Procedures for Real-time Earthquake Risk Reduction of Industrial Plants and Infrastructures

P. Gasparini
Analisi e Monitoraggio del Rischio Ambientale (AMRA-Scarl), Italy

G. Cua
Swiss Seismological Service, ETH Zürich, Switzerland

and the REAKT WP7 team

SUMMARY
REAKT (Strategies and Tools for Real Time Earthquake Risk Reduction) is a 36 month FP7 EC project that started on September 1, 2011. REAKT addresses real-time earthquake risk mitigation from end-to-end, with efforts in operational earthquake forecasting, earthquake early warning, real-time vulnerability systems, and optimized end-user decision-making with uncertain information. Among the main outcomes expected from the project are feasibility studies considering the application of the developed methodologies towards the protection of industrial targets. These industrial targets include power plants, lifelines, railways, an industrial complex, bridges, a port complex, and a hospital.
A work package is dedicated to applications of REAKT methodologies at twelve test sites, ten of which are industrial facilities. Each test site/application involves a scientific partner and an industrial end-user, who jointly determine the real-time risk reduction measures appropriate for the site.

Keywords: earthquake early warning, real-time risk reduction, industrial plants, infrastructures

1. INTRODUCTION

Earthquake early warning methodologies are utilized in Japan for several purposes, including the protection of industrial centres and of lifelines. Although methods and real-time monitoring systems capable of providing early warning information are available in several countries of Europe, North America and Asia, only rarely this potential is used to mitigate earthquake risk in real-time in these countries. A European project, SAFER (Seimic Early Warning for Europe), was launched in 2006, within the FP6 framework. SAFER had a 3 year duration and, through joint efforts of the European and international research groups most active in the field, developed innovative methodologies and applications (see Allen et al, 2009, Iervolino et al., 2010 and references there contained) including very fast earthquake source parameters determination, quantitative criteria to decide on the feasibility of applications, optimal instrumental configurations etc.

SAFER ended in 2009, and has as its successor the REAKT (Strategies and Tools for Real-Time Earthquake Risk Reduction) project. REAKT is a follow up and an extension of SAFER. Its objective is to improve the efficiency of real-time earthquake risk mitigation methods and their capability to protect structures, infrastructures, and populations. REAKT aims to address the issues of real-time earthquake hazard estimation and emergency response from end-to-end, with work packages focused on operational earthquake forecasting, earthquake early warning (EEW), real-time vulnerability systems, and optimized end-user decision-making with uncertain information. The core and ultimate goal of the project is the application of the methodologies and tools developed in SAFER and being developed in REAKT at 12 selected test sites, 10 of which are industrial facilities. The feasibility studies, and in some cases, initial implementation, of these real-time methodologies and tools at these test sites, and the establishment of best-practices for their use, are structured as a collaborative effort between academic and end-user partners.

The REAKT project is structured into 8 work packages. WP1 is devoted to project coordination and management. WP2 focuses on "Physics of short-term seismic changes and its use for predictability of large earthquakes" and WP3 "Towards operational earthquake forecasting" will develop medium-term (years to months) and short-term (days to hours) time-dependent earthquake probability models. Operational earthquake forecasts predict the "earthquake weather" over a particular period of time, for instance, over the next 24 hours for short-term forecasts, or over the next 6 months for medium-term forecasts, based on theoretical models and patterns of previously observed seismicity and possibly of other transient phenomena. The goal of OEF is to provide authoritative information about the time-dependence of seismic hazard to help communities prepare for potentially destructive earthquakes (Jordan et al, 2011). Whether OEF models evolve to be reliable and skilled enough to be used to influence civil protection actions, or procedures at industrial facilities, is to be determined. WP4 is focused on "Early warning and rapid assessment of earthquake damage potential", and operates in the seconds to tens of seconds after the initiation of the earthquake rupture. The goal of earthquake early warning (EEW) is to provide information about the expected shaking in a particular region/location, before the onset of strong shaking, such that seconds to tens of seconds are available to take certain damage-mitigating actions. For example, in Japan, the high-speed Shinkansen trains have been slowed down to prevent derailment from strong shaking using EEW information since 1982. EEW algorithms are classified as on-site (ie, using P-wave information at a given location to estimate peak shaking/damage at the same location) or regional (using a network of stations to estimate location, magnitude, and expected shaking throughout a region) approaches. In REAKT WP4, the EEW approaches being tested are the hybrid on-site/regional PRESToPlus approach developed by the AMRA group in Naples (Zollo et al, 2010, Colombelli et al, 2012), the regional Virtual Seismologist approach from ETHZ (Cua et al 2009, Cua and Heaton 2007), the regional, threshold-based Istanbul Earthquake Rapid Response and Early Warning System (IERREWS, Sesetyan et al 2011, Erdik et al, 2011), and the performance-based earthquake early warning approach (Iervolino, 2011), where the minimization of expected losses, given a model of the building response, and predictions of expected shaking, are used to determine structure-specific alarm thresholds. WP5 is focused on "Real-time, time-dependent risk assessment". In particular, the focus of WP5 is the development of real-time, time-dependent vulnerability models, taking into account the effects of aging, and cumulative earthquake loading on buildings, as well as the generation of damage and loss estimates in near-real-time. Each of WPs 3, 4, and 5 represent links in an earthquake risk-reduction chain. A goal of REAKT is the characterization of uncertainties at each link of this chain. In WP6, a probabilistic cost-benefit framework will be developed that will help the potential users make optimal decisions that will prescribe how to use uncertain information/estimates from WP3, WP4, and/or WP5 to make the optimal decision in real or near-real time. In WP7, the various tools and methodologies developed in the other work packages are applied, in the context of the 12 selected test sites. WP8 deals with the dissemination of results throughout the scientific and end-user communities, as well as the public.

