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The contribution of EUROSEISTEST and building monitoring arrays in Earthquake Early Warning and Rapid Damage Assessment in Thessaloniki

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ABSTRACT

We present initial results from the incorporation of strong motion data from instrumented sites and buildings in the area of Thessaloniki in a recently established Earthquake Early Warning (EEW) and rapid damage assessment system. Data from structures monitoring networks are repeatedly processed to compute up-to-date fragility curves, taking into account the actual state of the buildings (e.g. ageing effects of the construction materials, possible pre-existing damages, changes in geometry and mass distribution). In the case of an earthquake alert message, the expected (or on-site recorded, if available) peak ground acceleration value is combined with the building-specific fragility curve to provide a rapid assessment of the most probable level of damage during strong ground shaking. Off-line testing with data from past earthquakes, widely felt in Thessaloniki, provide satisfactory results.

Introduction

Exposure and vulnerability of modern cities to earthquake hazard lead to an emerging need for developing operational frameworks that can be used by the authorities (e.g. civil protection, medical services, public building administrators, industry) to establish decision making procedures and risk mitigation strategies. An Earthquake Early Warning (EEW) and rapid damage assessment system, which detects imminent strong shaking and provides alerts on the expected level of damage on a building-specific and structure-specific scale in general, could prompt actions toward the protection of life and property. Even if "lead time" of such an alert, i.e. the period from the moment of alert issuing until the moment of strong shaking, is too short to prompt actions, even automatic ones, end users still acknowledge the usefulness of the service toward situation awareness. The effectiveness of such rapid systems greatly depends on the amount and quality of available real-time data of ground shaking. This leads to a need of maximum engagement of already existing networks, such as permanent monitoring stations and special networks, as for example for building and lifelines monitoring.

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A combination of newly installed networks with pre-existing arrays (i.e. EUROSEISTEST) was recently pursued in the frame of the REAKT project (European Community's Seventh Framework Programme, FP7/2007-2013) in Thessaloniki, in Northern Greece. In this work we present a brief description of the cooperating arrays and networks and of the use of their data toward the establishment of an EEW and rapid damage assessment system for the city.

The Case of Thessaloniki – Monitoring Networks

Thessaloniki is located in Northern Greece and is the second largest Greek city with a population of over one million. It is also one of the most well studied urban areas worldwide regarding the fields of earthquake engineering and engineering seismology. The city's historical record of disastrous earthquakes (Figure 1a) implies that seismic hazard is imposed primarily by nearby faults, although damage to buildings has also been caused by quite distant (hundreds of kilometers) large-magnitude earthquakes (i.e., the 1928, M7.0 Plovdiv earthquake or the 1864, M7.6 North Aegean earthquake whose epicenters are plotted in Figure 1a). The most recent severe event that affected the built environment of Thessaloniki was a M6.5, on the 20th of June in 1978, at approximately 30 km to the east-northeast from the city center. The 1978 earthquake resulted in 50 deaths and a significant number of severely damaged buildings.

