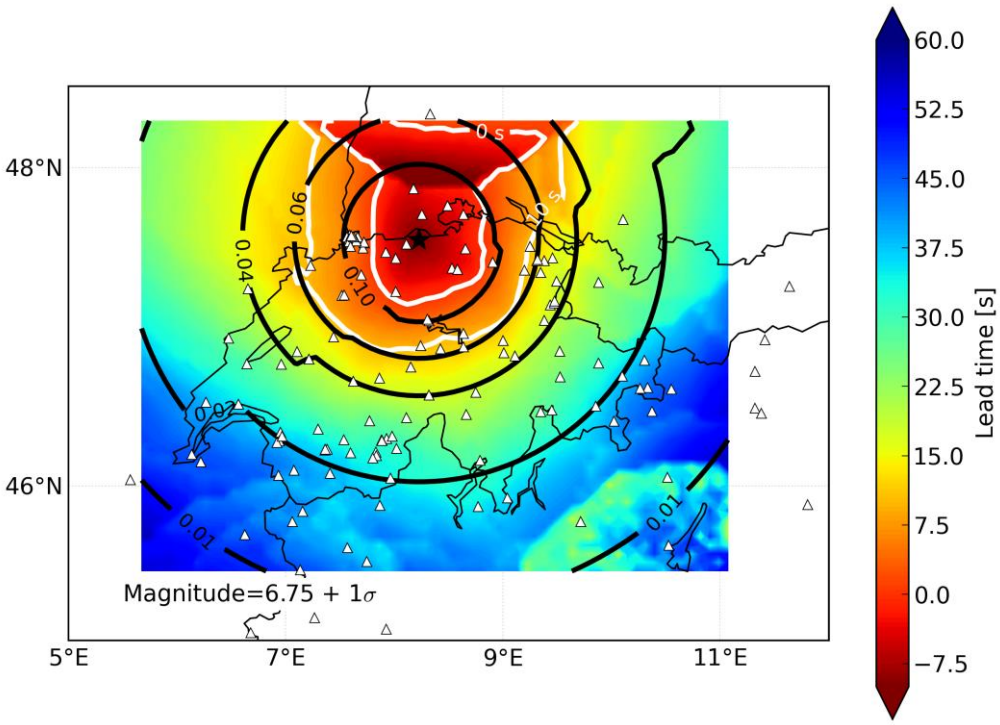

Figure 19.Map of expected lead times at Beznau for earthquakes of magnitude 6.75 potentially occurring at any point in the colored area, using a minimum number of six station triggers for event declaration. Contour lines of lead-time equal to 0 s (i.e. the blind zone) and 10 s are depicted as white curves. The black curves represent the loci of the earthquake locations that would cause PGA equal to a given threshold (e.g. 0.1, 0.06, 0.04, 0.01 g) at the selected target site (denoted by the star). Predictions are based on the parameterisation of the stochastic model of Edwards and Fäh (2013), with maximum stress parameter of 60 bar corrected for local site effects

XIX. USING EEW AT SCHOOLS

At the end of REAKT, the technical high-school Majorana in Somma Vesuviana (MAJI) runs a demonstration EEW system (Emolo et al 2014, Picozzi et al. 2015). The alerts are based on the EEW algorithm PRESTOPlus (www.prestoews.org, Satriano et al., 2011) and the recordings of the Irpinia Seismic Network, ISNet. Notable is that the stations installed at the school within the framework of REAKT contribute now in real-time to the ISNet waveform archive. Therefore the school is at the same time a target of the EEW messages and a node of the regional EEW system (Figure 20).

