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DETERMINATION OF NOISE SPECTRA FROM STRONG MOTION DATA RECORDED IN GREECE

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ABSTRACT

Strong ground motions have been mostly recorded by analog accelerographs. The processing of analog strong motion recordings introduces spectral noise in the signal and significantly affects the record. In the present paper a unified processing and determination of spectral noise for the Greek strong motion records is presented. Moreover appropriate relations are introduced for the lower cut – off frequency with respect to the epicentral distance and earthquake magnitude for record filtering.

KEYWORDS

Strong motion, analog accelerograms, processing, spectral noise, record filtering, cut-off frequency

INTRODUCTION

Ground motion from strong earthquakes, has a significant contribution to our knowledge on earthquake engineering, in seismic active areas as well to our studying of seismic waves. These ground motions are most of the times recorded from accelerographs, which in great majority, record seismic motion analogically. The conversion of these records into digital signals is obtained by digitizing and appropriately correcting them. Due to methods applied for recording, digitizing and processing of the records, spectral noise is introduced in the signal which notably affects the credibility of the components of the records, mostly in low but and high frequencies. This results in the reduction of the useful frequency bandwidth from which we can derive reliable information.

A representative example of the problems created from the introduction of noise in strong motion recordings is the unreal enlargement of low frequencies. The components of low frequencies including acceleration, velocity and displacement, are very important since the acceleration express the seismic force per unit mass, velocity is related directly with the kinetic energy of seismic waves and displacement gives us information for the deformation of the ground. Also low frequency seismic waves have a great contribution in the response of tall buildings and large constructions, such as bridges and dams. Low frequency signals are the ones affected most by spectral noise [1].

Due to the increase of the usage of strong motion recordings in engineering seismology and earthquake engineering and because of the need of independence of the results from the recorded noise level, a need for studying noise level in different recording systems has originated. Also the study of noise level during the processing of strong motion records has become a necessity. Techniques for processing these accelerograms have been developed aiming to the elimination or reduction of the presence of repetitive errors in ground motion recordings. Trifunac and Lee were the first to develop such techniques [2,3,4], while some modifications have been suggested by a number of authors [5,6,7,8]. In this work the results of the processing of 420 records of strong motion data recorded in Greece are presented. A robust method for processing and estimating spectral noise of the records is suggested. Also a relation for the estimation of the average spectral noise for Greece is introduced. Finally relations are introduced for reliable estimation of the lower spectral limit (low cut-off frequency) for use in strong motion records filtering.

INSTRUMENTATION AND STRONG MOTION RECORDS

The most common models of strong motion recording instruments are the Kinemetrics analog accelerograph SMA-1 and the digital SSA-1, SSA-2 and SSA-16 and the Altus series (ETNA, K2, etc.). The SMA-1 consists of three units for converting the three ground motion components into variations of the position of the trail of a light beam. These variations are recorded in a 70mm film, which is wrapped around a drum, rotating with a steady velocity equal to 1 cm/sec. These types of accelerographs consist ITSAK's (Institute of Engineering Seismology and Earthquake Engineering) basic accelerograph network and all the records used in this work have been collected from this network. Data recorded from digital accelerographs don't need digitization since they are digitized automatically by the accelerograph. On the other hand, data recorded from SMA-1 must be digitized with a semi-automatic or an automatic procedure [9,10]. Comparing the digitized data from the two-instrument types significant noise introduction in the SMA-1 data has been observed mostly in lower frequencies of the signal. This noise is produced by the digitization process and results in a smaller frequency bandwidth for which reliable information can be obtained than the one of data recorded from digital accelerographs [11].

The first correction usually applied in the digitized records is the baseline correction [12]. The baseline error is due to the deformation of the film and other similar problems and results the introduction of low frequency spectral noise in Fourier amplitude spectra. Generally, a small shift of the baseline in accelerograms' waveform produces a false linear trend in the velocity's waveform baseline, while in displacement the baseline has a false trend of a second order curve. This problem is ought to the second order integration in the acceleration for computing the displacement. A simple technique to correct this problem is the deduction from the acceleration and velocity waveforms of a straight line calculated with the least squares method. A more complicated way of diminishing this error is a three-step routine proposed by Hung [13].