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

All the industrial partners involved in REAKT WP7 will be considering the use of some form of earthquake early warning information from WP4. It is of critical importance that the academic partners are able to clearly convey to their end-users the caveats of real-time EEW information: 1) that all early warning systems have a blind zone in the region around the earthquake source, where no warning is available, 2) there is a strong trade-off between speed and uncertainty in EEW information, fast estimates can potentially result in longer warning times, but they come at the cost of higher uncertainties, 3) false and missed alerts will happen, and costs of false and missed alerts (from information provided by the end-users) have a significant role in determining the appropriate alert thresholds for a facility. Ultimately, real-time risk reduction measures are a complement, not an alternative, to well-engineered buildings and infrastructures.

2. THE REAKT INDUSTRIAL CASE STUDIES

2.1. SINES Industrial Complex, Portugal (Instituto Tecnico Superior, Lisbon)

The SINES Industrial Complex in Portugal is one of the largest industrial complexes in Europe, and houses a significant number of national and European critical infrastructures. The SINES complex is situated along the Atlantic Coast, within 180 km of the Gorringe Bank and Marques de Pombal faults, both capable of producing M8.5 to M9 earthquakes. The PGA levels expected from such events range over 0.2 – 0.24g on stiff rock to 0.4-0.5g on soft soils. Among the numerous industries and service providers located in the SINEX Complex, the Instituto Tecnico Superior (IST) and the Conselho Nacional de Planeamento Civil de Emergencia (CNPCE) have selected GALP Energia (oil refinery), REN Atlantico (natural gas storage), and EDP Producao (thermoelectric power plant) to participate in the feasibility study of using earthquake early warning information at the SINES complex. The goal of this application is to help the end-users decide whether an earthquake early warning system would be a worthwhile investment to protect the complex. In large part, this will be based on simulating the effects of a suite of earthquakes (from a catalogue consisting of over 400 hazardous historical and instrumentally recorded events) at the SINES complex. A GIS-based earthquake risk simulator will be developed that will convolve the shaking effects from events in the catalogue, with the inventory and critical infrastructures situated at the complex. Given the performance statistics of the Virtual Seismologist algorithm from WP4, the IST assist their end-users in a cost-benefit analysis of whether the benefits of a real-time installation of Virtual Seismologist would justify the costs of setting up such a system. As part of WP5, the IST team are also involved in developing time-dependent fragility functions for industrial and harbor facilities that will come into play in the loss calculations of their risk analysis.

