RECENT ADVANCES IN GREECE ON STRONG-MOTION NETWORKING AND DATA PROCESSING

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ABSTRACT

Significant progress has been achieved in Greece during the last two decades concerning the development and maintenance of the accelerographic networks, as well as in the acquisition and processing of the strong-motion data. Several new aspects for the design and deployment of the Greek strong-motion network have been recently adopted. A significant number of accelerographic arrays have been deployed covering a large number of applications in Engineering Seismology and Earthquake Engineering in different sites in Greece. The development of the Greek strong-motion network started in 1970 and consisted of several independent activities: network design, operation and maintenance, network management and research and data processing, emphasizing the management and operation of the network. The numerical processing of the accelerograms has been examined in detail and improved through different methods applied. On the basis of the evolution of these various developments through time, a presentation of the developments of the Greek strong motion network operation and data processing is made in the present paper.

Introduction

Earthquakes as a physical process are characterized by their frequency content, the geological and tectonic structure of the seismogenic region, seismic magnitude, focal depth, distance from source to site and site conditions of the recording site. Due to the aforementioned parameters seismic records are site specific, even in cases of events with the same magnitude. The strong motion records are fundamental for a dynamic research in earthquake engineering and essential for following studies regarding the structural behavior during strong earthquakes.

For strong motion data acquisition and determination of the basic characteristics of earthquakes in a wide region, such as Greece, a rational long-term research is indispensable in the sense of a detailed work combining seismotectonics, seismicity, seismic hazard and strong-motion prediction studies. In addition to this research, a time span is needed until a satisfactory number of recordings will be available for further development concerning engineering purposes. The only way to solve these problems is to establish and deploy wider and denser networks for strong ground motion recording covering broader seismogenic areas. Such accelerographic networks have been installed all over the world mainly in high seismicity regions (USA, Japan, Taiwan, Italy, Turkey etc). As a result of this deployment, a great number of strong motion recordings have been collected and used in strong-motion studies worldwide.

The strong motion instrumentation program in Greece started in early 70's. The Geodynamic Institute of National Observatory in Athens (GI-NOA) established a basic network of instruments consisting of accelerographs (SMAC-B) and some more simplified instruments, seismoscopes (SR-100 Wilmot), located at Western Greece, the region with the highest seismicity rate in Greece, Drakopoulos [1]. Some of them recorded the strong earthquake, which occurred in Ionian Sea close to Cephalonia Island (Sept. 17, 1972, **M**6.3). In the following years this network was extended and enriched by new strong motion instruments SMA-1 manufactured by Kinemetrics- USA covering a wider area of Greece with almost 50 installations Kalogeras[2]. After the destructive earthquake, which occurred in Thessaloniki, Northern Greece (Jun. 20, 1978, **M**6.5), the Greek Ministry of Public Works established a new organization (Institute of Earthquake Engineering and Engineering Seismology-ITSAK), with mainly research activities in engineering seismology, soil dynamics and earthquake engineering. In addition to these activities, the Institute undertook the installation, maintenance, and operation of a large –scale permanent strong motion network in Greece. A rational installation and deployment of ITSAK accelerographic network in Greece was accomplished after an analytical study, which took into, account all the available seismological, seismotectonic and strong motion data Theodulidis [3]. To date, this network has been expanded with almost 100 installations in whole Greece, covering free field and structural installations, various site conditions and tectonic environments.

A significant number of strong motion data, has been collected by various accelerographic networks in Greece and it became obvious that the applied processing and correction techniques would be an important step before the final engineering use of those recordings. ITSAK recognizing the significance of strong motion data processing from the first moment, made an effort to install and develop a digitization and correction procedure for its accelerograms Margaris[4]. For this reason in the mid of 80's a semi-automatic digitization procedure for strong motion records processing was developed in collaboration with ENEA-ENEL Italy, Margaris [5], [6]. Because of the hardware and software advancements, at the beginning of 90's a scanner-based film accelerogram digitization procedure using PC was applied Nigbor [7]. Due to the rapid evolution of digital technology the analog units have been replaced by the new "generation" digital accelerographs in strong motion networks. From 2001 a significant number of SMA-1 analog instruments of ITSAK and GI-NOA institutes have been replaced by common digital accelerographs with an "almost" 11-bit A/D converter. The dynamic range of those instruments is not much better than the analog ones, however the main advantage of these accelerographs is their remote accessibility through modem. The data analysis and processing of the aforementioned digital recordings are now carried out by a computer software provided by Kinemetrics[8].

