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REDUCING LOW FREQUENCY CUT-OFF FILTER EFFECTS ON SPECTRAL DISPLACEMENTS OF STRONG MOTION RECORDINGS USING SOURCE PROPERTIES

Andreas A. SKARLATOUDIS [1] and Basil N. MARGARIS[2]

ABSTRACT

Acquiring elastic spectral velocities and displacements from accelerograms almost always requires removal of long-period noise by filtering. The filter properties (e.g. characteristic frequencies, causal-acausal types) control frequency content and peak values of the derived elastic spectra. Taking into account the new tendency of using displacement values in most of the engineering applications and displacement based design, the effort in minimizing filtering effects in elastic spectra derivation is becoming even more important.

Filtering of digital data is considered to be a more straightforward procedure than filtering of analog data because the noise levels of digital instruments are considerably lower than the analog ones and the useful frequency content is greater.

The ratio of analog-to-digital recordings in the ITSAK strong-motion database is still in favor of analog data, imposing a need for reconsidering older filtering schemes used for reliably estimating velocity and displacement values. Most of the filtering schemes are correcting the errors imposed by the instrument and the digitization procedures without considering seismological parameters, which control the frequency content of the record. In the present work an attempt is made to combine, in the filtering scheme, the corner frequency of the source spectrum as a parameter that will control the long-period cut-off frequency of the applied filter. Finally more accurate elastic spectral displacements will be derived from analog and digital recordings of large earthquakes of ITSAK strong-motion database.

Keywords: Digital strong motion data, elastic spectral displacement, long period filtering.

INTRODUCTION

Strong ground motion recordings contribute significantly to our knowledge on earthquake engineering in seismic active areas, as well as to the study of seismic wave propagation. Strong motion datasets produced by digital (18bit or 24bit) sensors are certainly of higher quality comparing with the ones produced by analog or by low resolution digital ones (<12bit) but still they are far from characterized as noise-free datasets. As shown in many cases (e.g. Wang et al., 2003) due to imperfections in the manufacturing of the recording instruments or various other reasons, instrumental and digitizing noise is still present in the signal and notably affects the credibility of the record components, mostly in low but also in high frequencies.

Following modern demands for producing strong motion datasets with very low frequency content, new techniques and methods for calculating characteristic frequencies for the low pass filtering should be used. In the present paper an effort of using the seismological information from the strong motion

[1] Msc Geophysisist, Department of Geophysics, University of Thessaloniki, Greece, Email: askarlat@geo.auth.gr
[2] Researcher, ITSAK, Thessaloniki, Greece, Email: margaris@itsak.gr

records was made. The stress parameter, $\Delta\sigma$, of the earthquake was estimated by fitting the theoretical source spectrum to the observed for each recording. The comparison of the estimated corner frequency, f_0, with the cut-off frequency of the low-cut filter, showed the marginal cut-off frequency were records should be filtered.

For this study a high quality strong motion data set produced by an intermediate depth earthquake occurred in January 8, 2006 in Kythera, Greece was used. The earthquake triggered a significant number of ITSAK's strong motion network instruments, with different digital or semi-digital sensors (ETNA, QDR, CMG-5T). The aforementioned accelerograms exhibited some new interesting characteristics such as very long duration and different frequency content in comparison to strong motion data by shallow seismic events recorded in the same area.

DATA AND METHODOLOGY

In Greece more than 60% of the European seismicity is released with earthquakes of magnitudes up to **M**8.2. The Kythera earthquake was an intermediate depth (D=64 Km) earthquake (**M**6.7), occurred in the western part of the Hellenic Arc as shown in Figure 1. Hypocenters published from various institutes, Aristotle University of Thessaloniki (AUTH), National Observatory of Athens (NOA), Harvard Seismology (HARV), European-Mediterranean Seismological Centre (EMSC) are denoted with the red stars, while ITSAK's strong motion stations used in the present study are shown with the yellow triangles. Faulting mechanisms proposed by AUTH, NOA and HARV are also shown.

