AN ULTRA-DENSE STRONG-MOTION URBAN NETWORK BASED ON IN-HOUSE DESIGNED MEMS ACCELEROGRAPHS: THE CASE OF LEFKAS CITY, GREECE

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ABSTRACT

The present research and technological effort proposes a low-cost instrumentation methodology for areas of interest (typically urban ones), in order to effectively capture the actual strong motion variations over a dense network during at least light intensity seismic events. For this purpose, an autonomous triaxial accelerograph based on MEMS sensor technology was designed and manufactured in-house, together with custom software for wireless device configuration, data retrieval and processing. The cost of the developed devices is an order of magnitude lower than the presently available commercial products, thus making economically feasible their deployment as a network over the urban area under study. After validation of the device quality and accuracy at the EPPO-ITSAK laboratory, an ultra-dense network of 21 devices was installed in 2013 in the broader area of the city of Lefkas, a high-seismicity urban area in Greece. Since its installation, the network (with a maximum distance of approximately 1200 m and a minimum of less than 100 m between sensors) has recorded the local variability of strong motion for several earthquake events occurring in the broader region. In the present paper we present an overview of the development of the sensors, the ultra-dense network at Lefkas, and the results for several recorded earthquake events.

Keywords: Low-cost accelerograph; MEMS; Strong motion dense network; PGA distribution; Seismic hazard; Site effects.

1. INTRODUCTION

In the present paper, we present the results of an on-going research effort for the development of ultra-dense strong motion networks in areas of interest (e.g. urban ones), through use of low-cost accelerographs. It is well known that due to local geological and geophysical conditions, the local site response due to strong ground motion may significantly vary in different locations of an urban area (among others; Borchertd, 1970; Seed and Schnabel, 1972). Therefore, the traditional seismic zonation on a regional level (adopted in Seismic Codes), may be inadequate for a site-specific seismic hazard assessment and hence for a reliable estimation of the seismic risk on a local level. This drawback led to the development of microzonation studies for medium to large cities, typically requiring the application of analytical methods based on borehole data, surface geology shear wave velocities, standard penetration test values, possibly micro tremor measurements etc., in order to produce respective microzonation hazard maps. Apart from the relatively high cost, the accuracy and reliability of the results highly depend on the quantity and quality of the original field measurements, and the effective reduction of the accumulative effect of the uncertainties, inherent in the various steps of the complete procedure, is not always guaranteed or quantifiable. An alternative to these implicit
theoretical approaches, a complementary explicit approach herein proposed is the use of low-cost devices that allow the deployment of dense networks which will record the actual spatial distribution of the earthquake excitations of interest. Towards this aim, the research team designed and produced autonomous accelerographs based on the micro-electro-mechanical sensor (MEMS) technology, which has rapidly grown in the last decade (e.g. Kim et al., 2006; Picozzi et al., 2010). An effort was made to optimize cost-effectiveness, while not compromising the basic requirements for the proposed application, i.e. the accurate capturing of at least light intensity earthquake events (PGA larger than approx. 0.014g (Picozzi et al., 2010). After proper quality and accuracy tests performed at the EPPO-ITSAK laboratory, an ultra-dense urban network of 21 devices was installed in the broader urban area of Lefkas city, Greece. Since its installation in 2013, the network was triggered by several earthquakes and the results for three major recorded events are presented. Comparisons with high-accuracy adjacent accelerographs at two station locations (one at a building’s basement and the other in nearby free-field conditions) confirmed the satisfactory accuracy of the developed devices, at least for light intensity seismic events. Spatial PGA distribution maps are also presented and a first discussion is made on the questions raised about the reliability of theoretical and seismic code related investigations, which are based on relatively few high-cost instruments. It is believed that the proposed approach is a promising complementary one towards the mitigation of seismic consequences on the built environment. Finally, an extra advantage that should be mentioned is that the low cost of the devices practically eliminates the need for specialized repair facilities and personnel, since it is economically feasible to just replace a defective unit with a new one.