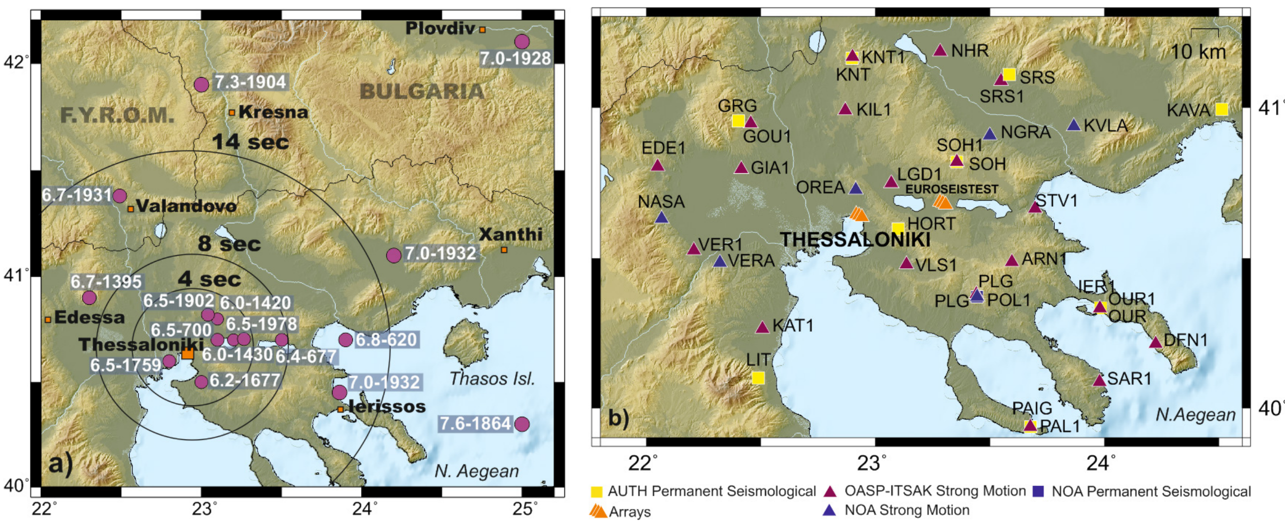

Figure 1. a) Map with locations of past earthquakes that are known to have affected the built environment of Thessaloniki. Black circles denote approximate S-P time to the city center. b) Stations distribution (strong motion and seismological) at the broader area of Thessaloniki. The EUROSEISTEST array is located at the epicentral area of the M6.4, 1978 earthquake.

The broader area of Thessaloniki is being relatively densely monitored by permanent seismological and strong motion stations (Figure 1b). These stations are operated by the Aristotle University of Thessaloniki (AUTH), the National Observatory of Athens (NOA) and the Institute of Engineering Seismology and Earthquake Engineering (OASP-ITSAK). In the frame of the REAKT project, the Research Unit of Soil Dynamics and Geotechnical Earthquake Engineering of AUTH (SDGEE-AUTH), in close cooperation with the German Research Center for Geosciences, GFZ, managed to combine data from these existing networks with data from newly installed arrays in selected buildings and facilities in Thessaloniki in order to use them in an EEW and rapid damage assessment system. At present, data being used by this system come from:

1. The EUROSEISTEST network (http://euroseisdb.civil.auth.gr, Pitilakis et al., 2013). EUROSEISTEST is an array of 21 accelerometric stations, 6 in boreholes and 15 at surface, which has been in operation since 1993. The communication components of the network hardware were recently upgraded to ensure continuous, real-time data flow. EUROSEISTEST is located at the epicentral area of the 1978, M6.5 earthquake, which remains one of the most hazardous in terms of earthquake potential for the city of Thessaloniki.
2. Building monitoring SOSEWIN arrays. GFZ and SDGEE-AUTH have recently installed several arrays of SOSEWIN short-period accelerometers aiming to monitor targeted building (e.g. Bindi et al., 2014; Karapetrou et al., 2014), i.e. one of the buildings of the central AHEPA hospital, consisting of two units (Figure 2) with a structural joint, one of the buildings at the port and two buildings at AUTH campus. Data from these arrays are being used to monitor in real-time the seismic response of the buildings, but are also incorporated in the EEW system.
3. Three permanent broadband accelerometric stations operated by AUTH inside Thessaloniki.
4. Five acceleration stations of the NOA (NASA, VERA, OREA, PLG, NGRA in Figure 1b).