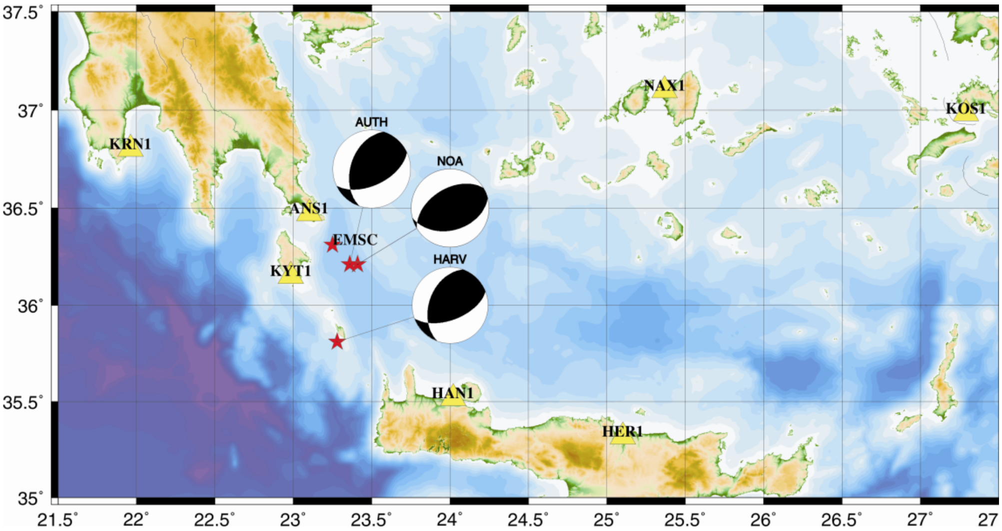


Figure 1. Map of the southern Aegean area. ITSAK strong motion stations are denoted with the yellow triangles. Epicenters of the earthquake calculated from different institutes are shown with the red stars. Faulting mechanisms proposed by AUTH, NOA and HARV are also shown.