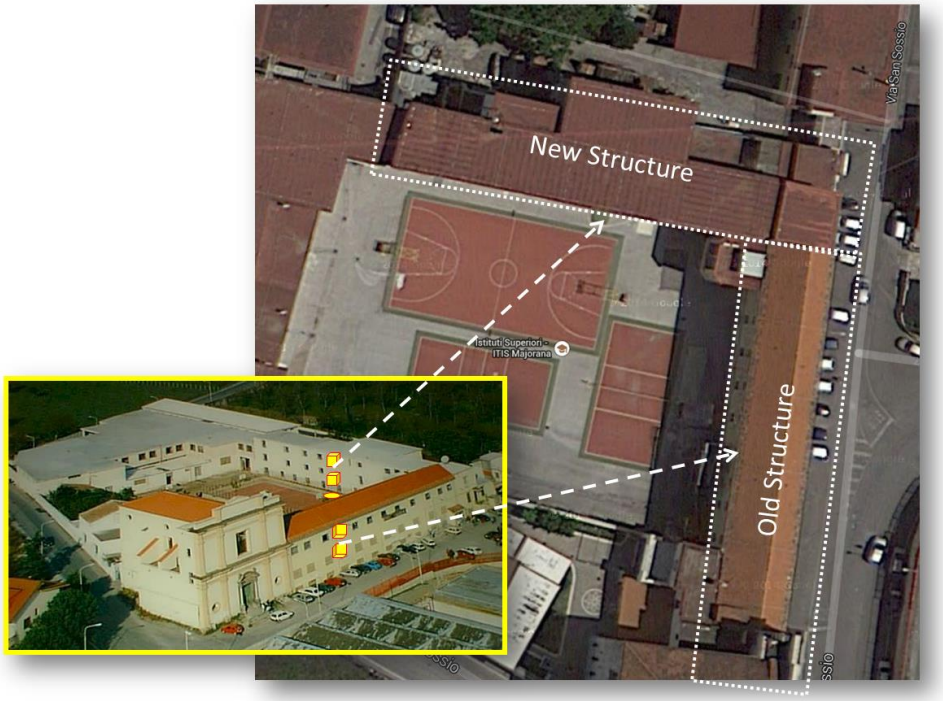

Figure 20-- Instruments deployed at the MAJI schoolhouse.

Unique example in Italy, the school is equipped now with an earthquake 'Sentinel' able to both listen and interpret messages coming from PRESToPlus, as well as to start emergency procedures when necessary (Figure 21). The Sentinel was developed within REAKT in close collaboration with the students and the teachers at MAJI. The Sentinel consists of a low-cost intelligent electronic device Arduino® (http://www.arduino.cc) that is easily programmable and configured to act as an EEW actuator. The EEWS at MAJI is designed so that PRESToPlus analyses the streaming of seismic data from both the on-site and the regional network, and in case of an earthquake it provides the Sentinel with an alert string containing the EEW information. Then, depending on the distance from the earthquake source, and therefore on which system between the regional and the on-site has the fastest response, the Sentinel can receive two different kind of alert messages: 1) information from the regional system concerning the event and including the date, the UTC time, latitude, longitude, magnitude, and most important the prediction of the ground motion shaking in terms of peak ground velocity *PGV* at the school; 2) information from the on-site system with date, the UTC time, ground motion peak associated to P-waves (*Pd*) and predominant period (*Tauc*). The EEW system and the Sentinel were successfully tested at MAJI during blind drills performed in November 2014. The participation and feedback of students and teachers was excellent.

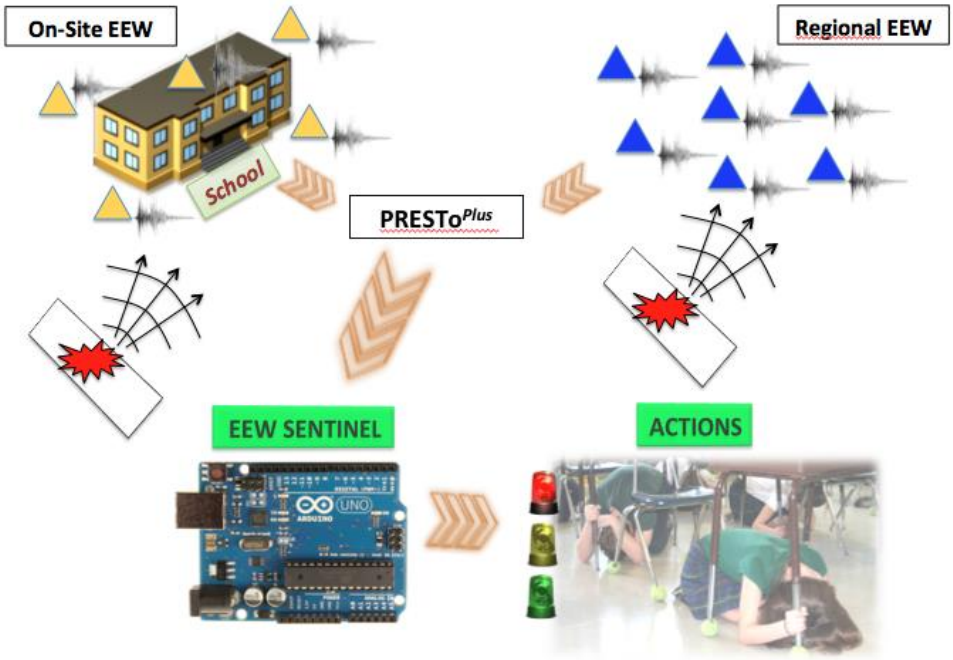

Figure 21 - Schematic overview of the EEWS for the School, which comprises an On-Site system and a Regional one managed by PRESToPlus, which in turn sends alerts to the EEW Sentinel placed within the school that can be used to warn students and teachers.