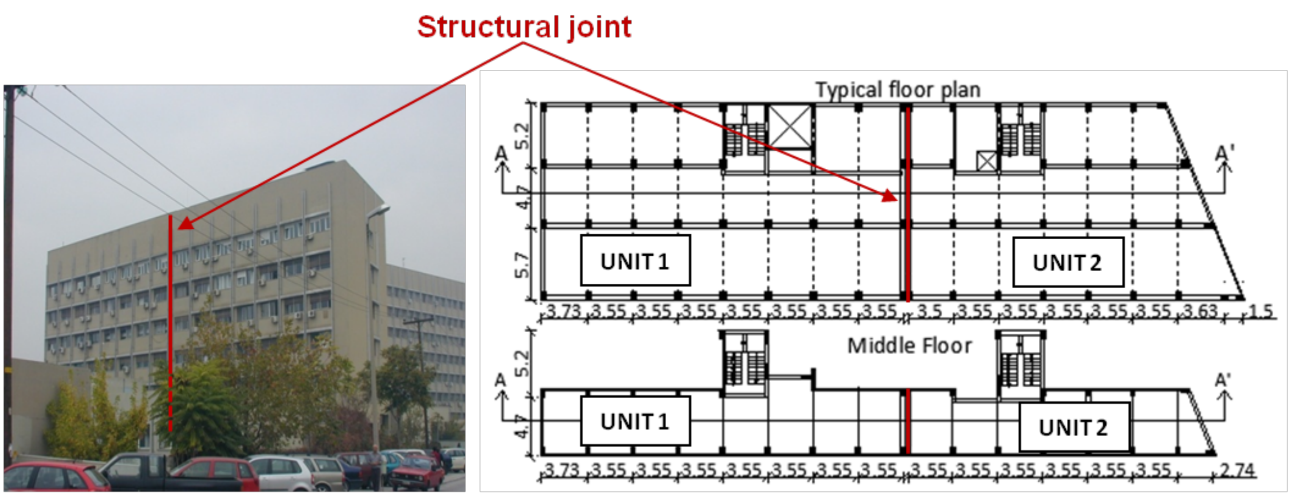

Figure 2. The monitored building in the AHEPA hospital complex: typical floor plan and middle floor with the structural joint.

Re-assessment/Update of Buildings/Facilities Vulnerability

Part of the monitoring networks data are being used to re-assess/update the vulnerability of monitored buildings and/or facilities. The use of field monitoring data constitutes a significant tool for the representation of the actual structural state, reducing uncertainties associated with the building modeling properties as well as many non-physical parameters (ageing effects, maintenance, etc) enhancing thus the reliability in the risk assessment procedure. Building monitoring data are used to identify the actual model properties of a structure based on system identification and operational modal analysis (Reynders 2012). The modal identification results are used in the context of finite element model updating to yield more reliable structural models with respect to their real conditions in terms of structural detailing, mass distribution and material properties. In Figure 3 we present an example comparative plot of building-specific fragility curves for the initial and updated finite element models of the monitored hospital building units in the AHEPA complex (Karapetrou et al. 2014). The initial models are based on the design and construction plans and reflect the as-built state of the buildings, while the updated models have been derived using data from dense arrays of broadband instruments temporarily installed on the monitored structures, and describe the buildings current state of health. It is seen that the up-to-date curves present a shift to the left in comparison to the initial ones for both damage states considered (IO: Immediate Occupancy, CP: Collapse Prevention), indicating an increase in the structure's vulnerability. Since we have no reports on geometrical modifications of the initial model or significant damages from past earthquakes, we attribute the increase of the building's fragility to ageing effects (e.g., corrosion). We note that differences between the initial and updated models are much more noticeable for the Collapse Prevention (CP) damage state and not for the Immediate Occupancy (IO) one, which is expected as structural deterioration due to ageing effects would lead to a more brittle failure mechanism.