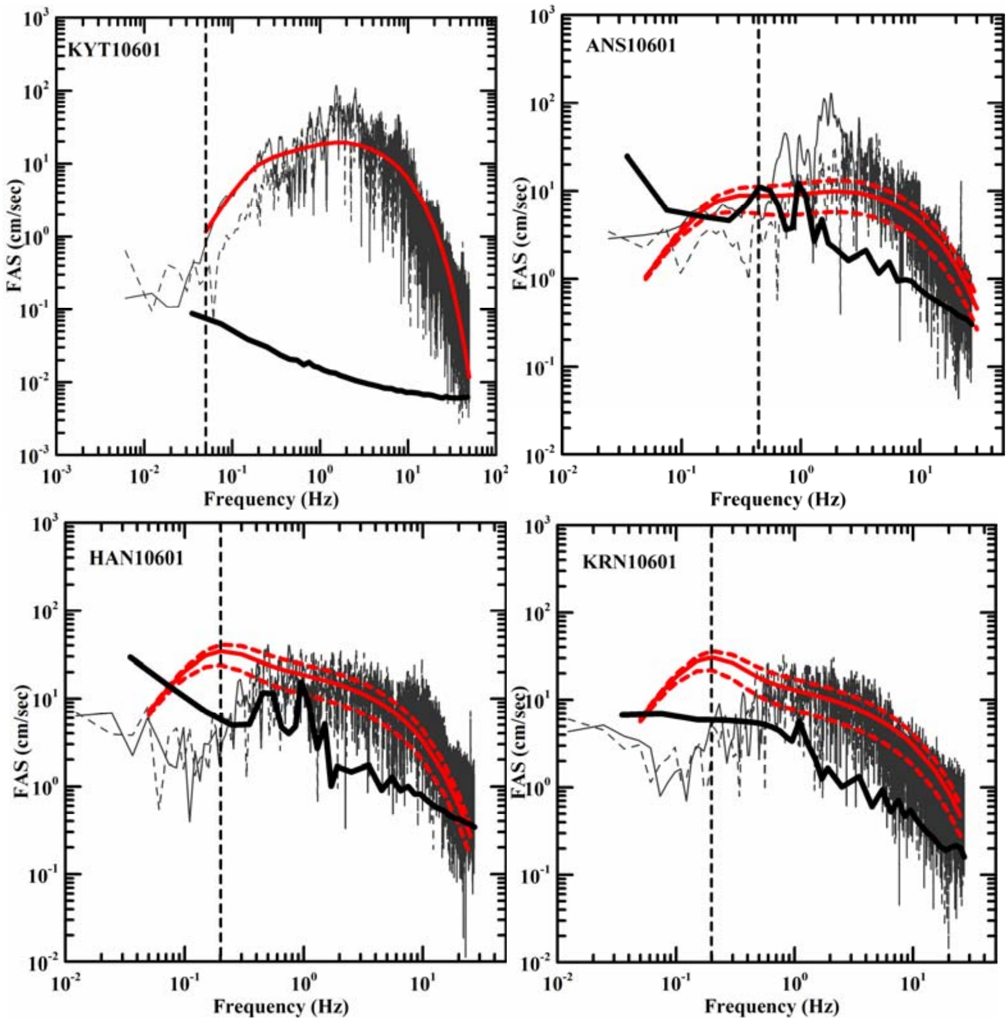
The earthquake was strongly felt in most of the regions of Greece and in the broader area of Eastern Mediterranean Sea, from Southern Italy to Egypt and Jordan. Most of the damages were observed in the village Mitata of Kythera Island (EERI newsletter March 2006). Inversion of broadband and teleseismic waveforms revealed a thrust focal mechanism with a considerable strike slip component (Strike 50, Dip 55, Rake 115;AUTH 2006, http://lemnos.geo.auth.gr/the_seisnet/WEBSITE_2005/station_index.html). In Table 1 details of the recording station locations, instrument types and distances of the records used are given. QDR is an instrument of low-resolution digital sensor (<12-bit), ETNA uses a digital sensor with resolution 18-19 bit and the CMG-5T is a fully digital 24-bit sensor.

In order to calculate the low cut-off frequency for each record the corresponding Fourier Amplitude Spectra (FAS) were calculated and plotted together with each instrument's noise curve. The instruments' noise (FAS) curves were either calculated from the digitized time-mark when available (QDR instruments) or from the sensors' noise curves (ETNA and CMG-5T instruments) (Skarlatoudis et al., 2003).

Table 1. Recording station locations, instrument types and distance from the epicenter and the hypocenter of the earthquake.

Station Name	***Longitude***	***Latitude***	***Ep. Dist. (Km)***	***Hyp. Dist. (Km)***	***Sensor***
KYT1	36.150	22.983	34	78	*ETNA*
ANS1	36.472	23.101	37	79	*QDR*
HAN1	35.518	24.019	97	116	*QDR*
KRN1	36.802	21.961	141	155	*QDR*
HER1	35.318	25.102	186	199	*QDR*
NAX1	37.100	25.367	205	217	*CMG-5T*
KOS1	36.983	27.290	362	368	*ETNA*

The cut-off frequency for the low-cut filtering was defined as the frequency where the signal FAS was exceeding the corresponding noise FAS. The criteria for the estimate of the low pass cut off frequency proposed by Skarlatoudis et al., (2003) were not applied in this case, in order to preserve as much as possible of the low frequency content of the records due to the intrinsic characteristics of this intermediate-depth earthquake. The previous procedure is graphically represented for each recording in Figures 2. The low cut-off frequencies estimated with the previously described method are shown in Figure 2 with the vertical dashed line.