In this paper a brief introduction regarding of the seismicity and seismotectonic setting in Greece is presented. The accelerographic installations in the last decade and the recent developments in strong motion networking are also discussed. A description of the accelerograph stations in Greece with respect to the seismic activity of the whole region is shown. The variation of the number of accelerograms with time since the initiation of the network operation, is also given. A comparison of the average noise level of the different recording instruments is attempted, focusing in the improvement of the correction procedure. Correlation of the Greek strong motion noise level with other ones from different seismic environments is also presented.

Seismotectonics - Seismology Setting in Greece

Three major plates Eurasia, African and Arabian mainly affect the active tectonics of the broader Aegean area, studied in this work (fig. 1). However, the plate motions are not adequate enough to describe the basic seismotectonic properties in Greece and adjacent areas. A model of the relative plate motions with respect to Eurasia is described in Papazachos [9]. The convergence between the Eurasian and African lithosperic plates is taking place in a NS direction (N181^{0}E) in the southern boundary of the Aegean area and the rate of this convergence (at 35^0 N, 31^0 E) is slightly less than 1cm/yr McClusky[10], while the movement of the Aegean area with respect to Africa is taking place at a much larger rate (~4-4.5 cm/yr) and in a SW direction. As a result of this fast SW motion, the Eastern Mediterranean lithosphere subducts under the Aegean, resulting in a well-defined Benioff zone with intermediate-depth events, with depths up to ~160km. The Arabian plate, on the other hand, only indirectly affects active tectonics in Greece, as it moves in a NNW direction and the rate of motion along its northern boundary (at 38^0 N, 40^0 E) is ~2.5 cm/yr, “pushing” Anatolia westwards (towards the Aegean).

This complicated geotectonic setting has resulted in strong spatial variations of the stress-field and the corresponding earthquake generation process. This is also seen in figure (1), where four main zones of compression (Hellenic Arc subduction and Adriatic-western Balkan collision), strike-slip faulting (North Anatolia-North Aegean Trough and Cephalonia area), E-W extension (parallel to the compression zone) and N-S extension (most of the back-arc Aegean area) are shown. N-S extension dominates the back-arc area, with a NNE-SSW direction in NW Turkey (e.g. east of the Biga and Bergama area) and a NNW-SSE direction in the western Greek mainland Papazachos[11].

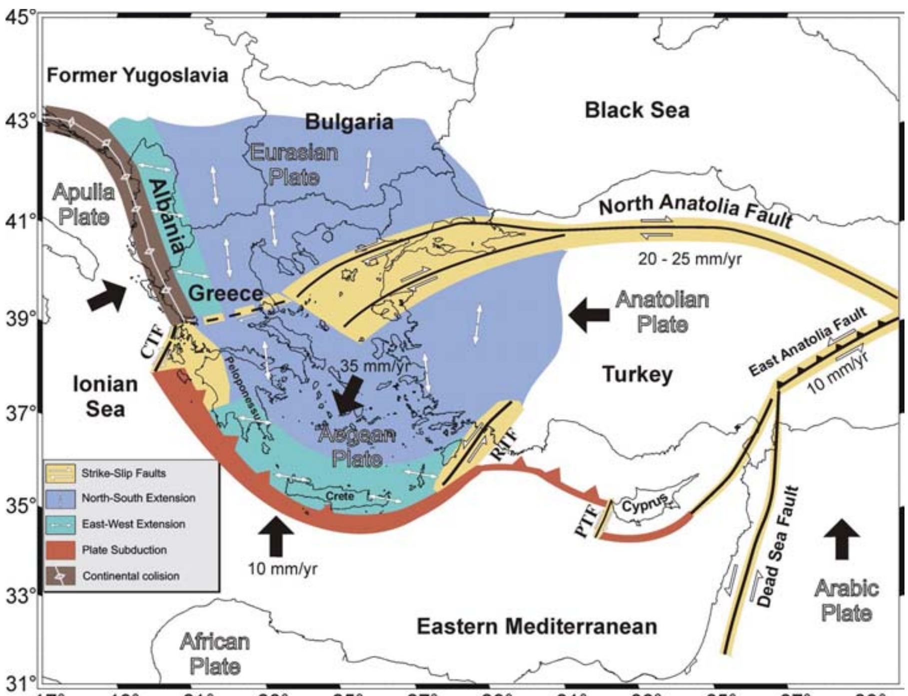


Figure 1. Plate motions which affect active tectonics in the Aegean and surrounding area and corresponding stress-field (modified from Papazachos [12]).