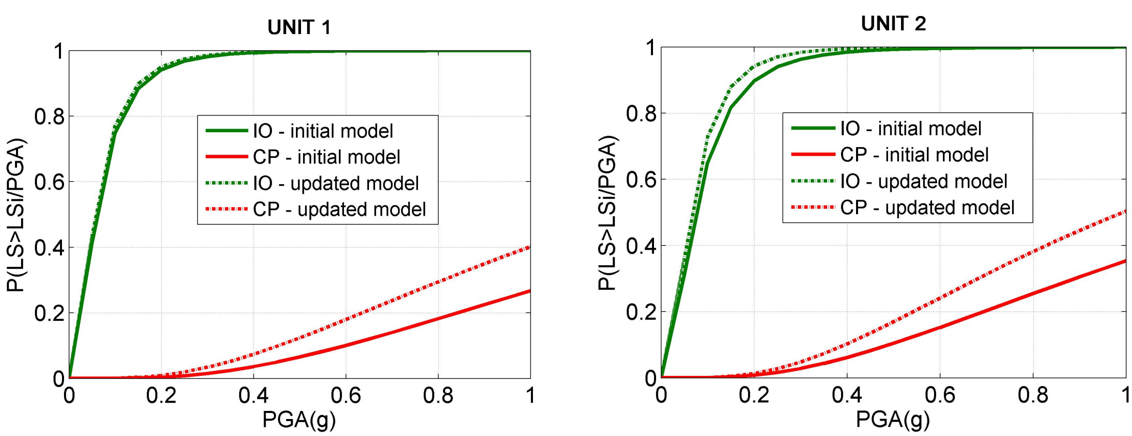

Figure 3. Comparative plot of the building-specific fragility curves derived for the initial and updated building units of the AHEPA hospital in Thessaloniki.

Earthquake Early Warning

The updated fragility curves are incorporated as input data in the overall EEW and rapid damage assessment system. In order for the fragility curves to be used in the rapid damage assessment part of the methodology, a trigerring mechanism is needed. This is provided by the EEW system and its output earthquake alert messages. At the present, several EEW approaches and codes are being tested in real-time in Thessaloniki. Among them, are the PRESTo EEW software (PRobabilistic and Evolutionary early warning SysTem, http://www.prestoews.org) (e.g. Satriano et al., 2008; Lancieri and Zollo, 2008; Zollo et al., 2010; Satriano et al., 2011) and an onsite EEW algorithm implemented on the SOSEWIN instruments that have been installed at the selected buildings in Thessaloniki.

PRESTo has been in pilot, real-time application since June 2014, but so far no significant earthquake has occurred in the monitored region. Based on the geographical distribution of the available strong motion stations, we expect PRESTo to be able to provide EEW messages for earthquakes close to the epicentral area of the 1978, M6.4 event. To test this capability, we used the strong ground motion records dataset that has been collected during the 20-years of operation of the EUROSEISTEST array to playback events from the specific area. After simulating more than 20 weak-to-moderate events, our basic conclusion is that EUROSEISTEST stations on their own cannot provide accurate estimates of the source parameters of earthquakes that occur in the specific area unless they are complemented by data from at least one more distant station.

SOSEWIN units contribute their data as parts of the regional EEW network used to run PRESTo, but are also used as stand-alone units for onsite EEW and probabilistic damage assessment. The underlying methodology from the event detection stage to the probabilistic damage assessment is outlined in the following section.

Rapid Damage Assessment System

Two different approaches have been under testing for the post-earthquake damage assessment of the selected instrumented buildings in Thessaloniki. The first approach is intrinsically related to the onsite EEW and fully implemented inside each SOSEWIN unit, whereas the second is 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.