References

Satriano C, Elia L, Martino C, et al. (2011) PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives. Soil Dyn Earthq Eng 31:137–153. doi: 10.1016/j.soildyn.2010.06.008

Emolo A., Picozzi M., Zollo A., Verderame G., Martino C., Elia L., Colombelli S., Amoroso O, De Risi M. T., Bindi D., Parolai S., Boxberg T., Miranda N., Buonaiuto L., Amelia A., Feasibility study on Earthquake Early Warning for Schools In Southern Italy, Proceedings of the 2ECEES (Second European Conference on Earthquake Engineering and Seismology), Istanbul, Turkey, August 24-29, 2014

Picozzi M., Emolo A, Martino C., A. Zollo , N. Miranda, G. Verderame T. Boxberger and the REAKT working group, Earthquake Early Warning System for Schools: a Feasibility Study in Southern Italy, Seismological Research Letters March/April 2015, v.86, p.398-412 doi: 10.1785/0220140194

XX. POTENTIAL FOR A NATION-WIDE EEW SYSTEM FOR ITALY

This research task successfully explored the technical and scientific aspects of the feasibility of a nation-wide earthquake early warning system for Italy based on the recordings of the RAN network (Picozzi et al. In press). While very useful recommendations were provided as to the necessary technical improvements of RAN stations towards a telemetry strategy suitable for real-time applications, the most significant results obtained herein are related to the scientific aspects of the feasibility study. Based on the present network geometry and a minimum number of three stations to declare an event and raise alerts, the expected blind zone throughout the Italian territory was found to have a radius ranging between 25 and 30 km for most of areas with a higher seismic hazard, and to be in general smaller than 40 km. Such dimensions of the blind zones indicate that a regional EEW

approach would provide positive lead times only for events having magnitude larger than 6.5. On the contrary, for smaller magnitude events on-site EEW methods should be considered.

Notable is the approach adopted in this study to assess the feasibility of a possible RAN-PRESTo system based on a nation-wide grid of synthetic sources with the same spacing of the grid used to compute the official seismic hazard map of Italy, *http://esse1-gis.mi.ingv.it/s1_en.php*. The lead times were estimated under the assumption that each synthetic source could be the focus of 475-yr return period earthquake (Figure 22). Furthermore, each grid node was considered as a seismic source capable of generating earthquake sequences with magnitude varying according the properties (Gutenberg-Richter relationship) of the enclosing seismogenic zone over repeated virtual testing periods of 50 years. The results substantially confirmed the conclusions derived from the geometrical configuration of the network. This is expected since the station distribution of the RAN is highly correlated with the observed and expected seismicity.

One practical indication of interest derived from this study is that, if a long-term program for the implementation of a nation wide EEWS in Italy would start, besides the upgrade of the network to a real-time data telemetry, as first step an increase of the stations density in areas classified at the moment with lower seismic hazard would be necessary, especially in northern Italy and in Sicily, where the worst EEWs performance are presently expected. Further, a critical step in EEW operations would be to integrate the regional methods and the on-site, 'threshold based method' analyses in a unique EW decisional platform.

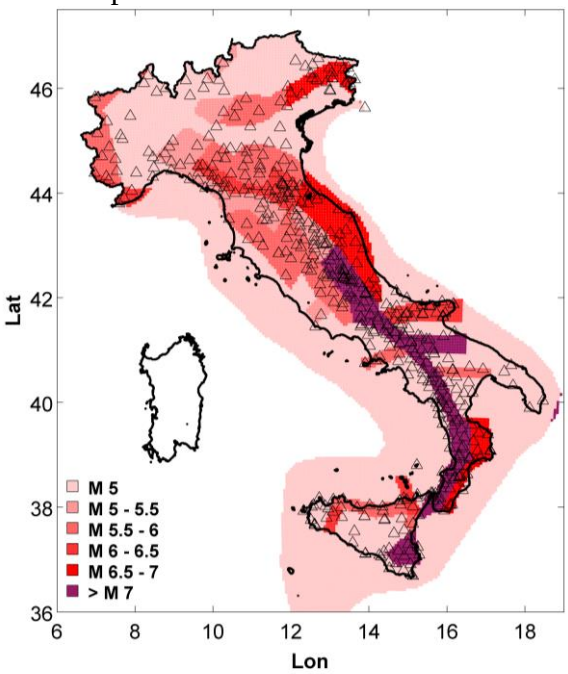

Figure 22 - Magnitude values corresponding to the 10% probability of occurrence in 50 years with respect to which the EEW system RAN-PRESTo was tested.

References

Picozzi M., Zollo A., Brondi P., Colombelli S., Elia L.,Martino C.,(in press) Exploring the Feasibility of a Nation-Wide Earthquake Early Warning System in Italy Journal of Geophyical Research - Solid Earth

XXI. REAL-TIME RISK MITIGATION AND RAPID AUTOMATIC DAMAGE ASSESSMENT FOR THE NATURAL GAS NETWORK OF ISTANBUL

REAKT enabled the implementation of an Early Warning and Rapid Response System at the IGDAS natural gas network of Istanbul, through the installation of 110 strong-motion accelerometers installed at district regulators , its integration into the Istanbul Earthquake Early Warning and Rapid Response System (Figure 23) and the development of an algorithm calculating several ground motion parameters at the site able to cut the gas flow at the district regulators (Zulfikar et al. 2014).