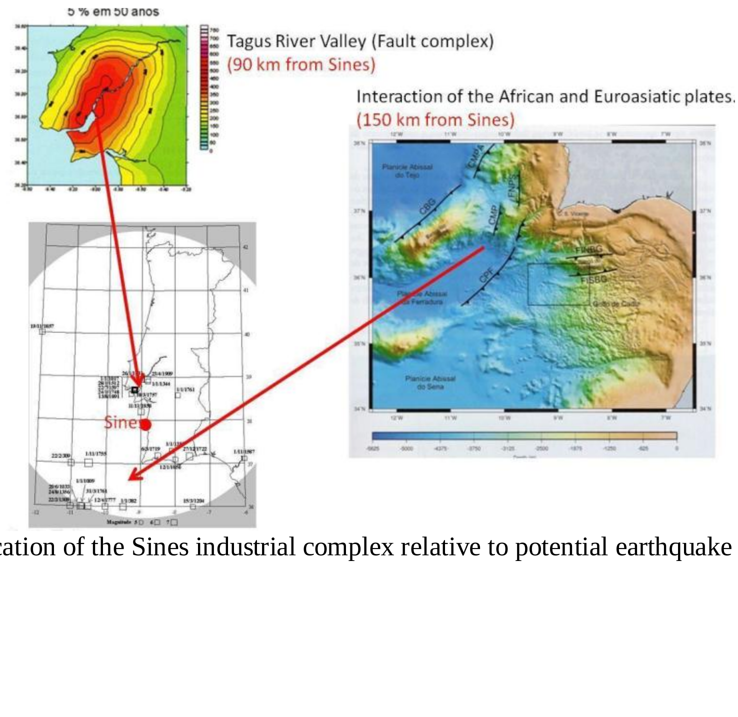

Figure 1: Location of the Sines industrial complex relative to potential earthquake source zones.

2.2. Nuclear Plants in Switzerland (Swiss Seismological Service, ETHZ, Zürich)

Swissnuclear, the nuclear energy section of swisselectric, operates the Swiss nuclear plants Beznau, Gösgen, Leibstadt, and Muhleberg. Together, these plants meet 40% of the electricity needs of Switzerland, producing more than 26 billion kilowatt hours per year. Swissnuclear is interested in evaluating the use of EEW and OEF information to improve plant safety.

Since 2004, ETHZ has been developing and implementing the Virtual Seismologist (VS) EEW algorithm in Switzerland and California. The VS algorithm, along with the OnSite (Wu and Kanamori, 2005, Boese et al, 2009) and ElarmS (Allen and Kanamori, 2003, Brown et al, 2009) algorithms, form the basis of the California Integrated Seismic Network (CISN) ShakeAlert system, a prototype California-wide EEW system being funded by the US Geological Survey. In this REAKT application, a real-time installation of the VS algorithm will be set-up to run on stations of the Swiss national network, and will send information in real-time to display in the control offices of swissnuclear plants. The real-time user display developed within the CISN ShakeAlert effort will be modified for use in Europe within REAKT. Swissnuclear plant operators will thus become acquainted with real-time earthquake information. In addition, Swissnuclear is also interested in evaluating whether OEF is reliable enough such that plant maintenance schedules should be modified, based on forecasted seismicity. Based on costs provided by Swissnuclear for potential mitigation actions (for instance, rescheduling plant maintenance, fast shut-down of reactors), the cost-benefit approach developed through WP6 will be applied to help evaluate whether the use of EEW and OEF information can be optimized in nuclear plants.

2.3. Hydropower Plants and Power Transmission Plants in Iceland (Icelandic Meteorological Office, Reykjavik)

Landsvirkjun is a state-owned power company that generates about 75% of the electrical energy produced in Iceland. The company serves both power-intensive industries, such as aluminum factories, as well as the general market. The building of hydropower plants, situated along rivers, involves the construction of dams to form reservoirs for the plans to even out seasonal variations in the rivers' flow, and to generate the required vertical head of the water level. The dams range in length from a few hundred meters to over 6km. Maximum elevations range between 20 and 198 m. Networks of tunnels and dykes are also part of the hydropower plant construction, and contribute to the vulnerability of the power generation and distribution system as a whole. There are a total of 72 km of tunnels at the Karahnjuka hydropower plant. Landsnet is an independent limited company that operates the transmission systems carrying electricity from the power plants to the consumers. All of Landvirkjun's existing and planned hydropower plants and dams, and all of Landsnet's power transmission networks are at risk from events from the South Iceland Seismic Zone (SISZ), where events up to M7.3 have occurred over the last 1000 years, with recurrence times of approximately 100 years.

IMO will focus on high-precision relocation of aftershocks, with the goal of estimating fault planes of historical events. Mapping these fault planes can potentially influence decisions regarding where future power plants should be constructed. IMO will collaborate with end users Landsvirkjun and Landset to produce near-real-time probabilistic seismic hazard maps for western Iceland and the SISZ and develop procedures for optimal use of such maps in protecting the hydropower plants, dams, and transmission lines. A feasibility study, and possible initial implementation of the Virtual Seismologist EEW algorithm on IMO's real-time seismic network will also be considered.

2.4. IGDAS Natural Gas Network and the Fatih Sultan Mehmet Bridge in Istanbul (Bogazici University, KOERI, Istanbul / GFZ Potsdam)

Istanbul Gas Distribution (IGDAS) is the primary natural gas provider in Istanbul, and operates an extensive system of 9,867 km of gas lines, with 550 district regulators and 474,000 service boxes.