PROCESSING OF STRONG MOTION RECORDS

Digital Filters

In order to remove all previous mentioned errors and the exact determination of ground parameters (acceleration, velocity and displacement) various correcting procedures of accelerograms have been developed. The procedure usually relies on the use of appropriate digital filters. In the present paper the following low-pass filter was used:

$$
\begin{aligned}
&H(f)=0 \qquad |f|\geq f_c \\
&H(f)=\frac{|f|-f_c}{f_r-f_c} \qquad f_c>|f|>f_r \\
&H(f)=1 \qquad |f|\leq f_r
\end{aligned}
\tag{1}
$$

where f_c and f_r are cut-off and roll-off frequencies respectively. Reverting the inequalities of the previous filter we can get the corresponding formulas for the high-pass filter. In practice, the processing of strong motion data relies on the comparison of the Fourier spectrum of the recorded components and the corresponding noise spectrum, which allows us to estimate the frequency bandwidth that gives us reliable results. By applying a band-pass filter for this bandwidth we can get the corrected data, which are partly free from noise.

For the estimation of the characteristic frequencies of the high–pass filters that will be applied on the uncorrected data, an appropriate processing program was written, which uses the Fourier amplitude spectra and calculates the frequencies for which the signal to noise amplitude ratio is 2:1, 3:1, etc. After testing different filters for the records, we chose for cut-off frequency f_c, the frequency where signal to noise ratio was 2:1 and for roll-off frequency f_r, the frequency where signal to noise ratio was 3:1.

Strong Motion Data

The data used in the present work correspond to records from ITSAK's national accelerograph network for a period of seventeen years between 1980 and 1997. From all the available records only the ones that conformed to the criteria usually used from ITSAK were digitized. The criteria used were:

1. The earthquake which produced the accelerogram must have an equivalent moment magnitude $M_W \geq 5.0$
2. The accelerograph record must have peak ground acceleration $PGA \geq 0.05g$
3. The record can have peak ground acceleration $PGA \geq 0.05g$ but is corresponds to the same

   earthquake with another record with peak ground acceleration bigger than 0.05g. The number of records finally digitized and processed with the following technique are 420.

Digitization of Strong Motion Data

The first stage of the processing is the digitization. Every record was converted, with an A4 scanner, into (.tif) image files. The choice of the scanning resolution was done after the studying of every record spectrum for scanning resolutions of 300, 600 and 1200 dpi. The comparison of Fourier spectra for the previous scanning resolutions showed that the spectra produced with scanning resolution of 300 dpi were much more “noisy” than the spectra produced with scanning resolution 600 and 1200 dpi, especially in frequencies greater than 10 Hz. On the contrary spectra with a scanning resolution of 600 and 1200 are almost identical, which is evidence of minimization of the noise due to scanning resolution. Due to the limitations of the analog recording instruments which have a maximum recording frequency of about 30 Hz and because scanning with resolution of 1200 dpi would result in very large files, the scanning resolution of 600 dpi was preferred.

In the second stage of the digitization the (.tif) files were converted, from raster to vector format using the Kinemetrics software Scanview [14]. The procedure involves record selection, baseline determination (usually a fixed trace) and correction.

Data Correction

The second stage of data processing is concerned with the generation of the corrected data from the processing of the digitized records. Every digitized record is processed taking into account the recording instrument parameters and uncorrected data are produced. These are usually referred as files (.V1) files. In the next stage the Fast Fourier Transformation was estimated for the uncorrected data for frequencies up to 30 Hz, which is the response limit of the analog accelerographs, and for the complete record. The same procedure also was applied for the two digitized fixed traces. For the noise study the Fourier Amplitude Spectra (FAS) of the components and the corresponding fixed traces of the record were compared, as is shown for the Zak188-4 record in Figure 1.