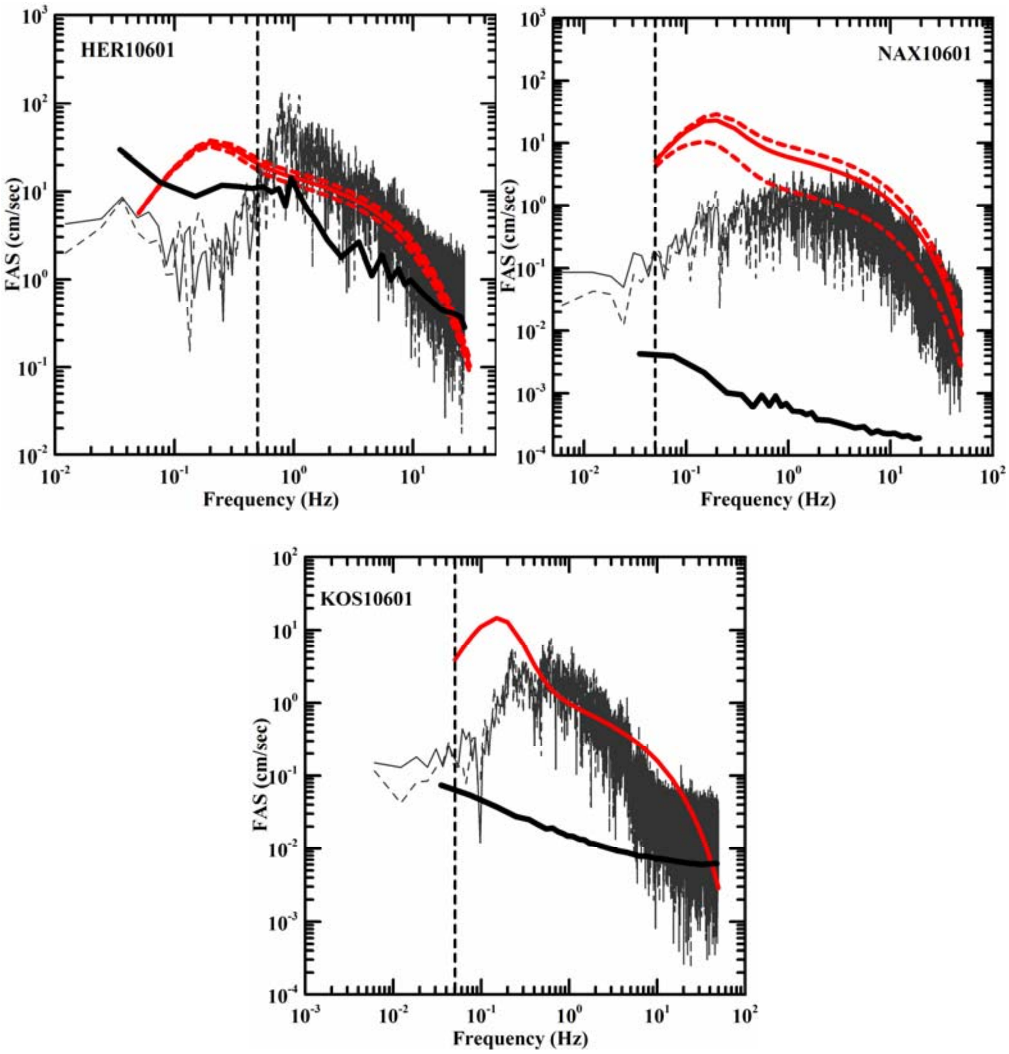


Figure 2. Observed (black solid and dashed lines) and theoretical (red solid and dashed lines) Fourier Amplitude Spectra (FAS) of each recording. The thick solid black line corresponds to the FAS of noise. The black solid and dashed lines correspond to the FAS of the two horizontal components of the record, while red dashed lines derived from the two different definitions of the stress parameters, Δσ. The low cut-off frequency is shown with the vertical black dashed line.

The two different corrections applied for producing corrected values of ground motion (KMI-SMA 1999, and Boore 2001, 2003) gave very similar results as shown in Skarlatoudis and Margaris, (2006). In the present paper all records were processed and corrected with the Boore (2001, 2003) method. This procedure achieves better correction of the uncorrected time histories and more reliable spectral values adopting zero padding of adequate length to the beginning and end of the recorded data segment, retaining as well this padding section in deriving velocities and displacements (Boore, 2005).