State-of-the-art protection systems automatically cut natural gas flows when breaks in the pipelines are detected. Since 2005, buildings in Istanbul requiring natural gas are required to install seismometers that automatically cut natural gas flow when certain thresholds are exceeded. IGDAS utilizes a sophisticated SCADA (supervisory control and data acquisition) system to monitor the state-of-health of its pipeline network. This system provides real-time information about quantities related to pipeline monitoring, including input-output pressure, drawing information, positions of station and RTU (remote terminal unit) gates, slum shut mechanism status, and dirt filter information at 581 district regulator sites.

KOERI operates the Istanbul Earthquake Rapid Response and Early Warning System (IERREWS), which combines a dense deployment of 100 accelerometer stations for near-real-time shakemap generation and loss estimation (Sesetyan et al, 2011; Erdik et al 2011), with 12 real-time early warning accelerometers located as close as possible to the Marmara fault zone. The IERREWS system can send shut-down signals to recipient facilities based on the exceedence of specified time-domain amplitude levels (Alcik et al, 2009; Boese et al 2008). In this application, KOERI will develop an interface to the IGDAS SCADA system, such that real-time alert information from the IERREWS can shut down gas distribution valves in case of a damaging earthquake. Low-cost SOSEWIN instruments (Fleming et al, 2009) will be installed and monitored in real-time by GFZ, to complement the planned KOERI installation 100 real-time accelerometer stations.

A second critical infrastructure in Istanbul is the Fatih Sultan Mehmet (FSM) bridge. The FSM bridge is one of two suspension bridges crossing the Bosporus strait, connecting Europe to Asia. Completed in 1988, the bridge is a modern, gravity-anchored suspension bridge with 2 steel portal-frame pylons, cables, suspenders, and an orthotropic steel box deck. The bridge is 1.5 km long, 1.1km of which is the main span suspended by vertical cables between two pylons. Suspension bridges are often critical nodes of major transportation systems. Their failures due to strong earthquakes are considered major threats, due to potentially high numbers of fatalities and interruption to emergency services. For these reasons, EEW and structural health monitoring of the bridge's design parameters, vibration characteristics, and dynamic properties are of vital importance.

2.5. Circumvesuviana Railway in Naples (AMRA)

The Circumvesuviana Railway system serves the areas of east Naples and along the Sorrento Coast in Italy. It is 203 km long, with 61 km on double track. On average, there are 521 trains operating on a given day, with an average of 125,000 passengers each day. The 3 primary lines are the Sorrento, Sarno, and Baiano lines. This particular application focuses on the Baiano line, which is closest to the seismogenic zone that produced the 1980 M6.9 Campania-Lucania earthquake. A significant portion of the Baiano line goes over viaducts that can be damaged by strong shaking. The most dangerous accidents involve derailments that can be caused by trains going over damaged tracks or viaducts.

This particular application involves a feasibility study on the use of 1) information from regional EEW systems, in particular, the PRESToPlus algorithm operated by AMRA on the Irpinia Seismic Network (ISNet), as well as the feasibility of 2) a hybrid on-site/regional approach where real-time data from instruments installed on the viaducts could be used to improve the damage predictions for the viaducts. This second approach would require the use of random field ground motion modeling to reduce uncertainties in the real-time risk analysis (Iervolino, 2011). Possible mitigation actions include i) allowing the continuation of traffic, if no damage is expected, ii) slowing trains on potentially damaged tracks and initiating rapid inspections, and iii) stopping trains on potentially damaged tracks and taking careful inspections. The possibility of using EEW-based structural control to improve the performance of the viaducts will also be considered, if time and resources permit. Performance-based earthquake early warning (PBEEW) will be applied, where the optimal alert thresholds for a given structure are determined by minimizing the expected losses.

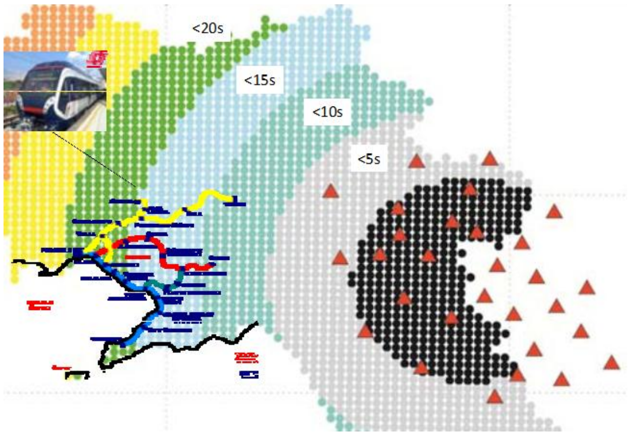

Figure 2: Contours show average warning time for a hypothetical event occurring within the ISNet network.