The instruments installed at the district regulators were produced by Turkish Scientific and Technological Research Centre (TUBITAK). In order to be able to cut the gas flow at the district regulators, an algorithm has been developed calculating several ground motion parameters at the site. The calculated ground motion parameters are *PGA, PGV, Ia, SI, CAV, PSA, PSV and SD*. The shaking thresholds are based on pre-computed scenarios of a M_W7.25 earthquake on the Marmara fault, corresponding to 40% probability of exceedance in 50 years of critical shaking parameters for the gas pipelines. The data transmission is achieved by fibre-optic communication line and alternatively with satellite communication line for EEW stations. For KOERI Earthquake Rapid Response Stations and IGDAS strong motion network 3G communications are used for data transmission. A fibre-optic communication line has been established between IGDAS Scada Center and KOERI in order to exchange real-time data. The integrated damage and loss maps are prepared both at IGDAS Scada Center and KOERI in real-time.

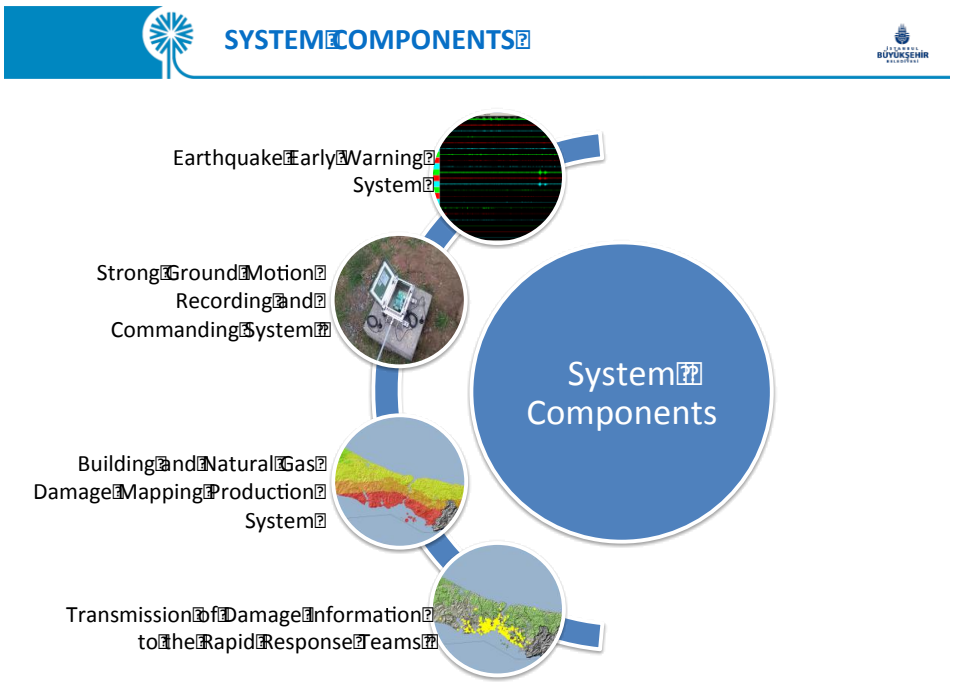

Figure 23-– ***IGDAS real-time risk mitigation system at a glance.***

References

Zulfikar, Pinar, Safak, Erdik - Implementation of EEWS to Istanbul natural gas network, Proc. of 3rd International Conference on Earthquake Early Warning, Berkeley, September 3-5, 2014

XXII. REAKT across the pond: towards EEW for the territories of the Easter Caribbean?

Notable in this study is the strategy adopted to investigate the feasibility of an EEW system based on broadband (0.1 – 25 Hz) numerical simulation of earthquake waveforms for selected scenarios critical for the region. Eleven EEW target sites were identified in the first half of the project in Trinidad & Tobago, Barbados, Antigua & Barbuda. The earthquake scenarios for the three selected islands were defined after a thorough analysis of the seismotectonic context of the Eastern Caribbean. Two sets of earthquake scenarios were tested for each island: the Maximum Credible Earthquakes (MCEs) and the earthquakes associated with a 475-year return period, obtained from the disaggregation analyses of *PGA*. The synthetic scenarios were validated through comparison of the simulated waveforms with strong-motion recordings at the rock station TBH (Trinidad), that contributes to the E Caribbean strong-motion dataset compiled in REAKT. The synthetic seismograms were produced both at the sensitive infrastructures and at the stations in the regional seismic networks (retrieved from the International Registry of Seismograph Stations, www.isc.ac.uk).

XXIII. Regional and on-site Eew efforts to alert strategic public infrastructures in Greece

Notable example of proactive collaboration among different research centers in Greece and first prototype implementation of EEW for the country, VS(SC3) – Behr et al. (2013) - is now used both in Patras (UPAT) and Thessaloniki (AUTH), based on real-time data from the Hellenic Unified Seismic Network (HUSN) and additional strong-motion stations managed by UPAT and AUTH. In Patras, the main target is the Rion-Antirion bridge, for which the current configuration can provide a few seconds of warning time for the S waves for events located at the southern end of Peloponnese or to the west of Cephalonia island. These are in fact the two seismogenic sources that have the potential to affect the bridge since they have generated strong events with ***M***~7 in the past.