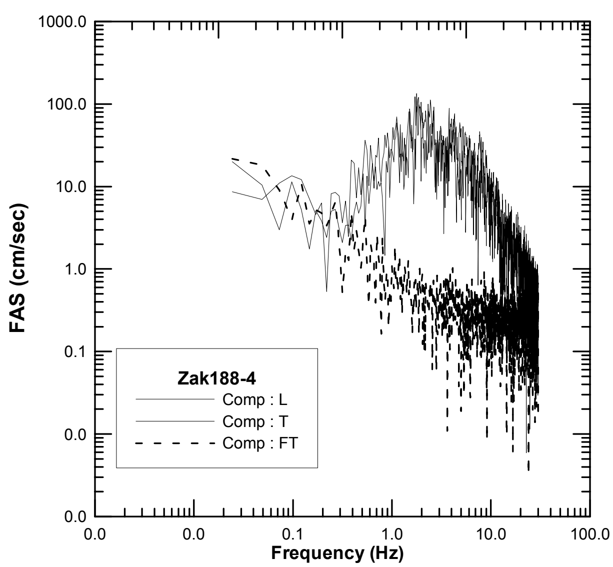


Figure 1: Fourier Amplitude Spectra of the horizontal components (L and T) and the fixed trace (FT) of the record Zak188-4

Studying the amplitudes spectra in Figure 1 it is evident that the seismic signal (continuous line) is higher than noise signal (dashed line) only in a certain frequency range. It is also obvious that both spectra show a “local” variation resulting in a difficulty in the determination of the filtering limits. This local variation is the result of the error involved in the application of the Fourier transformation to discrete measured data of continuous functions [15]. For this reason the Fourier transformations were smoothed as shown in Figure 2 where the smoothed logarithmic amplitude spectra of every component of the Zak188-4 record are plotted.

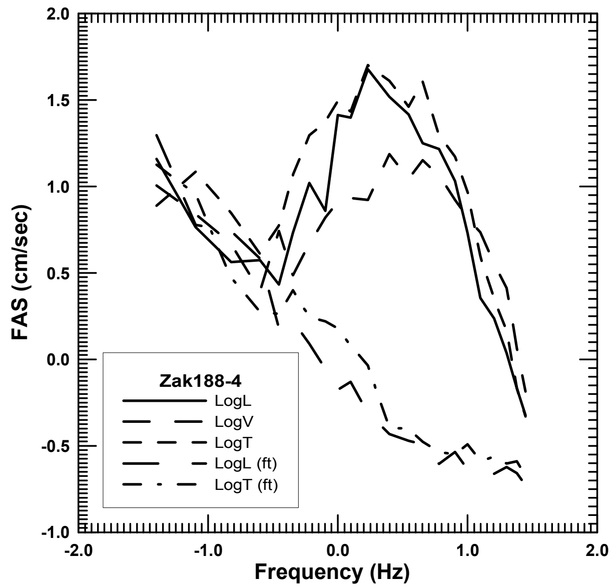


Figure 2: Smoothed logarithmic amplitude spectra of the components (L, V, T) and of the fixed traces (L-FT and T-FT) of the record Zak188-4

From the comparison of the spectra of the two horizontal components it is evident, as it is expected, that they don't exhibit a systematic bias. For this reason in the following processing stages an average spectrum was used for the spectra of the horizontal components. Similarly, the fixed traces spectra are also expected to be quite similar so in the following processing stages the average spectra of the two fixed traces was also used. In Figure 3 the smoothed mean values of the logarithmic amplitude spectra of two horizontal components (L, T), the vertical component (V) and fixed traces (LT-FT) of the record Zak188-4 are shown.

The high-pass filters were calculated for every record with the method previously referred. For the low-pass filters the characteristic frequencies of 25 and 27 Hz were used for most records in accordance with the frequency response of the recording instrument. This "rule of thumb" did not apply only in a few cases where we observed an intense reduction of the signal amplitude. By applying at the records the previous calculated filters, with the use of the proper software [14], we obtained the corrected data that are usually referred to as (.V2) files. A horizontal, -L-, and a vertical, -V-, component of the corrected record Zak188-4 that was produced with the previous procedure, is shown in Figure 4.

SPECTRAL NOISE PROCESSING

Mean Spectral Noise of Greek Records

It is reasonable to assume that the recorded noise level for the records, which have been processed, exhibits similar characteristics. Therefore, it is reasonable to derive an average noise spectrum from all records [16] [17]. For this reason we used the data from the smoothed spectra of all the fixed traces of the records.