2.6. City of Patras and the Rion-Antirion Bridge (University of Patras, UPAT) and the Eastern Caribbean Islands (EUCENTER, Pavia / The University of the West Indies / Council of Caribbean Engineering Organizations)

The city of Patras is the third largest urban area in Greece, and is an ideal candidate for an EEW pilot study because of its high seismic hazard, the existence of a modern, broadband real-time network, and the presence of critical infrastructures such as the Rion-Antirion bridge. The Rion-Antirion bridge, completed in 2004 by the GEFYRA Consortium, is the world's longest (2.8 km), multi-span cable-stayed bridge. It crosses the Gulf of Corinth near Patras, linking the town of Rion on the Peloponnese to Antirion on mainland Greece. The objective of this application is to supplement the existing network with 6 additional real-time strong motion stations, and to have a real-time Virtual Seismologist installation running on the UPAT network, and sending information in real-time to the Rion-Antirion bridge operators. The Civil Protection authorities of western Greece are also possible recipients of real-time information from the UPAT Virtual Seismologist installation. Potentially, the user displays modified for the swissnuclear application can also be used here. The distance of Patras from the Hellenic Arc, where the damaging earthquakes are likely to originate, is large enough such that tens of seconds of warning time may be available. UPAT will work with both end-users in exploring and optimizing possible use of EEW information.

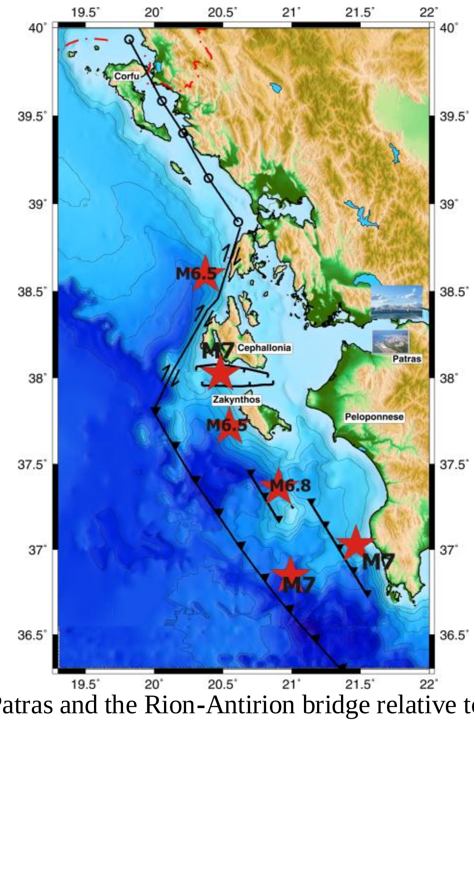

Figure 3: Location of the city of Patras and the Rion-Antirion bridge relative to potential earthquake sources.

The Eastern Caribbean Islands are a high seismicity area characterized by a complex seismotectonic setting dominated by subduction, crustal, and volcanic earthquakes. The occurrence of large and deep earthquakes (~M8.0 with focal depths up to 200 km) makes the region particularly suitable for implementation of EEW systems. Numerous critical infrastructures in the region, including hospitals, airports, schools, and energy production plants, are exposed to medium-to-high seismic hazard. The horizontal PGA expected on stiff soil, with 10% probability of exceedence in 50 years, ranges between 0.21 and 0.38g. EUCENTER and the Seismic Research Center of the University of West Indies are working on improving crustal velocity models in the region, seismic hazard deaggregation, and developing simulated suites of ground motions for scenario-based feasibility analysis of EEW algorithms such as PRESToPlus and Virtual Seismologist from WP4. In addition, EUCENTER and the Council of Caribbean Engineering Organizations (CCEO) are working on identifying sensitive infrastructures in the region, and conducting extensive surveys of whether potential industrial users would be interested in EEW, and what they would do with EEW information. Some of the potential EEW users in the Eastern Caribbean Islands identified thus far include the Trinidad and Tobago Electricity Commission, the Queen Elizabeth hospital and Grantly Adams international airport in Barbados, the Barbados Light and Power Company, and the Princess Margaret hospital in Dominica.