The most prominent manifestation of this complicated stress field and high deformation rates (the highest in the whole Africa-Eurasia collision zone) is the release of more than 60% of the European seismicity with earthquakes of magnitudes up to M_W=8.2 Papazachos[13]. Figure 2 shows the seismicity distribution in this area, with thrust events along the Hellenic Arc and intermediate-depth events in the southern Aegean Benioff zone (due to the subduction of the eastern Mediterranean lithosphere under the Aegean). However, significant seismicity is also observed in the back-arc area with normal faulting (fig. 1), showing intense internal back-arc deformation, especially in the northern part of the Aegean microplate (northern and central Greece, Albania, southern former Yugoslavia, southern Bulgaria).

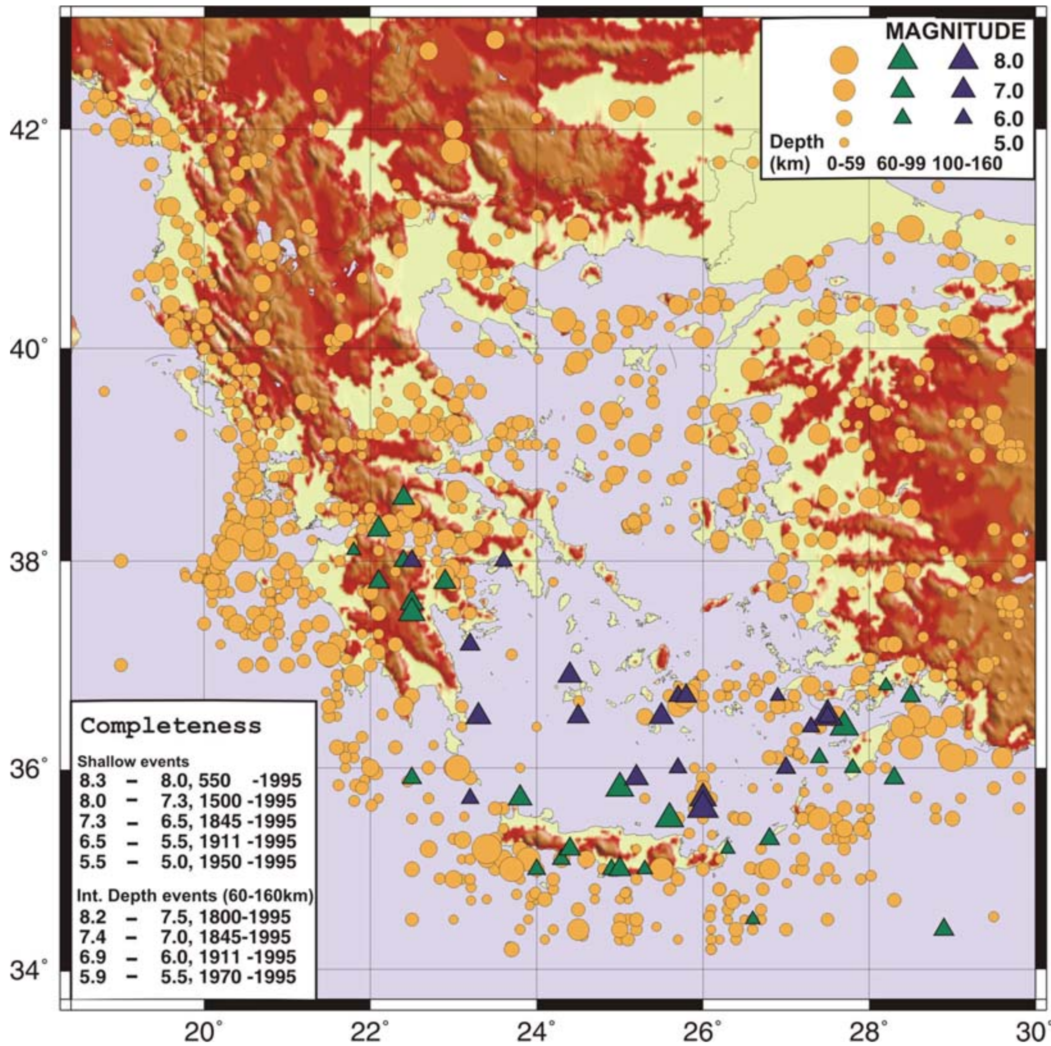


Figure 2. Epicenter map of shallow (circles) and intermediate-depth (triangles) earthquakes in Greece and surrounding area Papazachos[14].

