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REAL-TIME RISK MITIGATION TO CRITICAL INFRASTRUCTURES IN EUROPE: RECENT EXPERIENCES AND OUTLOOK.

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Abstract

The recent experience of the EC-funded project REAKT (Strategies and Tools for Real-Time Earthquake Risk Reduction has consolidated the research efforts of project SAFER (Seismic Early Warning for Europe) as to the use of real-time risk mitigation methods for a selected number of strategic facilities in Europe and worldwide through the development of response strategies to rapid earthquake information. Highly innovative in REAKT was the cooperation of academic experts and end-users throughout the project. Case studies in REAKT comprised: *i)* nuclear (in Switzerland), hydroelectric (in Iceland) and coal (in 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). In this contribution we present to the international engineering community the main achievements of the aforementioned component of the REAKT project, with a special focus on the use of earthquake early warning and operational earthquake forecasting for industrial facilities and critical public infrastructures. Emphasis is on the most successful applications as well as on the difficulties faced throughout the development of the work plans, with the aim of informing the vision for future similar projects.

Keywords: earthquake early warning, operational earthquake forecasting, real-time risk mitigation

1. Introduction

Project REAKT (Strategies and Tools for Real-Time Earthquake Risk Reduction, www.reaktproject.eu) was funded by the European Commission in 2011 within the 7th Framework Programme (contract number 282862). The project concluded at the end of 2014, after 40 months. The main goal of REAKT was to investigate the current limits and improve the efficiency of real-time earthquake risk mitigation methods and their capability of protecting critical structures, infrastructures and the population. REAKT developed methodologies to enhance the quality of information provided by operational earthquake forecasting (OEF), earthquake early warning (EEW) and real-time structural health monitoring (SHM) systems, and established best practices for how to use all of this information in a unified manner. Emphasis was on combining information into a probabilistic framework suitable for decision-making in real-time, including realistic estimates of the uncertainties involved.

REAKT gathered the main European institutions and research groups, in addition to major non-European ones, active on different aspects of earthquake early warning and operational earthquake forecasting. One of the work packages of the project, namely “WP7 - Strategic Applications and Capacity Building”, was devoted to applying and optimising the performance of real-time seismology methods to a variety of critical structures and infrastructures in Europe and worldwide (Fig. 1). The strategic applications included: *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 operational implementation efforts, based on the level of maturity expected to be reached by each application within the project timeline (~ 3 years originally).

Highly innovative in REAKT was the cooperation of academic experts and non-academic (private, public, industrial) end-users / stakeholders throughout the project, aimed at defining work plans for feasibility studies and implementation processes. While the original work plans for each applications were presented in [1, 2], we focus in this contribution - after the end of the project - on the main achievements of the work package. We highlight the most successful applications and their key features. We present the difficulties faced throughout the development of the work plans and our vision for a future similar project, with emphasis placed on optimising the interaction between academia and end-users of real-time seismology methods and tools.