Theoretical FAS values were calculated based on the stochastic source model (Boore, 1983; Margaris and Boore, 1998) for each strong motion accelerogram recorded by the stations shown in Figure 1. The analytical description of the applied methodology has been presented in detail in various publications (e.g. Boore, 1983; Atkinson and Boore, 1995, 1997, 1998) and its application for Greece in Margaris and Boore (1998) and Margaris and Hatzidimitriou (2002). Nevertheless most of the basic principles of this method are also presented in the present study.

The theoretical spectrum can be described by a radiated spectrum (see Joyner and Boore (1988) and Boore (1996) for more details), which is given as

$$R(f) = CS(f)A(f)D(f)I(f) \tag{1}$$

where C is a scaling factor, $S(f)$ is the source spectrum, $A(f)$ is the site amplification factor, $D(f)$ is the diminution factor, and $I(f)$ is a factor that includes the instrumental response. For the source spectrum, $S(f)$, an ω-square model of shear waves for the ground acceleration at the source is assumed, which follows the standard expression:

$$S(f) = CM_0 / \left[1 + \left(f / f_0\right)^2\right] \tag{2}$$

where M_0 is the seismic moment and f_0 is the corner frequency of the spectrum; these are the two parameters characterizing the source radiation. In the description of the source spectrum (equation 2), the corner frequency, f_0, determines the acceleration amplitude and controls the frequency content of the earthquake generated at the source. More objective methods for the calculation of the corner frequency have been proposed in various studies. In the present paper the corner frequency f_0 was computed with the methods proposed by Brune (1970, 1971) and Andrews (1986) and the average value of f_0 resulting from both models was adopted producing the theoretical spectrum and calculating the stress parameter.

The input parameters of the stochastic simulations used were the same described in previous studies by Margaris and Boore (1998) and Margaris and Hatzidimitriou (2002) for shallow earthquakes in the broader Aegean area. From the recorded accelerograms the stress parameter was computed, using the methodology proposed by Cocco and Rovelli (1989) and applied from Margaris and Hatzidimitriou (2002) in Greece. The estimated stress parameters for each recording station are shown in Table 2. The stress parameter was further utilized for the estimate of the theoretical FAS shown in Figure 2 (red dashed and solid lines) in comparison with the FAS of the observed records and the noise signals.

Table 2. Stress Parameters $\Delta\sigma$ estimated for each recording station for both horizontal components. For the stations depicted with red color (NAX1 and KOS1) the estimated stress parameters exhibit large uncertainties.

Station Name	***Stress Parameter Δσ (bars)***
KYT1	235
ANS1	168
HAN1	94
KRN1	132
HER1	348
NAX1	20
KOS1	130

These stress parameters were estimated by using the mean values of the two models for the calculation of the corner frequency (Brune, 1970;1971, Andrews, 1986) as were described in Margaris and Hatzidimitriou (2002). In Figures 2, the theoretical FAS estimated by the stress parameters of the two adopting models are depicted with the dashed red lines, while the red solid lines correspond to the theoretical FAS estimated by the mean stress parameter. While most of the theoretical FAS estimated were in a good agreement with the observed ones (e.g. KYT1, KRN1 in Figures2), theoretical FAS estimated for NAX1 and KOS1 stations did not exhibit the same behavior. For both NAX1 and KOS1 stations, only the Brune model could fairly simulate the observed spectral values. In Table 2 the values of stress parameters estimated for these stations are shown with red color. This misfit in the comparison of the theoretical and observed FAS for stations NAX1 and KOS1 could be partly attributed to their long hypocentral distances (greater than 200 km), in comparison to other recording stations.