Planning of Strong Motion Network

The basic concept of the Greek strong motion network enables the attainment of the basic information required for predicting the parameters of ground motion, the dynamic response of various types of structures, improvement of Seismic Codes, understanding the ground amplification effects, as well as the better investigation and perceiving of the consequences caused by the earthquakes. The initial ITSAK accelerographic network consisted mainly of SMA-1 type of instruments. The gradual installations of the first SMA-1's instrument began on 1982 in the most high seismicity areas of Greece, such as Western coastal sites, the Ionian Islands (Cephalonia Transform Fault, CTF in fig. 1), Gulf of Corinth, Athens and Thessaloniki cities. This installation program was completed at the end of 80's. The distribution of the Greek strong-motion instrument network was based on previous studies regarding the seismotectonic setting, seismicity and seismic hazard of the region Theodulidis[3]. The fact that a large part of Greece in which the major cultural and industrial centers are located is in zones of considerable seismic activity, fully justified the necessity of such network and its regular maintenance. Figure 3 presents the most recent ITSAK strong motion installation in Greece, including the dense arrays in populated centers, critical constructions (e.g. bridge) and special arrays for specific research projects. In the last decade, in the framework of a strong motion instrumentation project the upgrade of the Greek strong motion network with digital instruments (QDR, ETNA and K2 types from Kinematrics and CMG-5T type from Guralp) was performed.

Figure 3. ITSAK strong motion network in Greece

Digital instruments have been mainly used in installations for aftershock activities in Greece and for special dense arrays in Euroseistest and Evripos Bridge researching projects (fig. 4).

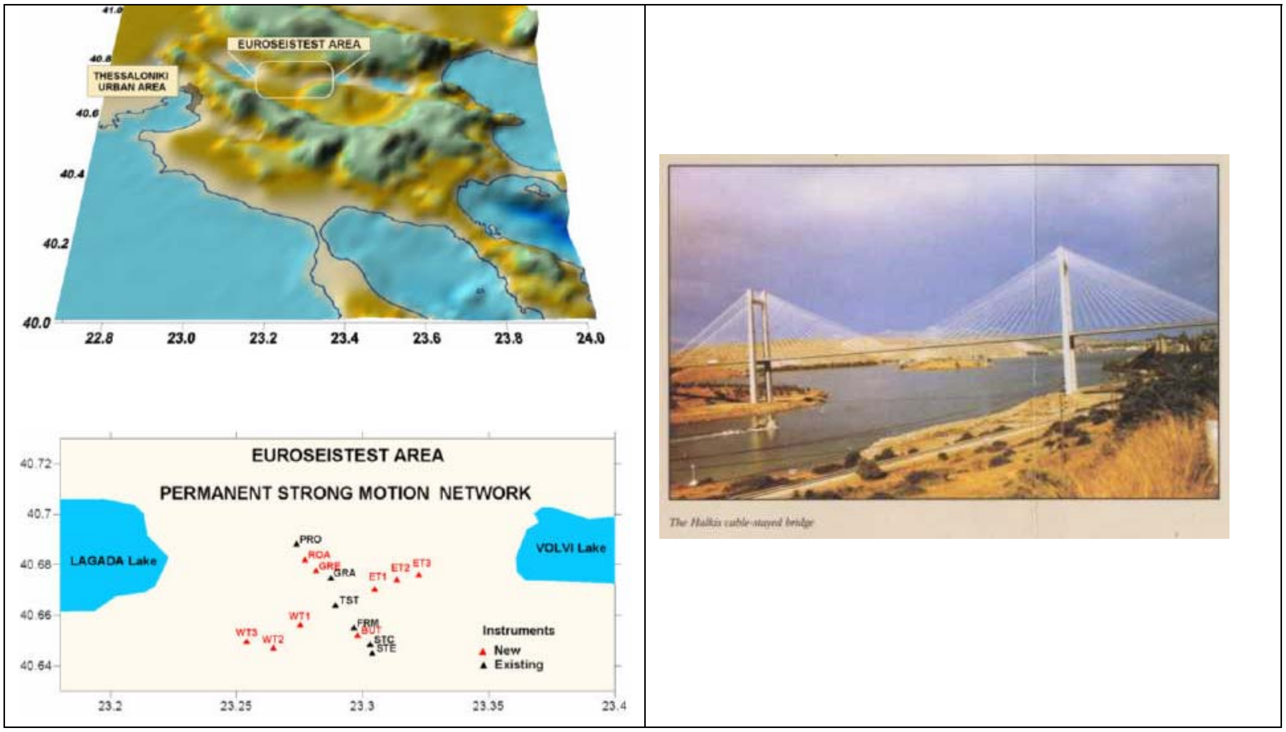


Figure 4. Euroseistest, Volvi Thessaloniki : A European test-site for Engineering Seismology, Earthquake Engineering and Seismology (left). The strong motion instrumented bridge in Evripos site (right).