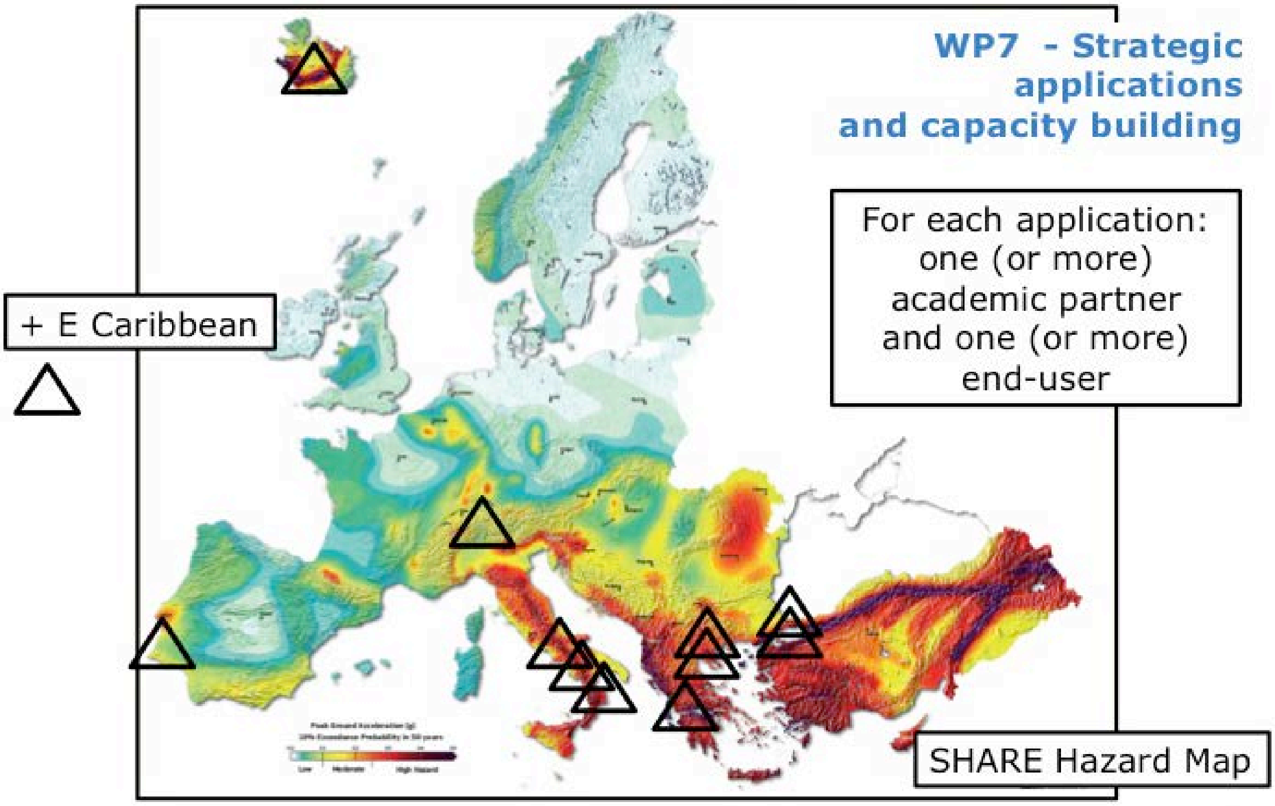


Fig. 1 – Overview map of the strategic applications of REAKT WP7 in: Portugal (Sines industrial site [3]); Switzerland (swissnuclear power plants [4]); Italy (Circumvesuviana railway [5], schools in Campania [6], Italian national strong-motion network RAN [7, 8]); Greece (Rion-Antirion bridge [9], port of Thessaloniki [10], AHEPA hospital in Thessaloniki [11]); Turkey (Istanbul gas network [12], Istanbul FMS bridge [13]); Iceland (hydropower plants and distribution grid [14]); the territories of the Eastern Caribbean (a variety of public and private structures and infrastructures [15]). Shown as background is the seismic hazard map (peak ground acceleration *PGA* on rock-like ground type and 475 years return period) developed in project SHARE [16]. The majority of applications is located in areas od comparatively higher seismic hazard. Adapted from [17].

2. The strategic applications of REAKT at a glance

In this section we present a graphic summary of the main achievements of REAKT WP7 for each strategic application (Task). For each Task we list in Fig. 2, 3, 4, and 5 the main academic partner and end-user (first column in each picture), the key issues investigated and results obtained (second column), and one or more representative pictures / snapshots. Namely, the strategic applications of REAKT were:

- Task 7.2: Feasibility studies and initial EEW implementation efforts for nuclear power plants in Switzerland;
- Task 7.3: Feasibility studies on EEW applications for the Sines industrial complex, Portugal;
- Task 7.4a: Feasibility studies on EEW application to the Circumvesuviana railway, Naples, Italy;
- Task 7.4b: Feasibility study on the use of EEW information and initial implementation efforts at high-schools in Campania, Italy;
- Task 7.5: Feasibility study on the implementation of hybrid EEW approaches based on the stations of the Italian national strong-motion network (RAN);
- Task 7.6: Risk assessment and initial implementation efforts for using EEW to protect the IGDAS Natural Gas Network, Istanbul, Turkey;
- Task 7.7a: Risk assessment and initial implementation efforts for using EEW to protect the Thessaloniki Port, Greece;
- Task 7.7b: Risk assessment and initial implementation efforts for using EEW to protect the AHEPA Hospital, Thessaloniki, Greece;
- Task 7.8: Near-real-time probabilistic seismic hazard mapping in Iceland;
- Task 7.9: Feasibility study of a regional EEW system for the Eastern Caribbean Islands;
- Task 7.10: Initial implementation efforts for an EEW system to protect the city of Patras, Greece, with special focus on the Rion Antirion bridge;
- Task 7.11: Risk assessment and initial implementation efforts for using EEW to monitor structural health of the FSM Suspension Bridge, Istanbul, Turkey.