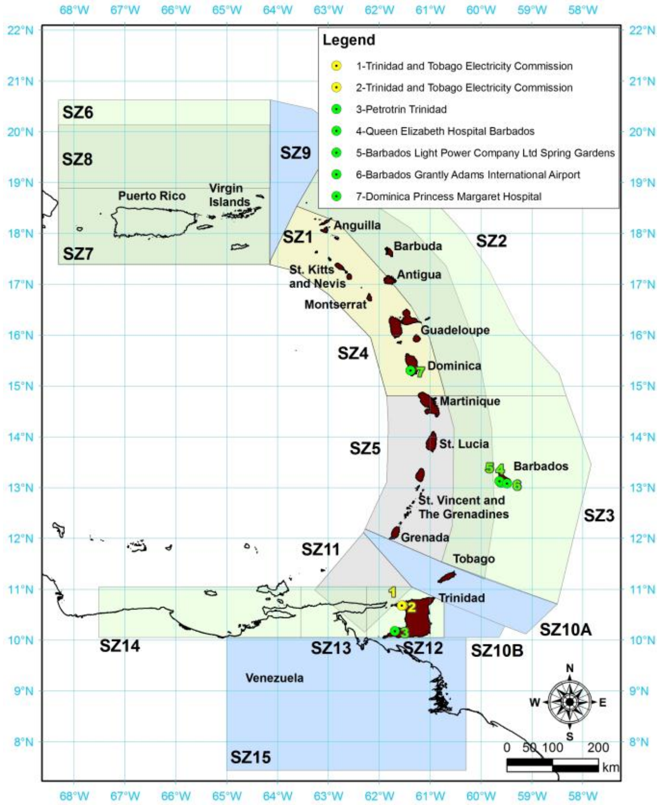

Figure 4: Selected EEW end users in the Eastern Caribbean (green confirmed, yellow to be confirmed), along with seismogenic sources which are: Zone1, the Volcanic Island Arc; Zone 2-5, the Subduction in the Lesser Antilles; Zone 6-8, Puerto Rico and Virgin Islands; Zone 9 and 10A, the Transition Zone; Zone 11, North of Paria Peninsula (Subduction zone); Zone 12, Trinidad Faults; Zone 13 and 14, El Pilar Fault; Zone 15, South of Trinidad.

2.7. Thessaloniki Port and AHEPA hospital (AUTH, Thessaloniki / GFZ, POTSDAM)

The port of Thessaloniki is a major European Port and the natural gateway for the economic activities of the inland markets beyond Greece. It serves the growing needs of those countries for the import and export of raw material, consumer products and capital equipment. The port is a vital element of the country's economy and plays a substantial role in the effort of Northern Greece and the city of Thessaloniki to establish themselves as the economic centre of South East Europe and the Eastern Mediterranean. Thessaloniki's port has a total quay length of 6,200m and a sea depth down to 12 meters. It has 600,000 m^2 of indoor and open storage area and modern mechanical equipment for the secure and prompt handling of all kinds of cargo, general, bulk and containers. Thessaloniki Port Authority (ThPA) is currently one of the major employers of Northern Greece with a workforce of more than 600 people. Over 2,000 people work daily on their premises. ThPA handles over 16,000,000 tons of cargo per annum (out of which 7,000,000 is dry cargo and 9,000,000 is liquid fuel cargo), 370,000 TEUs containers, 3,000 ships and 220,000 passengers. It covers an area of 1,500,000 m^2 and includes various facilities for cargo and handling equipment, waterfront structures, electric power, potable and waste-water, telecommunication, railway and roadway system, as well as numerous buildings of different typologies and uses as well all critical infrastructures.