The general objectives of the strong-motion project in Greece is to develop criteria for planning of an optimum accelerographic network and to provide a unified and homogeneously processed, credible strong motion database for research studies in seismology, soil dynamics and earthquake engineering. The main scopes of the network planning during the last years were directed towards detailed studies of the location of the instruments in order to achieve free-field conditions, study of previous earthquake ocurrence, downhole installations for site effect studies and installations in critical construction, such as bridges. The main result of this planning was the collection of a large number of strong motion data, which have been used in many engineering seismology, soil dynamics and earthquake engineering applications. In Figure 5, a cumulative number of strong motion data available versus time period is depicted while the slope of the curve emphasizes the rate of strong motion data collection in any time period. These accelerograms consisted of the basis for the creation of strong motion databases in Europe, Ambraseys[15] and in Greece, Theodulidis[16], which are utilized by a large number of geo-scientists and engineers.

Processing of Strong Motion Records

The large number of strong motion records recorded from early 80's until today from ITSAK's strong motion network is divided into two major subcategories. From early 80's until late 90's the strong motion network consisted mainly of SMA-1 instruments, recording analogue accelerograms. From late 90's until today the strong motion network consists mainly of digital accelerographs, producing accelerograms in various digital formats, with different resolutions depending on the instrument type. From the previous description the necessity for a homogeneous strong motion database and the knowledge of the strong motion instrument recording characteristics (recording, digitization and processing noise) is obvious.

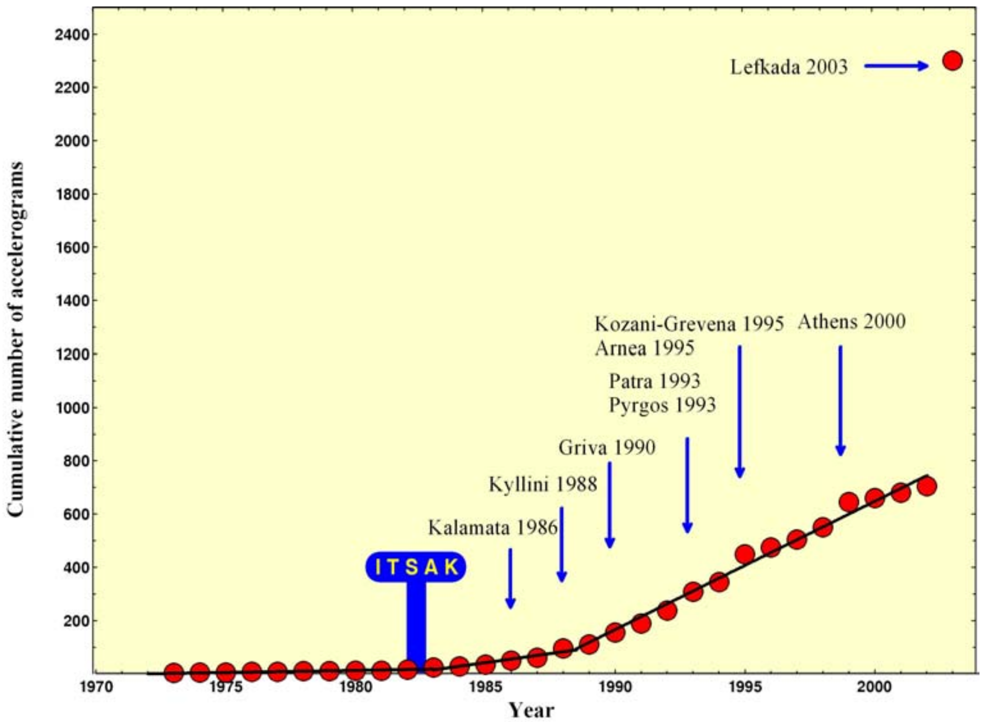


Figure 5. Cumulative number of strong motion records in Greece.