Tasks 7.2, 7.4b, 7.5, 7.6, 7.9, 7.7&7.10 were selected as highlights of REAKT WP7, *i.e.*, as the applications the achieved the highest level of maturity, with interesting and innovative results.

Task 7.2 focused on the optimisation of the Virtual Seismologist (VS [18, 20]) for improving situational awareness of nuclear power plants operators in Switzerland. VS is a network-based EEW algorithm originally developed at Caltech [28]. Delivering EEW information to swissnuclear required: (a) the parameterisation of the semi-stochastic ground-motion prediction model of [29] following [30]; (b) the implementation of site-specific amplification factors as a function of magnitude and bedrock *PGA*; (c) adopting the ground motion to intensity conversion equations of [31]; and (d) displaying peak values of ground motions and response spectra in a dedicated graphic user interface, along with reference design and serviceability spectra at the plant [18].

The main result of Task 7.4b is that the technical high-school Majorana in Somma Vesuviana now runs a demonstration EEW system. The alerts are based on the EEW algorithm PRESTOPlus (www.prestoews.org, [21]) and the recordings of the Irpinia Seismic Network, ISNet. Notable is that the stations installed at the school within the framework of REAKT contribute 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. The instrumentation consists of a high-quality (broadband CMG-5TC accelerometer and 24-bit Agecodagis Kephren datalogger) accelerometric station installed in the courtyard and four SOSEWIN [32] accelerometric stations school deployed at different locations within the building.

Task 7.5 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. 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.

Within Task 7.6, the IGDAS monitoring network (110 strong-motion accelerometers installed at district regulators within the first half of REAKT) was integrated within the Istanbul Earthquake Early Warning and Rapid Response System. The key elements of the operational system are: (a) EEW information is sent from IGDAS headquarter (Scada Center) to the IGDAS stations in case of event detection; (b) automatic interruption of gas distribution at district regulators if ground-shaking parameters (*PGA*, *PGV*, *Ia*, *CAV*, *CAV5*, *PSA*, *PSV*, *SD*, *SI*) and / or their combination threshold values are exceeded; (c) computed shaking parameters sent from stations to the IGDAS Scada Center and KOERI (Kandilli Observatory and Earthquake Research Institute); (d) integrated damage maps are prepared immediately after the earthquake.

Notable in Task 7.9 was 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.

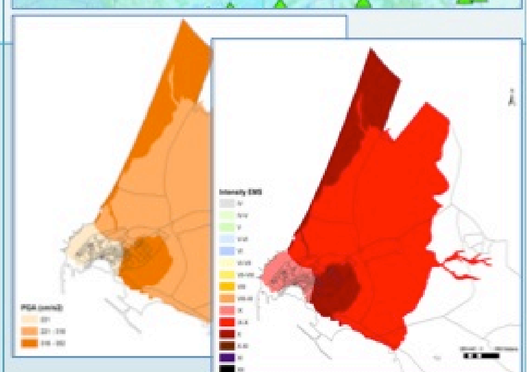
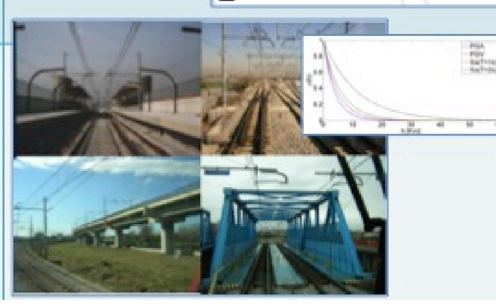
Task 7.2 (ETHZ & swissnuclear)	• VS performance assessment, based on datasets from Switzerland and California • Customisation of User Display for swissnuclear, messages sent from VS@ETH • Feasibility study on the use EEW and OEF at nuclear power plants; scrutiny of mitigation actions, costs and benefits • Situational awareness seen as a benefit for enhanced preparedness of operators in control rooms	
Task 7.3 (IST & GALP, REN, EDP, other Sines industries)	• GIS risk scenario simulator for SINES implemented • Inclusion of EEW information into stakeholders risk analyses • National workshop for potential end-users • More than 80% of end-users consider *"upmost importance to install a warning system for earthquakes and tsunamis"*; preliminary CBA indicates benefits 3 times larger than cost	
Task 7.4a (AMRA & Circumvesuviana)	• feasibility study on the use of performance-based EEW for the Circumvesuviana railway, based on advanced real-time hazard models	