Onsite Probabilistic Damage Assessment

The computational power of each SOSEWIN sensing unit allows each node to self-query and process in real-time the recorded data and to disseminate the results through the network. The installation in each sensing unit of an algorithm for performing on-site analysis is under testing. The main steps of the algorithm, labelled from A to G, are sketched in Figure 4. The initial step in the methodology (A) includes the filtering of the real-time data streams using a 4th order recursive Butterworth band-pass filter (typically 0.075–25 Hz). Then, an event detection algorithm based on short-term average/long-term average (STA/LTA) is applied. When the ratio exceeds a predefined threshold (B), a trigger condition is declared. Once triggered, the node computes several parameters over a window with pre-defined duration (typically 3 seconds; C). The most relevant parameters are the maximum acceleration, velocity (D in Figure 4), displacement (E in Figure 4) and the predominant period. If selected, the parameters measured over the early P-wave arrivals are used to predict some parameters for the S-wave, by using empirical relations (F in Figure 4). For example, the PGV for S-waves can be predicted from the PGD over P-wave using the Zollo et al (2010) empirical relationship. If fragility curves for PGV are uploaded in the system, then the probability of damages can be predicted in early-warning time. After the trigger, the algorithm produces messages at regular time (e.g., 1sec) including the peak ground motion parameters and the probability of damages accordingly to the fragility curves uploaded in the system for the specific monitored building, considered the PGA as demand parameter (G in Figure 4).

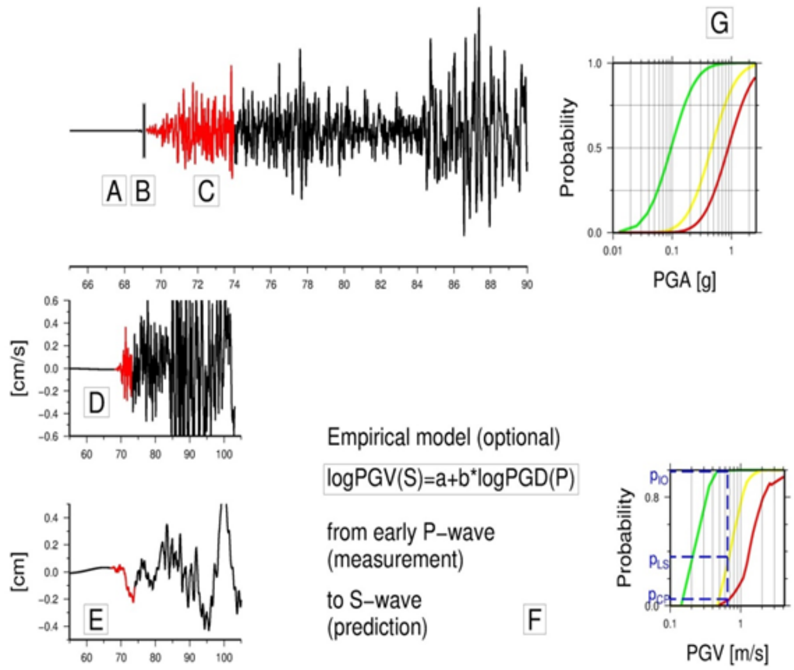

Figure 4. On-site algorithm for decentralized damage assessment. Labels from A to G are described in the text.

Externally triggered algorithm for building-specific probabilistic damage assessment

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. If not, 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 triggers the post-earthquake damage assessment procedure is a peak value of the ground acceleration (PGA). In the subsequent step, the available information on the PGA is combined with the pre-defined building-specific fragility curves to produce realistic estimates of the expected levels of damage.

The methodology has not been validated/verified in real-time as the EEW system is still under testing and furthermore no significant earthquake, in terms of damage potential, has occurred within the pilot operation time frame. However, we have performed tests in play-back mode, by feeding the corresponding code PGA values that have been observed at different sites in Thessaloniki in the past. Damage assessment has been conducted for a two-unit hospital building (AHEPA) that was studied in detail during the REAKT project. Basic parameters of the events that were selected to perform the tests are summarized in Table 1.

A common characteristic of the events presented in Table 1 is that they were widely felt throughout Thessaloniki, even though the ground motion level at most of them was quite weak. The 1978 mainshock (No 2 in Table 1) provided the strongest available record and in fact caused slight damage to the monitored buildings of AHEPA hospital.

Table 1. Basic source parameters, description of recording sites and recorded values of peak horizontal acceleration for the six events used to test the performance of the probabilistic damage assessment algorithm.