Processing of Analogue Strong Motion records

In order to create an analogue strong motion database homogeneously processed, Skarlatoudis[17] developed a technique aiming in reducing the noise introduced from digitization and processing of the analogue strong motion records. The noise minimization was achieved by using high scanning resolution (600 dpi), digitizing the analogue records using the Kinemetrics Scanview software Nigbor[7] and by estimating characteristic frequencies for the digital filters applied by comparing the frequency content of the two digitized horizontal components of the record with the frequency content of the corresponding digitized fixed trace. Furthermore, aiming in reducing the processing and digitization noise level even more, in the present paper we have further focused in the filtering the analogue strong motion records using only the energy window from 5% to 95% of the total energy of the record. Specifically the time instances $t_{5\%}$ and $t_{95\%}$ when the energy is equal to 5% and 95% of the total energy of the record are estimated and the recordings are filtered for a time window equal to $t_{95\%}$ - $t_{5\%}$ ($T_{5\text{-}95}$). In order to estimate the new characteristic frequencies of the digital filters applied, the Fourier Amplitude Spectra (FAS) for both components and fixed traces are recalculated for the equivalent time window ($T_{5\text{-}95}$). The results of this procedure are summarized and compared in figure 6 with the ones produced in Skarlatoudis [17] and Trifunac[18].

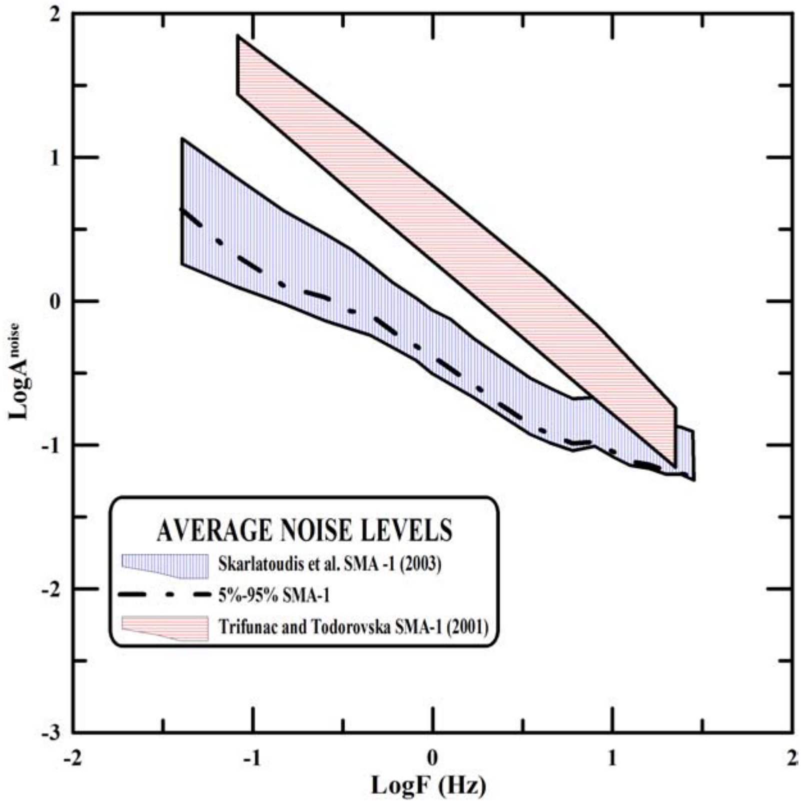


Figure 6. Average noise curves derived in the present work and comparison with the corresponding curves by Skarlatoudis[17] and Trifunac[18].

The comparison shows that for both procedures described above, the average noise level for the Greek analogue strong motion records is lower than the one proposed by Trifunac[18]. This can be partly attributed to the fact that all records used follow the ITSAK's criteria for their inclusion in the ITSAK's database (PGA≥5%g, **M**≥4.5), so that the accelerations are less affected by noise level. Also, all the records were scanned with a resolution of 600dpi, which is a critical factor for the minimization of noise introduced during the digitization procedure Skaratoudis[17]. Comparing the results from the two filtering procedures described, it is evident that the average noise level estimated from the 5%-95% procedure is lower than the one from the typical filtering procedure. This was expected because by choosing filtering in the equivalent time window (T_{5-95}) it is mainly the high amplitude section of the record (S waves), which contains the largest percentage of record's total energy that is filtered. The signal-to-noise ratio for the (T_{5-95}) time window is substantially higher than the one of the total record duration because: a) the early and the late parts of the accelerograms have usually smaller amplitudes from the high amplitude part, included in the equivalent time window and, b) in the latest part of the accelerograms surface waves, refracted and reflected body waves and other scattered waves are recorded, introducing mainly low frequency information in the strong motion record.