At AUTH, EEW from VS(SC3) is complemented with prototype installations of PRESTo (Satriano et al., 2011) and the on-site EEW algorithm implemented in the SOSEWIN instruments that have been installed at a number of selected buildings in the port and at the AHEPA public hospital. The dynamic behaviour of selected port structures and the AHEPA hospital (Bindi et al., 2015; Karapetrou et al., 2014) was carefully investigated within REAKT with the aim of collecting the basic information to enable the prediction of real-time damage potential. The combined use of different EEW approaches is consistent with the historical record of damaging events for Thessaloniki, dominated by local events.

Two different approaches were tested for the post-earthquake damage assessment of the selected instrumented buildings in Thessaloniki. The first approach (onsite probabilistic damage assessment) is intrinsically related to the onsite EEW and fully implemented inside each SOSEWIN unit. The second is building-specific and based on an algorithm which is triggered externally whenever there is an EEW message from any of the tested methodologies or even in near-real time when there is a preliminary earthquake location and magnitude estimation. In this latter case, depending on the type of the EEW, i.e. if it is provided by the regional network or the on-site EEW system, different actions are taken. If there is an onsite recorded ground acceleration waveform, then its peak value is read and subsequently used. Such situation could occur for example in the case of a very close to the city earthquake, where the instruments that are installed in the city will be triggered before there is an EEW from the regional network. If there isn't such a trigger, then the preliminary source information

included in the EWW message is used to compute the expected peak ground motion at the site of interest through the use of ground motion prediction equations. In either case, the information that initiates the post-earthquake damage assessment procedure is a peak value of the ground acceleration. In the subsequent step, the available information on the peak ground acceleration is combined with the pre-defined building-specific fragility curves to produce realistic estimates of the expected levels of damage. The flow chart of the underlying methodology, which is currently running in pilot mode, is briefly presented in Figure 24.

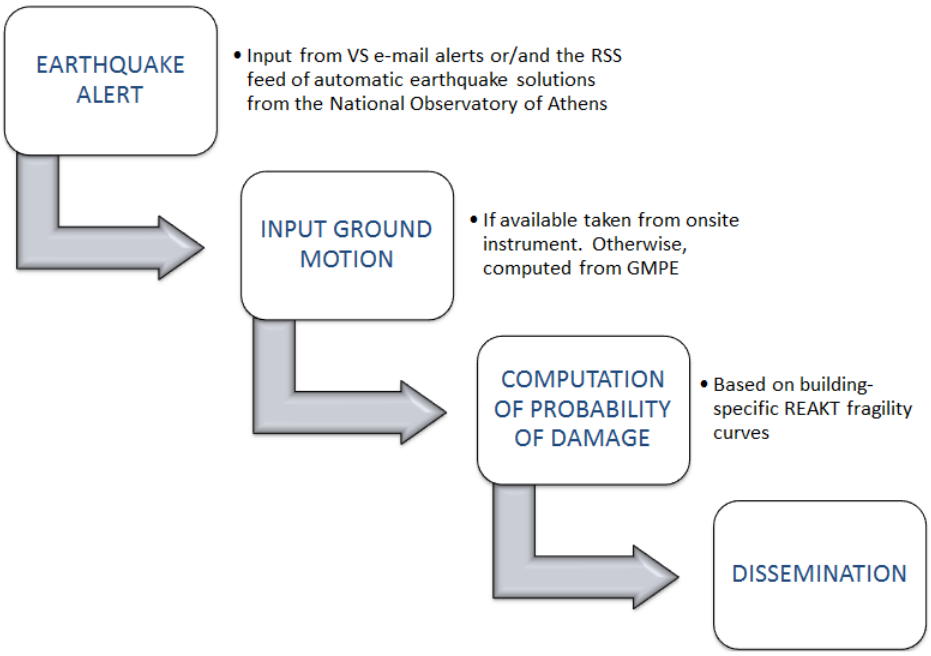

Figure 24 - Flow chart of the methodology used to assess the probabilities of occurrence of different levels of damage (e.g. slight, moderate, substantial, heavy, collapse) at the monitored structures in Thessaloniki.

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Bindi D, Petrovic B, Karapetrou S, et al. (2014) Seismic response of an 8-story RC-building from ambient vibration analysis. Bull Earthq Eng. doi: 10.1007/s10518-014-9713-y

Karapetrou S, Manakou M, Lamprou D, et al. (2014) "Real-time" seismic vulnerability assessment of a high rise rc building using field monitoring data. Proceedings of the 2nd ECEES. Paper no. 832.