The accelerograms were corrected using the observed low pass cut-off frequencies (OLC) estimated from the comparison between the signal and noise FAS and the displacement response spectra (DRS) of the records were calculated. In addition all accelerograms were corrected using the theoretical low pass cut-off frequencies (TLC) estimated from the comparison between the theoretical and noise FAS and new DRS were also computed. In Figures 3 both DRS for each accelerogram are shown. With the black solid line the DRS derived from the OLC are depicted, while with the red dashed lines the DRS using the TLC are shown. The values of the “observed” and the “theoretical” cut-off frequencies (OLC and TLC) estimated for each accelerogram are also shown in each plot.

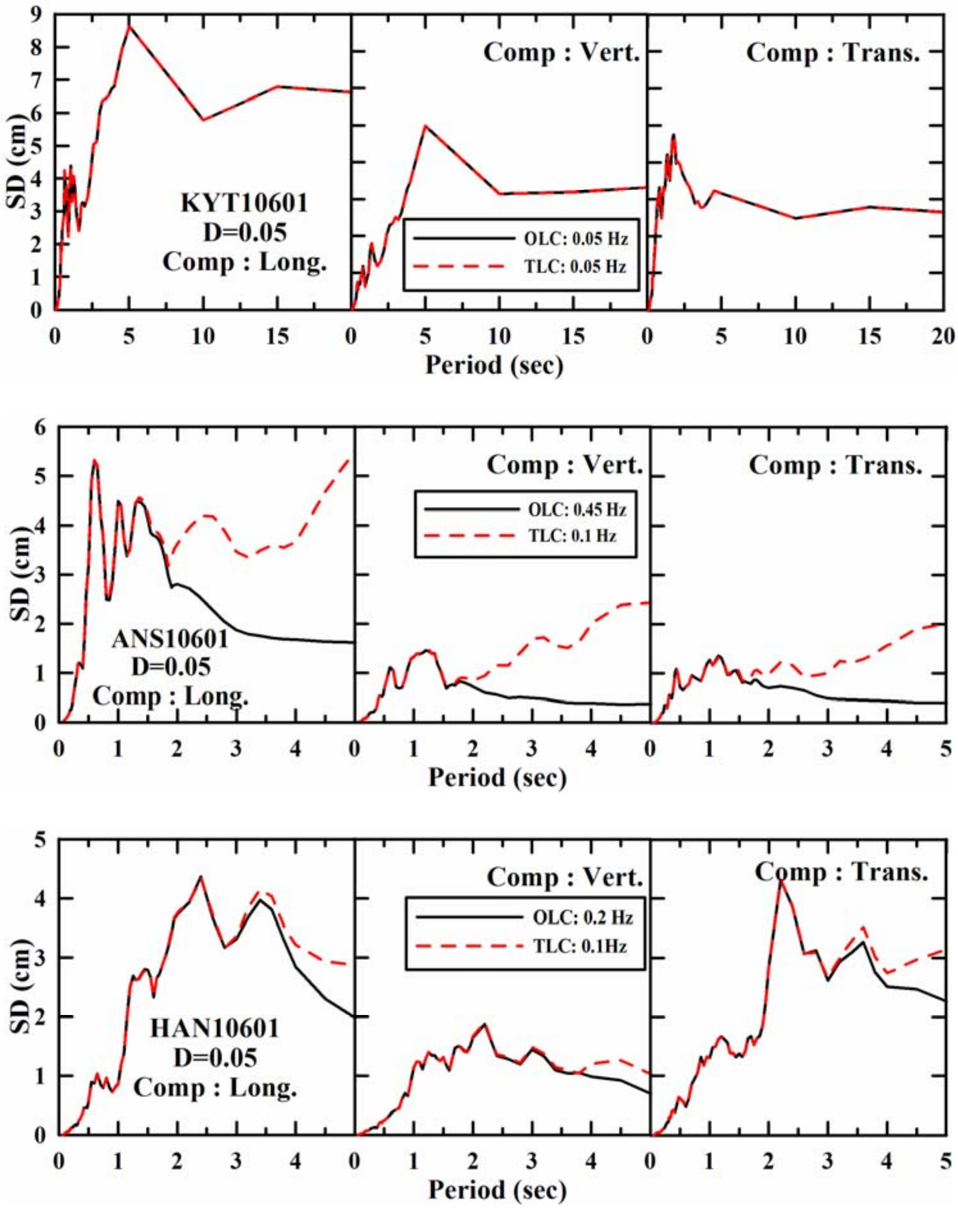


Figure 3. Caption on next page

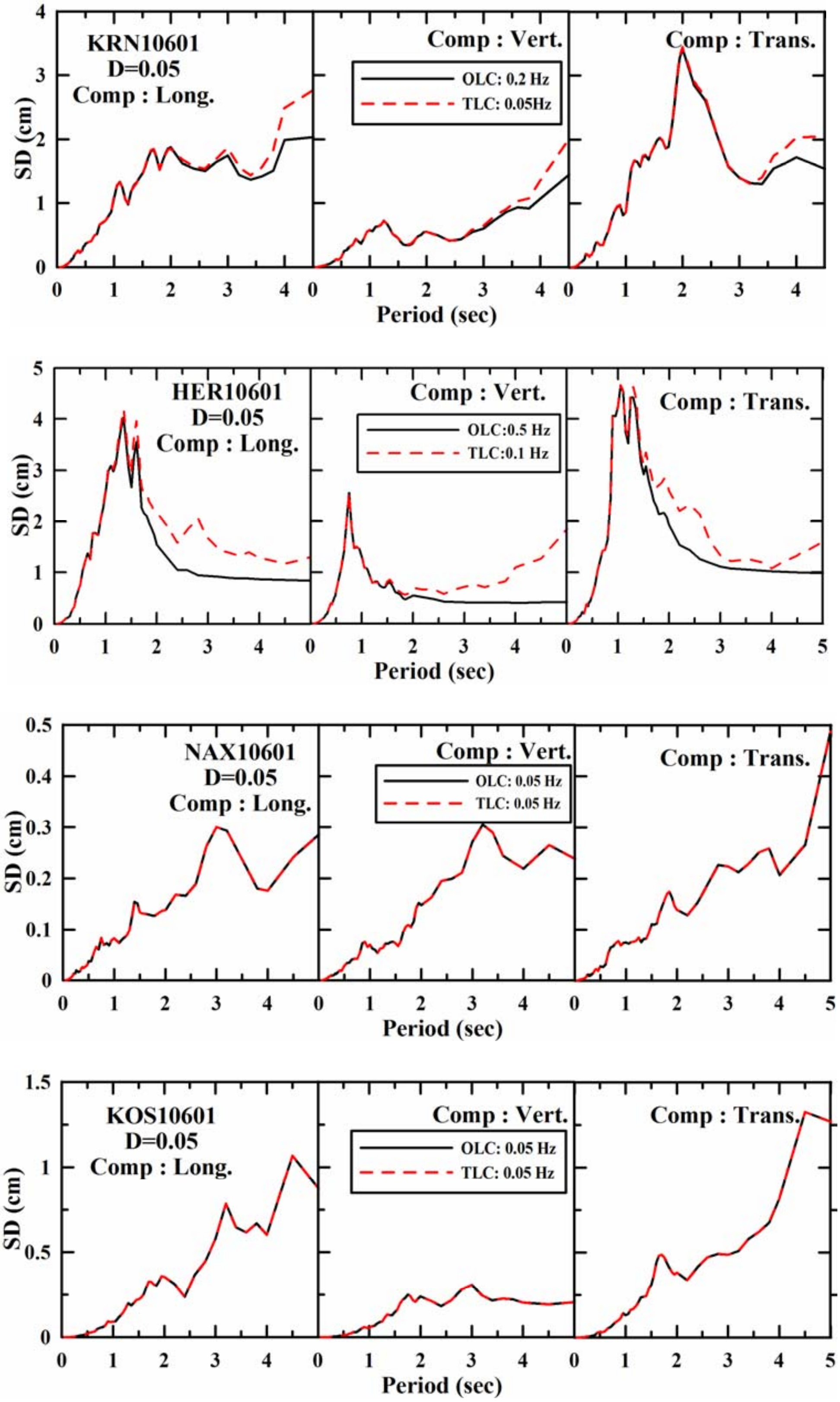


Figure 3. Displacement Response Spectra (DRS) of the recordings used. The black solid line curves correspond to the DRS for the low-cut filter estimated from the signal to noise ratio, while the red dashed lines to the DRS for the low-cut filter according to the theoretical spectrum for each accelerogram.

DISCUSSION – CONCLUSIONS

The stochastic simulation method described above was applied for the first time on an intermediate depth earthquake in the broader Aegean area. In most of the recordings (Figures 2) the agreement of the theoretical with the observed spectra was good, especially in the higher frequencies. However it is evident that in most of the cases the methodology failed to give results close to observed in the low frequency band. This could be partly attributed to application of the method as well as to the resolution of the recording instruments. The nature of the simulated earthquake and also the fact that the application of the method was based on our experience for simulating shallow earthquakes could be the source of this misfit between the theoretical and the observed FAS especially in the lowest part of the frequency content.