Analysis of Digital Strong Motion records

The main part of the ITSAK's updated strong motion network consists of QDR digital recorders. In order to shed some light into the average noise levels introduced by these instruments in the strong motion records and define the effective frequency window which information about the strong motion characteristics can reliably be extracted, an additional noise analysis was performed. This includes analysis of strong motion records that "barely" triggered the accelerograph, hence their amplitudes were very small (near the lower recording threshold of the QDR instruments) and analysis of the recorded time marks which were available in many cases. A comparison between the average FAS of the strong motion records and the recorded time marks is made for exploring a possible relation between them. In figure 7 the comparison between the averaged FAS of the records and time marks of the Greek QDR instruments and average noise level for QDR instruments introduced by Trifunac[18] is shown. From this comparison the following results can be concluded: a) The FAS of the strong motion records and the time marks do not match, especially at higher frequencies and this is probably due to the fact that the frequency content of the strong motion records includes also some frequencies which originated from other sources (e.g. physical noise). The use of these records in order to define the instrument's noise level could be misleading and must be made with cautiousness. b) After the frequency of approximately 10 Hz the FAS of the strong motion records exhibit significantly high values (see also Figure 8a). This effect is shown for all strong motion recordings, independent of the site conditions of the instrument's installation site or the characteristics of the triggering event (e.g. earthquake, physical noise etc). The consistency observed between these records and the final result in their averaged FAS is strong evidence about the recording characteristics of the QDR instruments and probably this is an evidence for the upper frequency limit of the effective frequency bandwidth of these instruments. c) The comparison among the Greek mean noise curves, mostly the one derived from the recorded time mark, and the one introduced by Trifunac[18] shows grossly the same trend and behavior for different frequency windows but much lower amplitudes for the curve proposed by Trifunac[18]. This bias between the proposed curves can only be attributed to a different method of the curve estimation and not in different instrument characteristics, since the instrument parameters used in Greece are the same with the ones described in Trifunac[18].

Another characteristic related with the average noise introduction in the digital strong motion records examined was the site conditions of the installation site of the instrument. The strong motion records examined were recorded mainly in three different soil categories B, C and D according the NEHRP [19] categorization. The averaged FAS of these records for each site category are calculated and the comparison is shown in figures 8a and 8b. It is evident that the most significant differences exist in lower and higher frequencies of the frequency domain. The comparison exhibits higher amplitudes of FAS for softer and more inconsistent soil categories (C and D), in accordance with our knowledge for the site effects in strong motion records (higher accelerations in softer and more "loose" soils).

Comparison of Instrumental Noise Spectra

As it was mentioned in the previous paragraphs, ITSAK has installed various types of strong motion instruments in all over Greece recording the strong ground motion. QDR ("almost" 11-bit), ETNA (18-bit), K2 (18-bit) type recorders manufactured by Kinemetrics have been installed in the main network, special arrays, and critical constructions. Nowadays CMG-5T (24-bit) recorders manufactured by Guralp Systems [20] are used in the permanent installation as

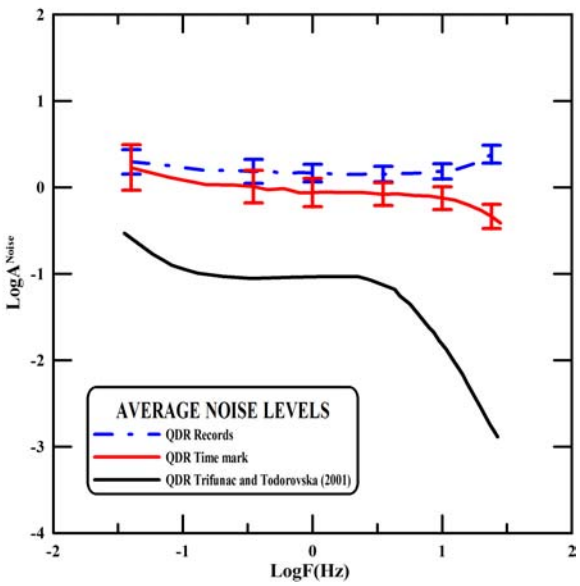
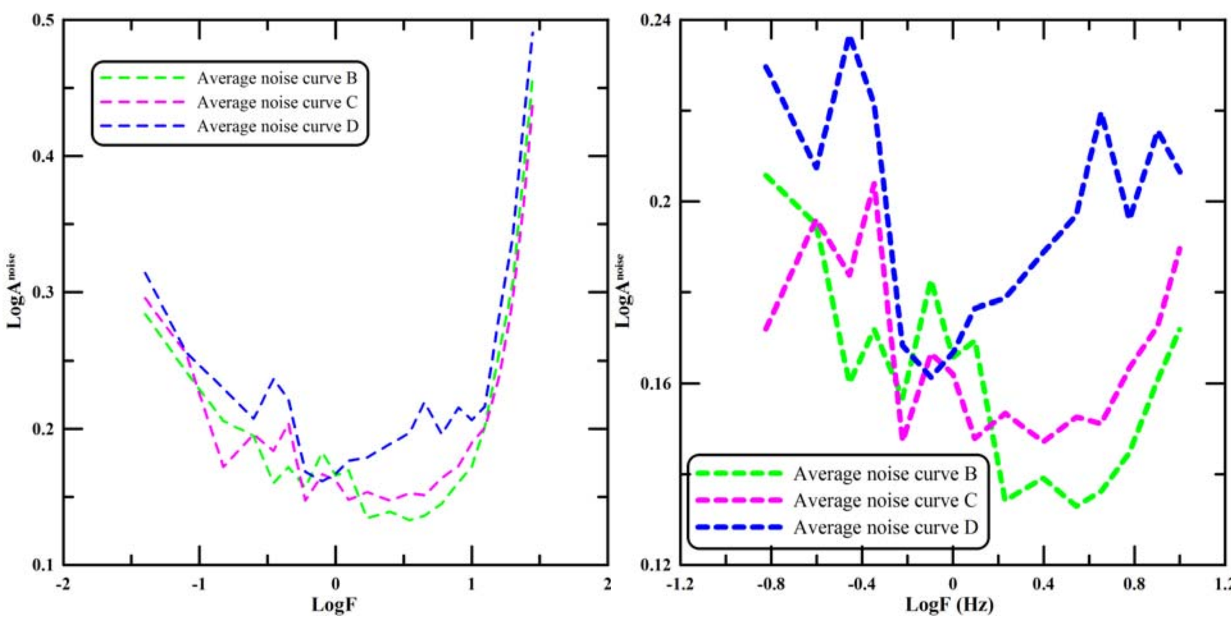