Satriano C, Elia L, Martino C, et al. (2011) PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives. Soil Dyn Earthq Eng 31:137–153. doi: 10.1016/j.soildyn.2010.06.008

XXIV. CAPACITY BUILDING

REAKT Project (and its predecessor SAFER) created a core community of top European seismologists and engineers working in the field of short term forecast and early warning of earthquakes. REAKT prompted exchange of information and methodologies amongst most of the scientific institutions running monitoring seismic networks all over Europe and among the research groups dealing with "real time seismology". The project formed several tens of young researchers, creating an European young community able to continue and forward the research in this field, of crucial importance for the high earthquake risk areas of Europe.

An approach of the dissemination of research results in the REAKT EU project is to assist young researchers with understanding and participating in disaster risk management. Two short courses conducted in Vienna, Austria (29 April, 2014) and Varenna, Italy (8-11 June, 2014) allowed the opportunity for the project's research results to be demonstrated and discussed.

The workshop in Varenna, Italy involved a four day conference on operational earthquake forecasting and decision making. 64 participants attended from a number of countries with a wide variety of expertise in seismology, science communication and engineering.

The short course in Vienna, Austria was attended by 36 participants and focussed on earthquake early warning concepts, approaches and future challenges. Furthermore, analyses of case studies and the use of computer simulations in designing an EEW system were provided.

The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results

REAKT has provided a common field where most of the European and extra-European research groups active in the fields of earthquake forecasting, early warning and real-time vulnerability systems have compared and discussed their results setting the scene for an effective integration of methods applied to the various temporal scales of relevance for hazard and risk mitigation.

A practical result of this has been the development of the early warning visual display unifying the alerts given by the two main software development in REAKT (PRESTo and Virtual Seismologist) and able to support any other procedure of earthquake early warning (Highlight 17). This highly innovative and user friendly tool can have a major impact on the diffusion of EEW methods all around the world.

The scientific results of the REAKT Project are widely known in all the community dealing with earthquake and natural risks thanks to the large numbers of papers published in international journals and books and to the participation to international meetings.

The scientific production of REAKT in fact includes about 90 papers on scientific ISI journals and 170 oral and poster presentations in international meetings.

A special issue of the Bulletin of Earthquake Engineering entitled "***Strategic applications of real-time risk mitigation strategies and tools: case studies and lessons learned in REAKT"*** is in preparation and will be published within May 2016. The guest editors are C. Cauzzi (ETH, Zurich) P. Gasparini, coordinator of the REAKT project(AMRA, Italy), S. Wiemer (ETH, Zurich) and J. Zschau (GFZ, Potsdam).

A book on Real Time Seismology and the REAKT project, editors P. Gasparini, (AMRA, Italy), S. Wiemer (ETH, Zurich) and J. Zschau (GFZ, Potsdam). is being prepared to be published by Elsevier, U.K.

REAKT achievements have been presented and discussed to the most important conferences and meetings on earthquake risk. They include:

- Five American Geophysical Union Fall meetings (AGU 2011-2015),
- Four General Assemblies of the European Geosciences Union (EGU 2012-2015);
- The IASPEI (International Association of Seismology and Physics of the Earth's Interior) Assembly held in Gothenburg,
- The 15th World Conference On Earthquake Engineering (15 WCEE) held in Lisbon in 2012,
- The European Conference on Earthquake Engineering and Seismology (ECESS) held at Istanbul in 2014;
- The International Conference on EEW, held at the University of California, Berkeley in 2015.

Finally the REAKT results have contributed to develop internationally accepted formats for reporting on real time risk mitigation and early warning cases and to better understand the EEW potential especially for industrial and strategic applications.

REAKT attracted the interest of the European Parliament through a question asked on September, 30, 2014. Actions are being taken to promote a STOA conference at the European Paliament on major advances on earthquake risks produced by FP6 and FP7 projects.

To promote and disseminate seismic early warning in the Hyogo Framework of Action, a presentation of REAKT project to the German committee for disaster reduction (Deutsches Komitee Katastrophenvorsorge e. V., www.dkkv.org) has been organized within the International Strategy for Disaster Reduction (ISDR) on October 1st, 2014 .

The REAKT project has been also presented to the 3rd World Conference on Disaster Risk Reduction organized by UNISDR which took place in Sendai, Japan on March, 14-18 2015.

Several special events and workshops have been also organized in the framework of REAKT project for promoting real time risk reduction through the dissemination of the project's results.

The most relevant event organized to this aim has been the REAKT special session held during the 2nd European Conference on Earthquake Engineering and Seismology (2ECEES), in Istanbul, Turkey, on 24–29 August 2014. It focused on the results achieved by the project in real time mitigation of seismic risk to industries and strategic facilities showing the usefulness of the real time mitigation measures in this field of applications.

Other two relevant workshops have been:

- the REAKT Workshop organized in Barbados and Trinidad, Easter Caribbean, on February 25-26, 2013;
- the REAKT Workshop held in Sines, Portugal, on 15-16 October, 2014.