Another factor that should be taken into account is that seismic waves generated from the intermediate depth earthquakes that occur in the broader Aegean area have specific source and path characteristics. In the back arc areas seismic waves are traveling through high temperature in almost melted materials. This phenomenon causes a significant diminution in the amplitudes of the S waves, enhancing this way the low frequency content of the traveling waves. On the opposite waves that are traveling along the arc do not suffer this diminution and even more its energy is transmitted in very long distances comparing to shallow earthquakes with similar energy characteristics.

Moreover most of the recording stations had hypocentral distances greater than 100 Km because of the depth of the earthquake. In the applied method anelastic attenuation and geometrical spreading term is controlled by the factor R. For ranges up to 100 Km, R can be described by distance. Thus anelastic attenuation and geometrical spreading are assumed to describe with the term 1/R (R<100 km) and $1/\sqrt{R}$ for distances greater than 100 km. For distances greater than 150-200 Km the previously suggested terms seem to be insufficient to describe the attenuation of the wavefield. This fact is also supported by several tests performed with accelerograms from this earthquake recorded in long distances, which are not shown in the present study.

In Skarlatoudis et. al., (2004) and in Skarlatoudis and Margaris (2006) it was pointed out that low resolution instruments failed to record long period ground motions because of their intrinsic limitations and also because of digitization noise introduced in low frequencies. The comparison of the results in Figures 2 with the regarding information from Table 1, revealed that in most cases (e.g. HER1, KRN1) recordings from QDR instruments could not reproduce correctly the long period ground motions, while high resolution instruments such as the one installed in station KYT1 (19-bit ETNA) reproduced correctly the ground motion in all frequency bands. Nevertheless results for the NAX1 station do not follow the previous conclusions, but this could be attributed to the long hypocentral distance of the station and the methodological problems discussed in the previous paragraph.

Concluding the January 8 of 2006 earthquake in Kythera produced a high quality dataset of strong motion records. The largest strong motion dataset ever recorded in Greece from an intermediate depth earthquake. Different types of recording instruments combined with the specific characteristics of this earthquake gave the opportunity for various types of studies. In the present paper an effort was made to combine accelerograms with the seismological information carried by them. The stress parameter $\Delta\sigma$, of each record was estimated by fitting its theoretical and observed Fourier Amplitude Spectra. This information was used to estimate marginal cut-off frequencies for low-cut filtering of the strong motion records.

In most of the cases the low pass cut-off frequencies estimated by signal to noise ratios were in a good agreement with the ones indicated from the seismological information. The filters used in all records, removed most of the low frequency noise introduced by the recording instrument and digitization procedures. Finally the need for higher resolution instruments was made obvious since the modern needs of engineering applications require records with very low frequency content.

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