2. DEVELOPMENT OF THE LOW-COST MEMS ACCELEROGRAPH

2.1 Device description and validation – hardware development

The in-house designed and manufactured prototype device SeismoBug® (www.seismobug.com, Figure 1a) was developed between 2012 and 2013 at the Institute of Engineering Seismology & Earthquake Engineering (EPPO-ITSAK), within a post-doctorate research grant by the Greek Secretariat of Research and Technology (GSRT). It is an autonomous triaxial accelerograph based on the MEMS sensor technology. The device can operate totally unattended on external power supply with battery backup, featuring automatic event triggering and non-volatile local storage. It also incorporates pre-trigger buffer memory, auto-calibration, accurate event timestamping, low-noise output and compact size. After its design and in-house assembly, the prototype units were validated at the EPPO-ITSAK laboratory, in order to test the output accuracy both in terms of time and acceleration readings for various harmonic and random excitations and at different frequency levels. For the testing, the devices were mounted collinearly (successively along each of their axes) to a high accuracy and high cost commercial accelerometer (Güralp® Systems CMG-5TDE), on a uniaxial seismic table. The results were overall very satisfactory, especially for at least light intensity levels of excitation (e.g. Figure 1b, where the two devices yield practically identical results).
In lower excitation levels, the higher noise level of the SeismoBug© sensor is noticeable, but in general the device can adequately record excitations higher than approximately 2 mg, satisfactory for civil engineering purposes. More details on the hardware features of the device and the validation procedure can be found in Papanikolaou & Karakostas (2013).

2.2 Data retrieval and management - software development

A suite comprising of three different custom-made programs was developed for data retrieval, processing and management. The software SeismoBug© Monitor allows device configuration and data retrieval (in spreadsheet format) via a Bluetooth connection to a host computer. It also allows a quick view of the downloaded time series and a graphical comparison among various recordings both in time and frequency domain (Figure 2a). For fast viewing and postprocessing of the data volume collected from all installed devices, the SeismoBug© Browser software was developed (Figure 2b), in the concept of a ‘file explorer’: a single record is selected at a time and a considerable amount of meta-information is generated, usable for quick identification and assessment. Specifically, the time-acceleration histories for all directions (X, Y, Z) are displayed, together with the corresponding velocities and displacements (through integration), frequency domain (FFT) decomposition, elastic response spectra and statistics for parameters used in the incorporated triggering algorithms (STA/LTA/RMS). Furthermore, the software can perform record resampling, linear/quadratic baseline correction and bandpass filtering.

Finally, for the compilation of ground motion variability maps after a successful recording of an earthquake, the collected records from the grid of installed devices are corrected/filtered and forwarded to the GIS-type SeismoBug© Manager software (Figure 2c). The individual device locations are automatically marked on an online map and the various concurrent records (within a user defined time window) are automatically identified and grouped as ‘events’. The software also communicates with the EMSC data base (https://www.emsc-csem.org/) allowing to verify if an actual earthquake triggered the displayed ‘event’ and retrieve the relevant data (epicenter, magnitude, depth
etc.). Using a seamless integration with a third-party contour mapping software (3DField) the selected event data can be displayed in various forms of PGA contours and intensity distribution maps. The PGA value was selected as the main parameter for compiling the above intensity maps, since it is the only one typically adopted in current Seismic Codes. However, within the same software framework, other ground motion parameters (e.g. Arias intensity etc.) can be easily implemented in the future. More details on the developed software can be found in Papanikolaou & Karakostas (2014).

3. THE ULTRA-DENSE NETWORK IN LEFKAS

After development and testing at EPPO-ITSAK, a total number of 21 seismic logging devices were installed in the high-seismicity wider urban area of the city of Lefkas (Lefkada), located in the northeastern part of the namesake Ionian Sea island (Figures 3a, 3b). The main criteria used for the selection of installation locations were (a) the regularity of the network grid in the broader city area, which should become denser towards the more highly populated city centre, (b) the implementation of free-field conditions at the selected locations, if possible and (c) the availability of uninterrupted power supply. These conditions were mostly met by installing most of the devices inside feeder pillars (steel enclosures) that provide electric power to street lights or in waterproof electrical junction boxes on the ground (Figure 3c).