Fig. 2 – Overview of task 7.2, 7.3 and 7.4a. From top to bottom, the pictures show: an open-source early warning display developed within the project [18], capable of monitoring different targets and showing background shaking maps; planning shaking scenarios for the industrial complex of Sines; viaducts of the Ciurcumvesuviana railway and their fragility curves.

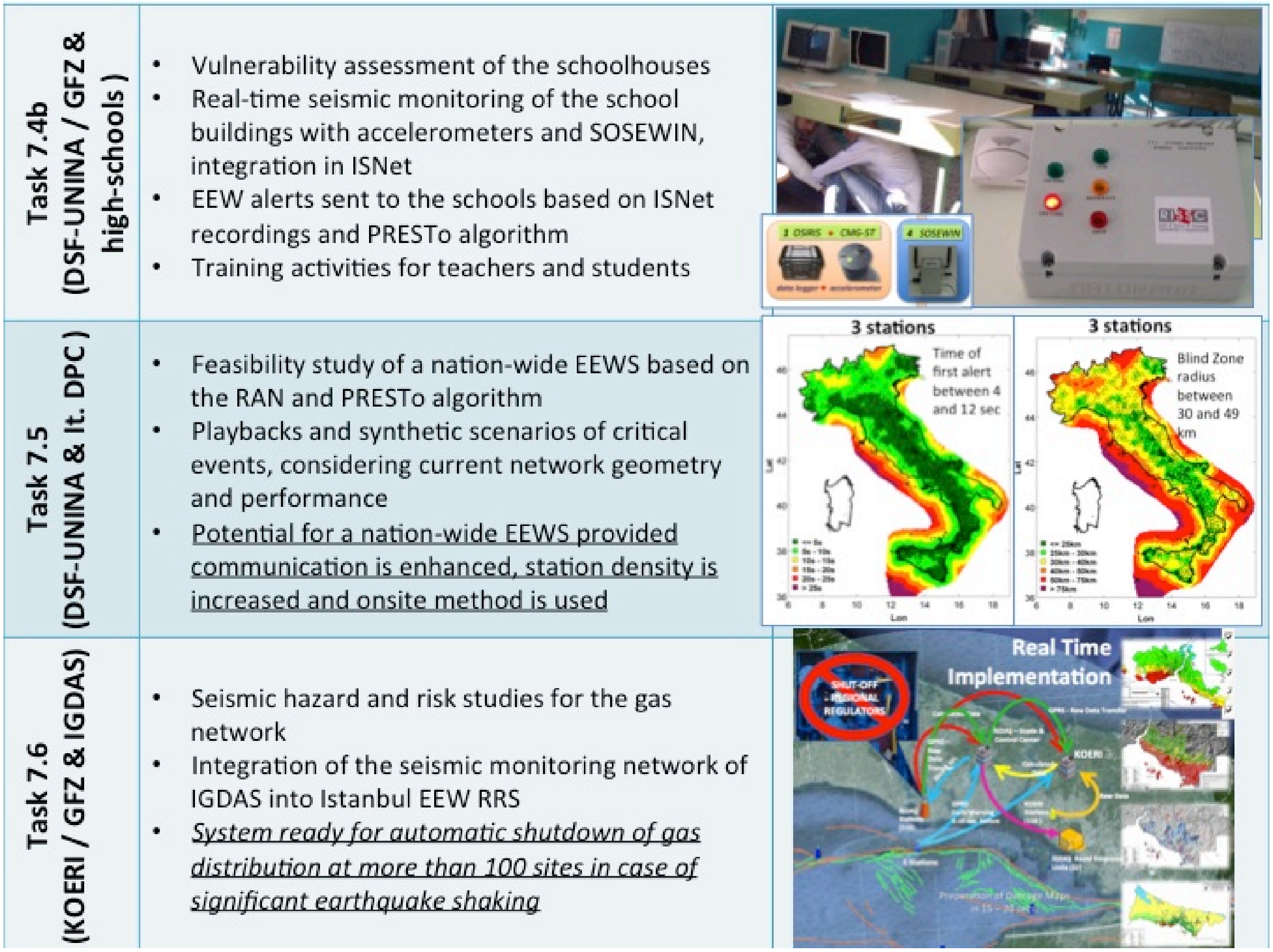


Fig. 3 – Overview of task 7.4b, 7.5 and 7.6. From top to bottom, the pictures show: a picture taken during an earthquake drill in a high-school and the Sentinel, *i.e.*, an EEW system for schools in Campania developed by high-school students; lead-time scenarios for an EEW system using the station of Italian national strong-motion network (RAN); the complex dependencies of the EEW and rapid response system used in Istanbul to mitigate earthquake risk to the local natural gas network.

Task 7.7 and 7.10 represented a notable example of proactive collaboration among different research centres in Greece and resulted into a first prototype implementation of EEW for the country. VS [20] is now used both in Patras (University of Patras, UPAT) and Thessaloniki (Aristotle University of 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 the two seismogenic sources that have the potential to affect the bridge since they generated strong events with ***M***~7 in the past. At AUTH, EEW from VS(SC3) is complemented with prototype installations of PRESTo [21] 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.