They were both aimed at presenting the REAKT project to several end users potentially interested in the project's results focusing the attention, respectively on the application in Eastern Caribbean to Hospitals, Port Authorities, Airport Authorities, Oil Service Companies and other Caribbean agencies/organizations and on the Portuguese strategic application: the Sines Industrial Complex .

In addition to these events some other workshops organized in the framework of the project activities must be cited. They contributed to the same aim being important opportunities for training not only researchers but also the end users involved in the project. These are the two Workshops on virtual seismologist held in Zurich the first on March 12-13, 2013 and the second on February 3-7, 2014 and the NERA-REAKT workshop held at Swiss Seismological Service (SED), ETH Zürich from March 19 to 20, 2013.

The key and most challenging goals of the project consisted in bridging the gap between earthquake science, engineering practice and decision making for a correct application of real time seismology procedures. This also means to make new - though consolidated - research findings available to real world applications. Or, in other words, ensure long-term optimised use of research ideas through applications in practice.

Throughout the duration of REAKT there was a continued effort to gather together researcher and practitioner from several countries in Europe and worldwide to find a practical answer to the question "What can real-time seismology do to mitigate seismic risk at strategic facilities?". A bilateral effort, where earthquake scientists offer the most up-to-date scientific approaches, and end-users provide operational feedback as to their applicability in practice. Costs and benefits, limits of applicability, reliability, ease of use.

These issues should be carefully considered towards common final goals: alerting critical infrastructures in due time, prior to strong shaking; implement (automatic) mitigation actions based on the expected damage. A collection of heterogeneous applications, from high-schools to nuclear power plants. Dramatically different earthquake impacts in case of damage, from the downtime of a local railway to the interruption of operations at a major international hub port. Implementation has

been achieved in some cases within REAKT. Within other case studies, awareness has developed as to the necessary steps toward implementation. Good reasons to insist, and go ahead.

REAKT has improved the reliability of operational forecasting and early warning extending the possibilities of their applications for protecting structures, infrastructures and people. This has been possible thanks to the close integration of end-users with the consequence of carefully considering the end- user perspective in the evaluation of each component of real time risk mitigation chain, including all the uncertainties. They were a key issue for evaluating the feasibility of application of the developed methods to different strategic targets.

Thanks to the strong involvement of different types of end users, a comprehensive view of the conditions favouring or hindering the application of short term earthquake forecasting and early warning methodologies was produced, identifying scientific and regulatory problems to be address in future research. This is certainly a major result of the project with the most relevant socio-economic impact and the wider societal implication. EEW demonstrated to be feasible and ready to use in the case of some applications like schools and gas network that are amongst the most successful applications in REAKT, where both the scientific and technical goals of the project were fully achieved while, in other cases, although feasible, it demonstrated that further aspects need to be considered before of implementing it.

The majority of end-users contributed with critical and informative comments. In particular, a strong request to further improve the reliability, understandability and ease of use of real-time risk mitigation methodologies is apparent in the majority of the questionnaires received. This request is accompanied by the awareness that a future project similar to REAKT should mainly focus on implementation cases, while the critical steps of feasibility studies should preferably be addressed within a preparatory phase of the project well in advance of its kick-off. Notable amongst the end-user recommendations are original ideas like e.g. the establishment of a European distributed EEW system (swissnuclear) and the careful scrutiny and definition of legal responsibilities of decision makers (Civil Protection of Italy). The practical indications of interest that we should get from these REAKT case studies are well summarised by their:

a) obvious benefits of real-time risk mitigation actions;

b) minor or negligible impact of false alarms;

c) strong interest of the end-user in collaborating with academic institutions.

These elements seem to be key to successful and timely applications of real-time risk mitigation strategies.

A main progress introduced by REAKT has been the development of a 2nd generation of forecast models introducing information from physics and geology (fault parameters) and incorporating the most relevant uncertainties.

The development of a Bayesian strategy permitted the evaluation and integration of different probabilistic forecasting models into a single ensemble model.

The results obtained by the application of these hybrid physical/statistical models have shown that the integration of physical constraints from Coulomb stress changes can increase the performance of a statistical model.

A workshop on Operational Earthquake Forecasting and Decision Making was convened in Varenna, Italy, on June 8-11, 2014, under the sponsorship of the EU FP 7 REAKT (Strategies and tools for Real-time EArthquake risK reducTion) project, the Seismic Hazard Center at the Istituto Nazionale

di Geofisica e Vulcanologia (INGV), and the Southern California Earthquake Center (SCEC). The main goal was to survey the interdisciplinary issues of operational earthquake forecasting (OEF), including the problems that OEF raises for decision making and risk communication

REAKT has started the consensus building on best practice in operational earthquake forecasting by developing guidelines and recommendation that actually represent a starting point for a wider application of operational forecasting. Guidelines on operational procedures based on probabilistic earthquake forecasting have been developed for the first time.