![Figure 3. The ultra-dense network at the urban area of Lefkas (a) General location (b) Network grid (c) installation at free-field conditions (d) adjacent SeismoBug© (LEF_DIM) and Guralp© (LEF2) accelerographs.](image)

Seven devices were installed inside buildings, mainly due to unavailability of suitable free-field conditions (five of them on ground level, two at the existing basement level). One unit (station LEF_DIM) was purposefully placed next to a high-accuracy (by Guralp©) one (station LEF2, belonging to the National Strong Motion Network operated by EPPO-ITSAK) at the basement of the Prefecture building of Lefkas (Figure 3d). At a distance of about 70 m from the Prefecture building, a similar pair of SeismoBug© (station LEF_DIMF) and Guralp© (station LEF3) accelerographs were
installed in free-field conditions in order to assess the effect of the Prefecture building’s response to the recordings at its base. As can be seen from Figure 3b, the installed network forms an ultra-dense grid with the distance between adjacent sensors ranging from a maximum of approximately 1200 m to a minimum of less than 100 m. After a one-year testing period using absolute acceleration trigger thresholds, the more elaborate STA/LTA value for each station was determined based on the triggering data collected during this initial testing period, thus resulting in a dramatic decrease of false triggering due to non-earthquake factors (e.g. traffic, machinery works etc.). More detailed information on the deployment of the network can be found in Karakostas & Papanikolaou (2014).

4. SELECTED RESULTS FROM THE LEFKAS ULTRA-DENSE NETWORK

Since its installation in August 2013, the Lefkas network has been operating with minimal fails, mainly due to external factors (e.g. power outage), and has been triggered by various earthquakes. An analysis of the collected data was able to identify 50 earthquakes in the broader area (red dots in Figure 4a, with size relative to the respective magnitude) that triggered some or all the sensors of the network. The network is deployed within the orange circle in the same Figure. In Figure 4b, the Magnitude vs Distance distribution of the respective earthquakes is shown.

![Figure 4](image)

Figure 4. Earthquakes that partially or fully triggered the Lefkas Network
(a) Epicenters and Magnitude (b) Magnitude vs Distance plot

4.1 Seismic data of selected earthquake events

In the following we give a concise presentation of the results for three major events that were strong enough to trigger all the network sensors. Namely, we refer to the following events for which more information can be found through the provided links to the EMSC database:

- M6.1 Cephalonia earthquake 26/1/2014 13:55:43 UTC (Figure 5a)  
- M6.5 Lefkada earthquake 17/11/2015 07:10:08 UTC (Figure 5b)  
- M5.0 Lefkada earthquake 18/11/2015 12:15:38 UTC (Figure 5c)  

The 26/1/2014 Cephalonia and 17/11/2015 Lefkas events were mainshocks, while the 18/11/2015
event was an aftershock of the latter one, yet being closer to the Lefkas network and yielded higher peak ground accelerations in the area.

Figure 5. Earthquake events presented in this study

4.2 Comparison between SeismoBug vs Guralp recordings

For the three aforementioned events, a comparison of the recordings between the adjacent (see Chapter 3) SeismoBug© and Guralp© accelerographs at the basement of the Lefkada Prefecture Building (stations LEF_DIM and LEF2) as well as at the nearby free-field conditions (stations LEF_DIMF and LEF3) are given in the following figures, both in time and frequency domain. It is noted that for the 18/11/2015 event, comparison is given only at the basement of the Prefecture building, due to lack of the Guralp© free-field recordings.

Figure 6. M6.1 Cephalonia mainshock (26/1/2014): Comparison of SeismoBug© (blue) vs Guralp© (red) recordings (a), (b) at the basement of the Prefecture building and (c), (d) at free-field conditions
Figure 7. M6.5 Lefkada mainshock (17/11/2015): Comparison of SeismoBug© (blue) vs Guralp© (red) recordings (a), (b) at the basement of the Prefecture building and (c), (d) at free-field conditions

Figure 8. M5.0 Lefkada aftershock (18/11/2015): Comparison of SeismoBug© (blue) vs Guralp© (red) recordings (a), (b) at the basement of the Prefecture building

The comparisons are presented at Figures 6-8. In lower levels of acceleration (see e.g. Figure 6), the inherent noise of the SeismoBug© sensor starts to play noticeable role. Despite this fact, as well as the lack of expanded capabilities incorporated in Guralp© (such as GPS time and telemetric data transmission), it should be noted that the expected commercial cost of the SeismoBug© would be an order of magnitude less than that of Guralp© or a similar high-accuracy unit. It is also observed from Figures 6-7 and Table 1 later in chapter 4.3, that significant differences exist (both in time-history amplitudes and frequency content) between recordings at the station (LEF_DIM) at the basement of the Prefecture Building and those of the nearby (at approx. 70m) free-field one (LEF_DIMF), an observation that triggered further specific investigations, beyond the scope of the present paper (Karakostas et al. 2017).
4.3 PGA distribution maps at the Lefkas network

As already described in Chapter 2.2, the collected data can be, among others, properly postprocessed with the custom-developed software to produce PGA distribution maps for each earthquake event recorded. The respective maps for the three selected events are presented in the following figures for all directions (N-S, E-W, U-D) each.