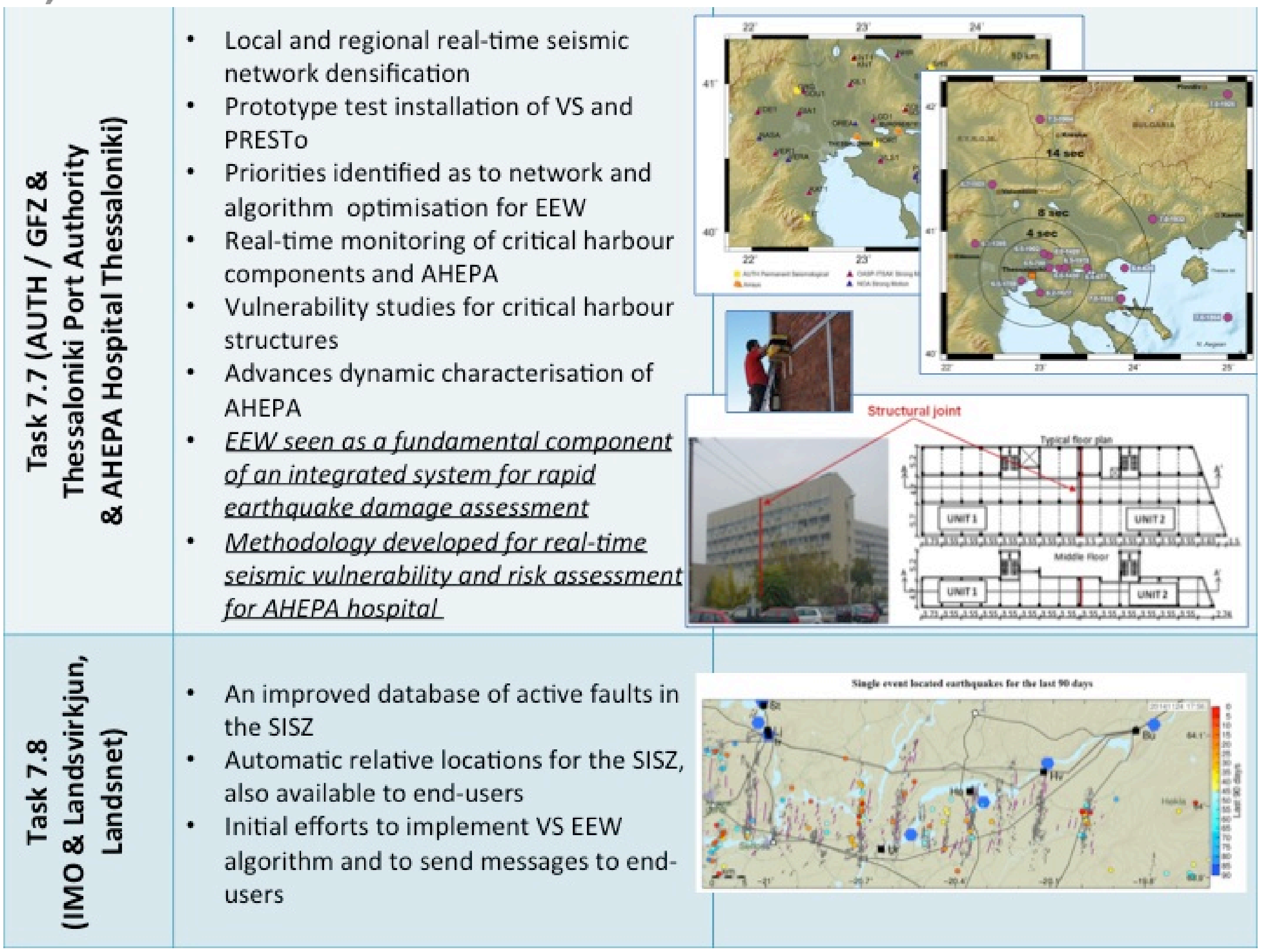


Fig. 4 – Overview of task 7.7a,b, and 7.8. From top to bottom, the pictures show: network configuration and lead-time scenarios for the area of Thessaloniki along with the installation of a SOSEWIN at the harbour of Thessaloniki; the AHEPA hospital in Thessaloniki and its structural outline; real-time relative relocations for the South Iceland Seismic Zone (SISZ).

3. End-user involvement and feedback

As previously mentioned, a key innovative component of REAKT was the cooperation of academic and industrial partners for the development and implementation of the work plans. End-user involvement and interaction was seamlessly sought throughout the project and continued after the conclusion of the project. End-user participation was facilitated by the organisation of dedicated events and outreach / dissemination activities comprising conference special sessions and workshops. The final comments and suggestions received by the representatives of end-users in REAKT are given in [19]. The majority of end-users contributed to these surveys 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 was found in the majority of the questionnaires received. Notable amongst the end-user recommendations are original ideas like, *e.g.*, the establishment of a European distributed EEW system, presently a major technical and political challenge