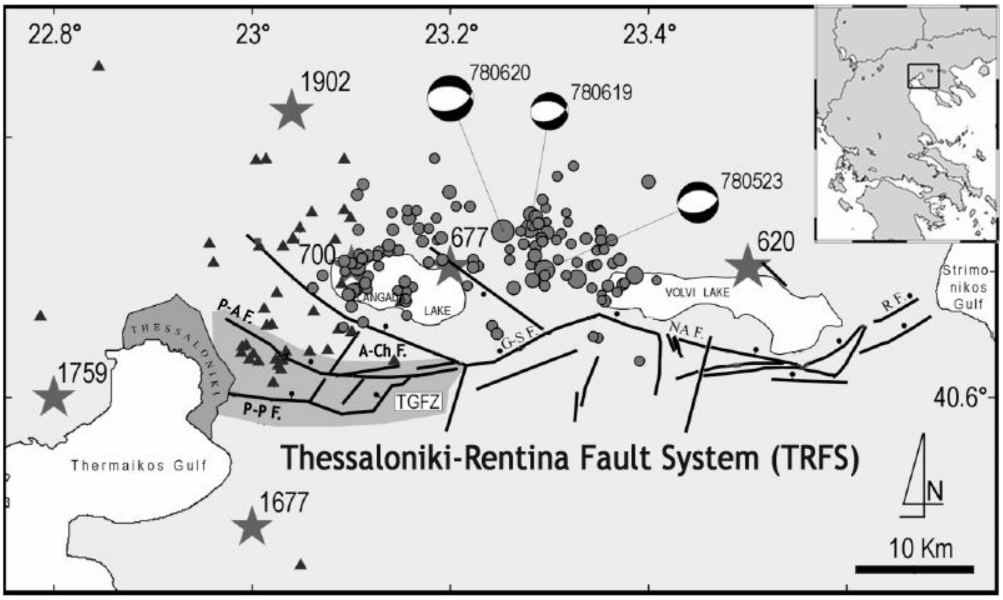

Figure 5: Active faults contributing to the seismic hazard in Thessaloniki, from Ameri et al (2008).

10 SOSEWIN nodes will be installed in 10 different buildings. The buildings will be selected based on their use, vulnerability, and typology of occupancy and location. Real-time measurements of ground motions in the different buildings will be used to produce real-time damage estimates after an earthquake, and to monitor structural response that can be indicative of possible changes in damage states during subsequent aftershocks. This task involves instrument installations and implementation of prototype systems. The testing of EEW algorithms from WP4 is under discussion.

The AHEPA general hospital in Thessaloniki is one of the largest hospitals in northern Greece. It is a major teaching and research hospital and part of the ESY (National Healthcare System of Greece). It covers all possible specializations of a large-scale major hospital (surgical, pathology, psychiatry etc). The hospital complex consists of 40 buildings of various functions and typologies, 2 electrical substations, a gas distribution network, and an underground water supply system. Many of these buildings were built before 1985 and are classified as low seismic code design structures. AHEPA hospital hosts ~750 beds and ~1900 employees. The supply of electric power is provided through 2 substations located inside the complex. The gas network includes 3 M/R stations, while the water system supply network of the hospital comprises two independent local networks with 2 underground water tanks and 2 pumping stations. In case of the emergency its central location in the city of Thessaloniki makes it one of the most important medical care centers for an efficient crisis management.

Two adjacent tall buildings of the hospital complex will be monitored using about 15 SOSEWIN nodes. These buildings host both administration and hospitalization activities. The preliminary instrumentation plan consists of installing (in both buildings) two sensors in the basement, two sensors in a middle floor, and three sensors on the roof.

At both the Thessaloniki port and the AHEPA hospital, the objectives are: 1) the application of methodologies developed in WP4 and WP5 for generating real-time risk estimates, 2) optimization of rapid, post-earthquake response based on real and scenario earthquakes, 3) installation of a real-time monitoring network, supported by GFZ; 4) estimation of expected damage after an earthquake in real or near-real-time, and monitoring structures for possible changes in damage states during aftershock sequences.

3. CONCLUSIONS

The REAKT selected applications represent the wide range of potentiality of real time earthquake risk reduction methodologies. The level of application has been chosen following the priorities indicated by each end user and is different for each case. It ranges from the provision of real time ground shaking distribution (for instance, the Sines industrial complex and Icelandic applications), to cost/benefit analysis and initial implementation of the EEW tools developed in SAFER and in REAKT WP4 (Swissnuclear, Istanbul area applications) to a combination of EEW and health monitoring (Thessaloniki applications and Circumvesuviana Railways).

It is expected that the outcomes of these studies will result in a clearer picture of the effectiveness of EEW and OEF in different cases and will also stimulate the development of the missing national laws and rules, which, are, up to now, a major constraint to the practical use of these methodologies.

ACKNOWLEDGEMENT
The WP7 team for the ten industrial applications include: Stefan Wiemer (ETHZ, Zuerich), Carlos Sousa Oliveira (IST, Lisbon), Iunio Iervolino and Bruno Montella (AMRA, Naples), Mustafa Erdik, Erdal Safak (Koeri, Istanbul), Jochen Zschau, Dino Bindi, Stefano Parolai (GFZ, Potsdam), Kyriazis Pitilakis (AUTH, Thessaloniki), Krystin Vogfjord, IMO, Reykjavik), Carlo Lai (EUCENTRE, Pavia), Tony Gibbs, (CCEO, Barbados), Walter Salazar and Joan Letchman (UWI, Trinidad) Efthimios Sokos (UPAT, Patras). The End User representatives for the various facilities are: Philippe Renault (swissnuclear), Isabel Pais (Sines), Arturo Borrelli (Circumvesuviana Railways), Hikmet Biyikoglu (IGDAS), Nurdan Apayin (General Directorate of State Highways, Fatih Sultan Mehmet Bridge), Georgios Vergoulas (AHEPA Hospital), Emmanouil Michailidis (Thessaloniki Port Authority), Vilbergur Kristinsson (Landsvirkjun), Ludvik Ogmundsson (Landsnet), Aris Stathopoulos-Vlamis (GEFYRA Consortium, Rion-Antirion Bridge), J. Kondilis (Civil Protection, Patras). This research was carried out in the framework of ECFP7 REAKT Project.