FINAL COMMENTS AND RECOMMENDATIONS

REAKT Project has shown that Real Time Seismology methods are mature from a technical point of view to be applied to protect specific structures.

All the technical and scientific conditions exist for application of early warning methods. The scientific basis of the method is not questioned anymore. Practical applications made in Japan and theoretical simulations have shown that false and missed alarms are a few percent of cases and therefore acceptable for most purposes. The tools developed in REAKT are being implemented in South Korea, Israel, Spain, all countries not participating to the project.

However the main obstacle to its application for public purposes in European countries relies on the lack of regulations indicating clearly duties and responsibility. Furthermore risk managers and people are reluctant to think and act in terms of probabilistic and not deterministic scenarios.

This is a major obstacle also for the adoption of short term earthquake forecasting. To make it really "operational" a careful analysis of socio-economic consequences of taking or not a given action must be evaluated.

Research perspectives to be considered in a EC call for final implementation of Real time Seismology methods to protect European countries should be based on the following considerations:

Combinations of on-site and regional earthquake early warning are developed to an extent that they could be pushed to a large number of applications for the protection of industrial facilities such as chip manufacturing, car manufacturing, petro-chemical plants, the medical sector and many others. A similar statement holds for OEF with regard to aftershocks.

Strategic aspects of applicability, that should be investigated include

- Framing seismic warnings and mitigation action in the context of **multi-risk**.
- **End-user integration. Understand the operational conditions and constraints of users from CP and industry**, both demanding efficiency and credibility of scientific and technical components of systems, clear identification of mitigation targets including cost-benefit analyses, user education, identification and clarification of responsibilities and liabilities.
- **New classes of end-users** to be investigated respect to the ones considered in REAKT (data centers, telecommunication, construction, chemical facilities, re-insurance, focus also on security).
- **Link systems to the safety requirements of institutions and industry**.
- A general requirement is the **integration of EEW, OEF, and Real-time Risk Reduction (RTRR) in classical risk management frameworks** such as the ISO 31000 and other more specific security standards related to critical infrastructures.

- Demonstrate **resilience gains** for warning and mitigation systems. A stronger focus on resilience and resilient cities. City wide applications, test beds? Towards a quantitative '**resilience concept'**.
- **Communicating EEW and OEF information to the public** remains a challenge. We are currently at the beginning of the learning curve. The fairly large body of social science research must be incorporated and substantiated in the EEW and OEF context.
- **Assessing the costs and potential benefits of OEF and EEW** in more quantitative ways might give good arguments for implementation.
- **Decision making and defining the acceptable risk under uncertainties**

In addition to these fundamental questions and demands there are a number of scientific and technical challenges that promise significant innovation:

- For large earthquakes ($M \geq 7, 5$) EEW has to be done essentially during the rupture of the earthquake, before a magnitude can be determined. This requires the development of novel methodologies for instance by utilizing assimilation of observed data and wave propagation simulation.
- **Underground experiments**, GeoEnergy Testbeds and anthropogenic seismicity in general may offer synergies for observing/modeling precursory processes and nucleation related effects
- **Dense real time GPS** networks can monitor the deformation in the vicinity of the source and has to be utilized in a more systematic way.
- **Instrumentation/monitoring/communication**: Supplementing accelerometric networks with GPS observations; utilization of displacement and accelerometric parameters in EEW; densification of networks with low cost accelerometers. EEW systems utilizing information retrieved from iPads, mobile phones, etc. on acceleration and displacement near the source during and after an earthquake.
- **High Performance Computing and modeling** may offer opportunities for more physics based modeling (Fluid-stress-fault interactions, ground motions, fault interactions, time-dependent hazard and risk, real-time shakemaps).
- **The warning for secondary earthquake effects**, specifically liquefaction and landslides in an early warning mode is currently underdeveloped.
- **Rapid assessment of infrastructure functionality** is an issue that needs further development. Contrary to the prediction of loss from individual facilities such as a building the prediction for infrastructures require sophisticated models of the infrastructures and the response to shaking including secondary phenomena (landslides, liquefaction).
- **Citizen based science, human sensors, and smart buildings** may allow for new kinds of data while at the same time opening up for a dialogue.
- **Reducing the blind zone**, working on the timeline and the stability of EEW will deliver steady but very important progress.
- **Improving the probability gain of OEF** likewise is promising steady progress (more physics, more geology, better statistics), brick by brick.

- **Validation and performance assessment** remain an important focus. Good science requires hypothesis driven research and reproducibility. Before applications are going public, their performance need to be validated/assessed in a honest, unbiased fashion.
- **Ensembles emerge in OEF and EEW** as the best way to bring stability to systems. Uncertainty reduction is also key.
- **Time-dependent vulnerability** (but maybe more on the short term) remains an open issue.
- The research of REAKT could be further enabled by selected key EPOS services: Testbeds for EEW and OEF developments, validation and applications.