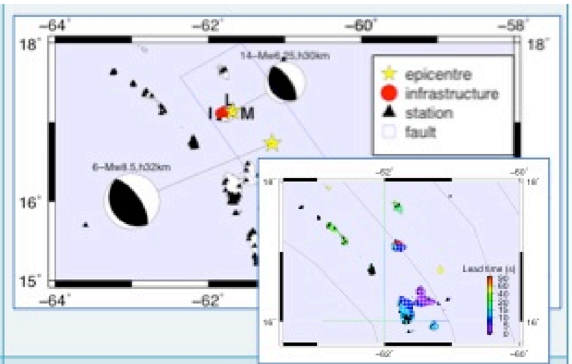
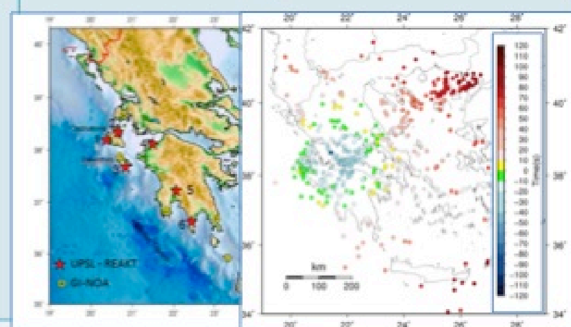
Task 7.9 (EUCENTRE / UWI & CCEO)	• Synthetic finite-fault shaking scenarios for several critical facilities in Territories of the E Caribbean • Performance evaluation of VS algorithm based on synthetics; <u>usefulness of EEW for MCE scenario (M_w8.3), i.e. moderate or even complete damage expected with a lead-time of 9-10 s</u> • Regional workshop for potential end-users	
Task 7.10 (UPAT & GEFYRA, Civil Protecton)	• Local / regional network densification • VS test implementation (first time in Greece) and performance evaluation • Priorities identified as to VS and network optimisation for EEW • EEW emails sent to Gefyra (and AUTH) • <u>With current implementation, EEW already possible from S Peloponnese and W Cephalonia</u>	
Task 7.11 (KOERI / GFZ & KGM)	• real-time structural monitoring of the FSM bridge based on 12 tri-axial accelerometers and ad-hoc processing software	

Fig. 5 – Overview of task 7.9, 7.10 and 7.11. From top to bottom, the pictures show: lead-time scenarios of potentially damaging earthquakes for selected infrastructures in the territories of the Eastern Caribbean; lead-time maps for the Rion-Antirion bridge in Patras based on earthquake catalogue of Greece; the outline of the structural monitoring network of the FSM bridge in Istanbul.