Figure 7. Average noise curves derived from the present work for QDR instruments and comparison with the corresponding curve by Trifunac[18].



Figures 8. Average noise curves derived in the present work for three different recording site categories, plotted for frequencies up to 30Hz (left) and 10Hz (right).

installed in the main network, special arrays, and critical constructions. Nowadays CMG-5T (24-bit) recorders manufactured by Guralp Systems [20] are used in the permanent installation as well as in the aftershock activity strong motion arrays. It would be quite interesting to compare the spectral noise level of all aforementioned strong-motion instruments. In figure 9 a comparison of the available spectral noise levels among the various accelerographs used by ITSAK network, are presented. The spectral noise levels of the ETNA and K2 type instruments are presented in figure 9. Using continuous noise record sent by Guralp Systems and noise from real strong motion record (pre-event: 20 sec), the spectral noise levels of CMG-5T were calculated (Fig. 9). The high resolution of the CMG-5T recorders present a significant lower noise level in comparison to spectral noise level of the other digital recorders

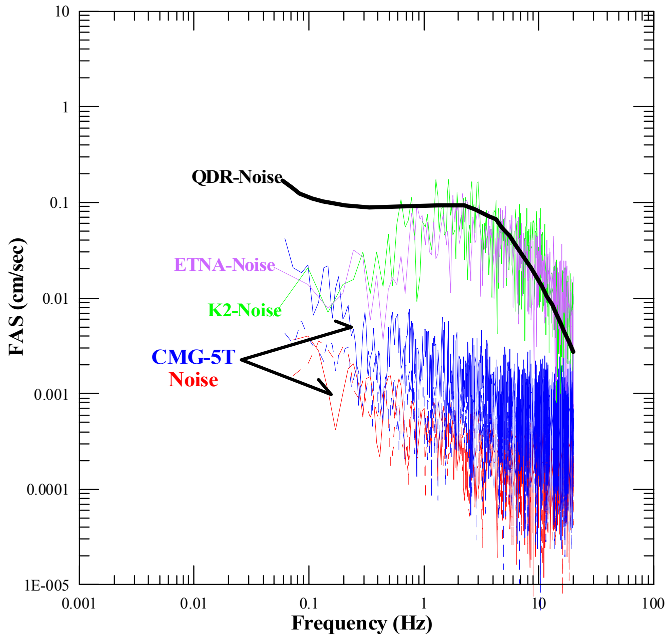


Figure 9. Spectral noise comparison from various digital recorders used by ITSAK strong motion network.

Concluding Remarks

The planning and deployment of the Greek strong motion network were mainly based on the seismic hazard and seismic design advancements, which have been carried out the last two decades in Greece. A rational accelerographic network was deployed throughout Greece, with the next target being to install additional stations in order to study site effect and structural problems. The processing of the strong motion recordings with the techniques adopted can contribute to a better correction of the collected data and can afford more reliable information for geoscientists and engineers. The availability of new digital accelerographs can also significantly improve the quality of the recorded strong motion data.

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