No	Date	Origin Time	Lat (°)	Lon (°)	h (km)	M	Recording site (RS) code	RS from AHEPA (km)	RS from Port (km)	Peak Ground Horizontal Acceleration (%g)
1	19780523	23:34:12	40.680	23.340	6.	5.8	CITY HOTEL	1.9	1.35	0.048
2	19780620	20:03:21	40.610	23.270	6.	6.5	CITY HOTEL	1.9	1.35	0.150
3	20050420	07:52:40	40.807	22.935	11.	4.2	Seismological Station	0.32	3.26	0.0043
4	20050912	19:08:30	40.695	23.363	2.	4.8	Seismological Station	0.32	3.26	0.0029
5	20131011	05:15:47	40.689	23.410	4.	4.4	Municipality Library (Station LIB of ITSAK)	0.81	2.45	0.0054
6	20140716	16:14:58	40.569	22.948	12.	3.0	Station TGMA of AUTH	0.17	3.17	0.0080

Table 2 Estimated probabilities (%) for different levels of damage at the two units of the monitored AHEPA building based on input peak ground acceleration values that have been recorded at close-by to the buildings sites in the past. Event numbering is as in Table 1.

			UNIT1			UNIT2		
Event No	PGHA (%g)	State of the Building	No damage	Immediate Occupancy	Collapse Prevention	No damage	Immediate Occupancy	Collapse Prevention
1	0.048	Initial	60.70	39.30	0.00	70.70	29.30	0.00
		Current	58.53	41.47	0.00	66.00	34.00	0.00
2	0.150	Initial	11.66	88.18	0.16	18.33	81.40	0.27
		Current	10.12	89.56	0.32	12.10	87.46	0.44
3	0.0043	Current	99.95	0.05	0.00	100.00	0.00	0.00
4	0.0029	Current	100.00	0.00	0.00	100.00	0.00	0.00
5	0.0054	Current	99.89	0.11	0.00	99.97	0.03	0.00
6	0.0080	Current	99.47	0.53	0.00	99.81	0.19	0.00

The results of the probabilistic damage assessment for the different levels of input motion in Table 1 are presented in Table 2 for the two monitored units of the AHEPA.

In the case of AHEPA, we have used the fragility curves that have been computed for each one of the two units. For the two 1978 events, which occurred quite soon after the construction of the monitored building (in 1971), we checked both the initial fragility curves, which probably describe better the state of the building at the time of the events, as well as the present fragility curves as they have been transformed by the ageing of the construction. The resulting damage potential values as were computed for the 1978 mainshock (Event No 2 in Table 1) indirectly suggest a larger ageing effect for UNIT2 as its current fragility curve increase the probability of damage in general by 6.23% compared to corresponding estimations with the initial fragility curve of the unit. Similar computations for UNIT1 suggest an increase in the probability of damage of 1.54%. The largest probabilities for damage at the two units were computed for the 1978 mainshock and correspond to the “Immediate Occupancy” level, thus suggesting slight damage, which was in fact the case after this destructive, for other buildings in the city, event. All other weak events tested provide probabilities of practically 0% for any kind of damage at the two units.

Conclusions

This work comprises an example of how permanent networks and special arrays such as those implemented for building monitoring or for geotechnical studies can be incorporated into a single system toward rapid damage assessment from earthquakes. Acceleration data are being used to re-estimate/update the fragility curves of monitored building and facilities and at the same time they supply an EEW system. Special arrays, such as the EUROSEISTEST array, can also contribute to such systems both through the incorporation of their real-time data, but also through the use of past data in the offline calibration of the system's components. After all, thorough validation and testing of methodologies and algorithms such as those described herein require a considerable amount of data, which can only be acquired by long-running networks. From this point of view, we do hope and expect to incorporate data from other permanent networks in our study area (Figure 1b) that will mostly contribute towards the more efficient calibration of the EEW component of our system.

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