End-users of regional (network-based) EEW algorithms typically requested additional research and technical efforts to improve the reliability of the estimates of the probability of corrects alerts *P(C)*, missed alerts *P(M)* and false alerts *P(F)* and appreciated the impact of seismic network quality and geometry on these quantities. All end-users actively involved in REAKT became aware of the relationship between available operational lead-time and levels of shaking. The preparation of lead-time scenarios and their comparison with real-time operations made dramatically apparent the need for network optimization (geometry / telemetry) for many countries / seismic networks participating in REAKT (see *e.g.*, [20]). Most end-users are still interested in receiving alerts based on ground-shaking levels, while a few of them requested that structural response parameters were delivered by the EEW system, consistent with a risk-oriented decision-making approach.

A large group of end-users and their academic partners asked for a user-friendly display of EEW messages. This was our reason to develop free and open-source software to display EEW information in real time, in an user-friendly, end-user oriented, customisable way. The original idea was to promote a community effort to develop a prototype client-side EEW end-user software (similar to the CISN ShakeAlert UserDisplay developed by Caltech) to build a European Early Warning Display 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. The software design and development was carried out by the Swiss Seismological Service (SED), the University of Napoli Federico II (UNINA) and gempa GmbH (https://www.gempa.de/). The European Open-Source Early Warning Display (EEWD) including its source code is freely distributed to interested partners through the REAKT website and GitHub (see [18]). The software is open-source and interested users are welcome to contribute to further developments, in particular to the inclusion of custom GMPEs, GMICEs, and intensity prediction equations (IPEs). Users who are willing to contribute to code development should contact SED and UNINA to coordinate the activities. The main elements of the EEWD GUI are sketched in Fig. 6.