Figure 9. PGA contour maps (N-S, E-W, U-D directions) for the 26/1/2014 (M6.1 @ 76.0 km) event
It is noted that the results for the 26/1/2014 event (as well as more details on the postprocessing of the respective recordings) are also presented in Papanikolaou & Karakostas (2014), but are nevertheless also herein included for comparison reasons. It is also noted that PGA values in the maps over areas covered by sea should be disregarded. In each figure, the direction and epicentral distance of the respective earthquake is shown by an arrow and respective value at the legend.

Figure 10. PGA contour maps (N-S, E-W, U-D directions) for the 17/11/2015 (M6.5 @ 23.7 km) event
From Figures 9-11, and Table 1, some obvious first conclusions are the significant spatial PGA variation (especially for the horizontal components) recorded for the same event within the very small area (Figure 3b) covered by the ultra-dense network, as well as the relative differences of the PGA distribution patterns among earthquakes of different magnitude and epicentral distances. All these first observations give rise to serious questions about the current practice – followed mainly due to high cost – of covering large urban areas with one (or in the best case only a few) accelerographs, and which (not giving, as shown, the actual intensity variation), may nevertheless be the only available for
the calibration of further theoretical studies of the seismic hazard in the area (i.e. microzonation studies). However, these questions go beyond the scope of the present paper, which tries to demonstrate the value of the proposed methodology of using efficient low-cost devices (such as the one designed by the research team) in dense urban networks as a complementary effort towards the mitigation of the earthquake consequences on the built environment.

Table 1. Variation of PGAs (mg) recorded by the Lekfas network

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5. CONCLUSIONS

In the present paper an overview of the development of low-cost MEMS accelerographs and related software by the research team is given. The developed devices were used to implement an ultra-dense network of 21 stations in the broader area of the city of Lefkas in Greece. Since its installation in 2013, the network recorded fifty earthquake events by some or all stations. In the present paper, the results of three strong earthquakes that triggered all the stations are presented. Significant differences were found (both in time-history amplitudes and frequency content) between recordings at a station at the basement of the Prefecture Building and those of a nearby (at approximately 70 m) one at free-field conditions. Comparisons with high-accuracy instruments of the Hellenic National Strong Motion Network clearly demonstrate the ability of the developed device to record to a very satisfactory degree (from an engineering point of view) at least light intensity earthquake events (i.e. accelerations > 2 mg). Also, presented PGA variation maps based on the recordings of the network demonstrate a significant spatial variation for each event within the small-size area of the network, as well as significant differences of the PGA distribution patterns among earthquakes of different magnitude, azimuths and epicentral distances. The latter is a strong indication of 2D or/and 3D response of the surface geologic formation underlain the city of Lefkas.

These first observations give rise to serious questions about the efficiency of the current practice – imposed mainly due to high cost – of covering large urban areas with one (or in the best case only a few) accelerographs, which are then used to assess the seismic intensity in the whole region, and which may not be adequate for the calibration of further theoretical studies on the site-specific assessment of seismic hazard in the area. The presented results demonstrate that the developed low-cost MEMS device makes it economically feasible to set up dense grid networks in areas or infrastructure of interest (e.g. urban ones, lifelines), to obtain the actual variation of the seismic waveforms during various earthquake events. It can also be used in studies of various effects in the field of Engineering Seismology and Earthquake Engineering (such as SSI effects, effect of a building at the recordings of a station at its basement etc.). An extra advantage of the low-cost device is that it practically eliminates the need for specialized repair facilities and personnel, since it is economically feasible to just replace a defective unit with a new one. In conclusion, it seems that the proposed approach is an effective and promising complementary effort towards the mitigation of the earthquake consequences on the built environment and large infrastructure.

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7. REFERENCES