REFERENCES

Alcik H., O. Ozel, N. Apaydin and M. Erdik (2009), A study on warning algorithms for Istanbul earthquake early warning system, *Geophys. Res. Lett.*, **36,** doi:10.1029/2008GL036659

Allen R. M., P. Gasparini, O. Kamigaichi and M. Böse (2009), The Status of Earthquake Early Warning around the World: An Introductory Overview, Seism. Res. Lett., **80**, 682-693, doi:10.1785/gssrl.80.5.682

Ameri, G., F. Pacor, G. Cultrera, and G. Franceschina (2008), Deterministic ground-motion scenarios for engineering applications: the case of Thessaloniki, Greece, *Bull. Seism. Soc. Am*., **98**, 1289-1303 doi:10.1785/0120070114.

Böse M., F. Wenzel and M. Erdik (2008), PreSEIS: A Neural Network-Based Approach to Earthquake Early Warning for Finite Faults, *Bull. Seismol. Soc. A.,* **98**, 366-382, doi: 10.1785/0120070002

Colombelli, S., O. Amoroso, A. Zollo, and H. Kanamori (2012). Test of a threshold-based earthquake early warning method using Japanese data. *Bull. Seismol. Soc. Am* (in press).

Convertito, V., I. Iervolino, A. Zollo, G. Manfredi (2008). Prediction of response spectra via real-time earthquake measurements. *Soil Dyn, Earthq. Eng*. **28**, 492-505, doi:10.1015/j.soildyn,2007.07.006

Cua G. and T. Heaton (2007), The Virtual Seismologist (VS) Method: a Bayesian Approach to Earthquake Early Warning, in Gasparini P., Manfredi G. and J. Zschau (Eds.), *Earthquake early warning systems,* Springer-Verlag, Berlin, 97-132

Cua G., M. Fischer, T. Heaton and S. Wiemer (2009), Real-time Performance of the Virtual Seismologist Earthquake Early Warning Algorithm in Southern California, *Seismol. Res. Lett.,* **80,** 740-747, doi: 10.1785/gssrl.80.5.740

Erdik M., K. Sesetyan, M.B. Demircioglu, U. Hancılar and C. Zülfikar (2011), Rapid earthquake loss assessment after damaging earthquakes **,** *Soil Dynam. Earth*, **31**, 247-266, doi:10.1016/j.soildyn.2010.03.009

Iervolino, I. (2011). Performance-based earthquake early warning. *Soil Dyn, Earthq. Eng.* **31**, 209-222 Doi:10.1016/j.soildyn.2010.07.010

Iervolino I., Zollo A., Erdik M., 2011. Foreward to Prospects and applications of earthquake early warning. *Soil Dyn, Earthq. Eng.* **31** (2), 105.

Jordan, T., Chen, Y., Gasparini, P., Madariaga, R., Main, I., Marzocchi, W., Papadopoulos, G., Sobolev, G., Yamaoka, K., & Zschau, J. (2011). OPERATIONAL EARTHQUAKE FORECASTING. State of Knowledge and Guidelines for Utilization. *Annals Of Geophysics*, *54*(4). doi:10.4401/ag-5350

Satriano C., L. Elia, C. Martino, M. Lancieri, A. Zollo and G. Iannaccone (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.20110.06.008

Sesetyan K., C. Zulfikar, M. Demircioglu,U. Hancilar, Y. Kamer and M. Erdik (2011), Istanbul Earthquake Rapid Response System: Methods and practices, *Soil Dyn. Earthq. Eng.*, doi:10.1016/j.soildyn.2010.02.012.

Zollo A., O. Amoroso, M. Lancieri, Y. M. Wu and H. Kanamori (2010), A threshold-based earthquake early warning using dense accelerometer networks, *Geophys. J. Int.*, **183,** 963-974, doi: 10.1111/j.1365-246X.2010.04765.x