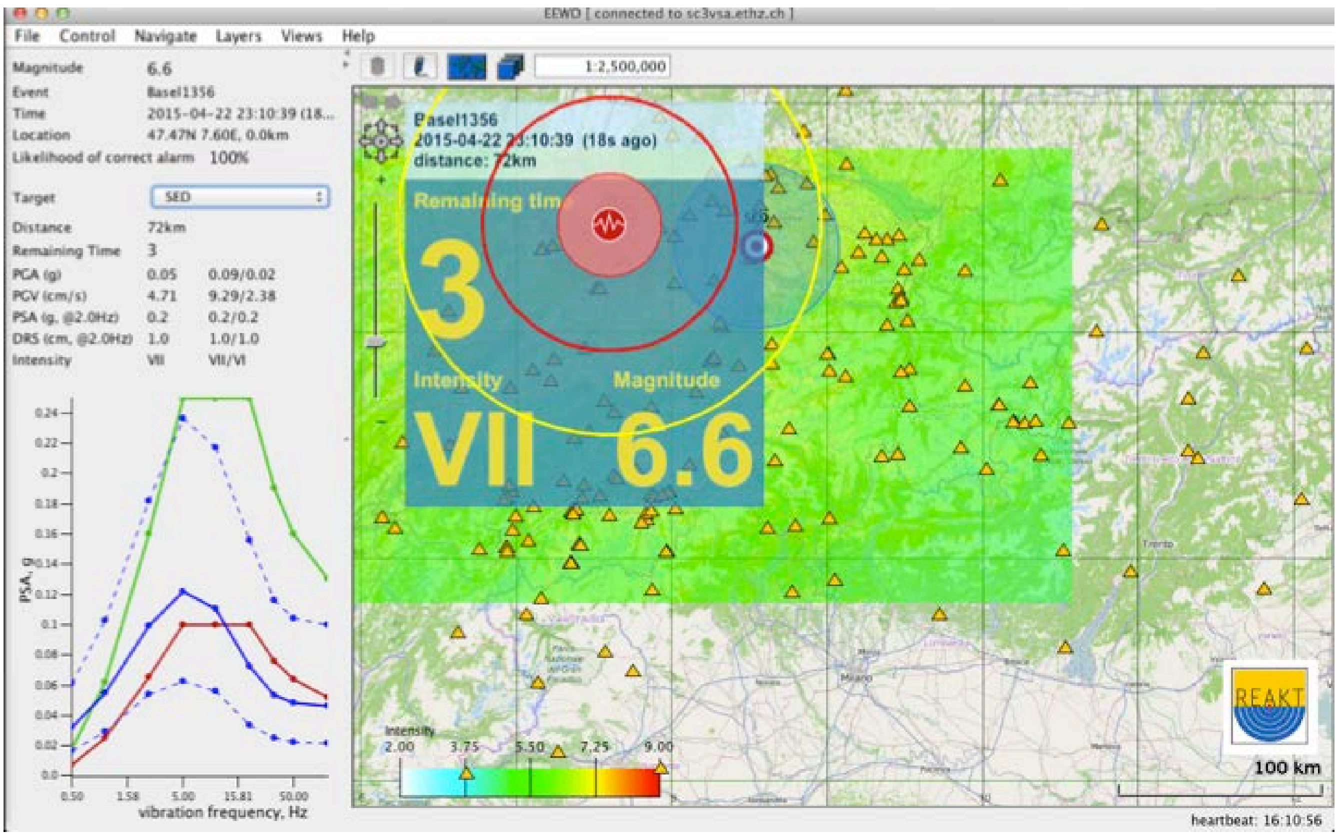


Fig. 6 – The open-source end-user earthquake information display developed in REAKT (see [17]).

4. Lessons learned and outlook

The experience of REAKT WP7 is presently being summarised in a special volume of the Bulletin of Earthquake Engineering, comprising some selected case studies [4, 6, 9, 11, 12, 15, 26] and three introductory papers on EEW, OEF and real-time structural monitoring [22, 23, 24].

Apparent from the REAKT WP7 experience is a strong potential for OEF not yet fully developed. While OEF proves very useful to enhance situational awareness in times of heightened earthquake hazard and can support EEW algorithms narrowing the search for earthquake location and magnitude [4], its routine application to mitigate seismic risk at structures and infrastructures of public and strategic interest requires solving issues that are today “formidable at least and unsolvable at worst” [23]. The main obstacle to coordinated European developments is “heterogeneity: of seismic stations, of data quality and availability, of seismicity rate and faulting styles” [23] along with unstable funding. Even so, there are significant progresses, especially in Iceland, Italy and Switzerland. Key to the transfer of OEF from the academic world to strategic applications will be moving from hazard information to statements about risk within the framework of operation earthquake loss forecasting [25, 26].

As to the real-time seismic monitoring of structures, REAKT presented interesting innovative possibilities offered by the increased availability of wireless sensing and computer units [22, 27], allowing the combined implementation of different approaches to real-time seismic risk assessment (*e.g.*, PBEEW, SHM) in a single hardware infrastructure local to the building or the structure of interest.

Earthquake Early Warning (EEW) was by far the real-time seismology tool better investigated in WP7. EEW system feasibility or implementation was a core element of all case studies in WP7. The strategic applications that focused since the beginning on the implementation of real-time risk mitigation strategies successfully reached operational demonstration level (*e.g.*, use of EEW at schools in Campania, EEW and real-time damage assessment for the IGDAS gas network in Istanbul). The most successful applications in REAKT were characterised by three key features:

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.

With this background we believe that a future project similar to REAKT should mainly focus on a limited number of 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. It is likely that future EEW systems across Europe will “at least partly replicate the first successful examples of REAKT in terms of end-user engagement, and in terms of algorithms will leverage the community solutions developed at major universities, though there is a definitive need to tailor any EEW system to local needs and experience” [24]. While a major issue facing core developments and coordination of EEW groups in Europe is that of the short duration of centralised funding from the European Commission, we hope that worldwide successes of EEW will demonstrate to European stakeholders the value of investing in EEW and will eventually stimulate direct private financial support from end-users.

4. Acknowledgements

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