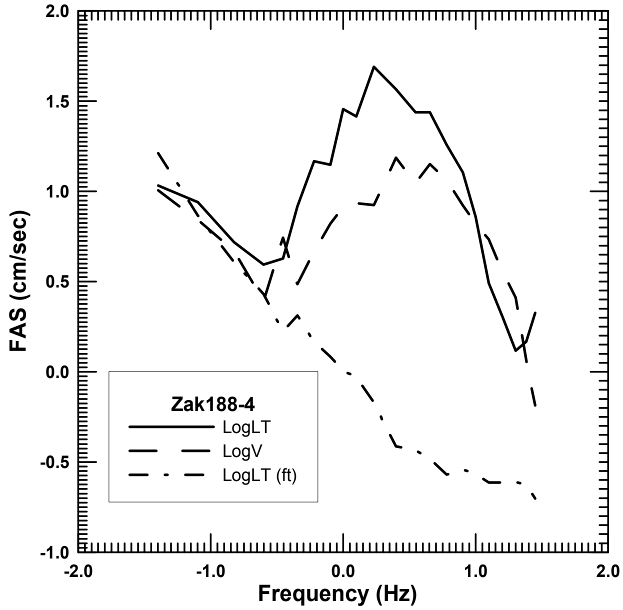


Figure 3: Smoothed mean values of the logarithmic amplitude spectra of two horizontal components (L and Ô), vertical component (V) and fixed traces (LT-FT) of the record Zak188-4

In Figure 5 in bi-logarithmic scale the average spectra noise level is shown. Moreover, the standard deviation, the best linear fit and the corresponding curves produced by Lee and Trifunac (1990) and Trifunac and Todorovska (2001) are also shown. It can be observed that the average noise level approximately follows a linear law with a negative slope.

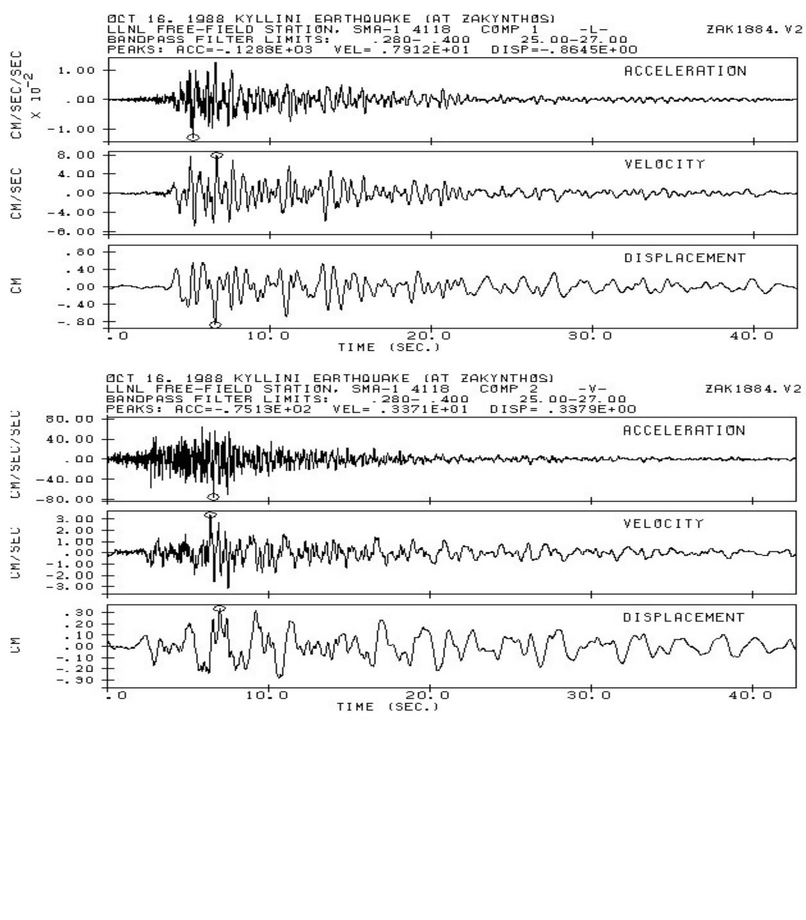


Figure 4: Horizontal and vertical component of the corrected record Zak188-4

The processing of the noise curve with the least squares theory gives Eq 2:

$$\log A^{Noise} = -0.65 * \log f - 0.25 \quad (2)$$

that has a linear correlation coefficient r=0.99 and standard deviation σ=0.067

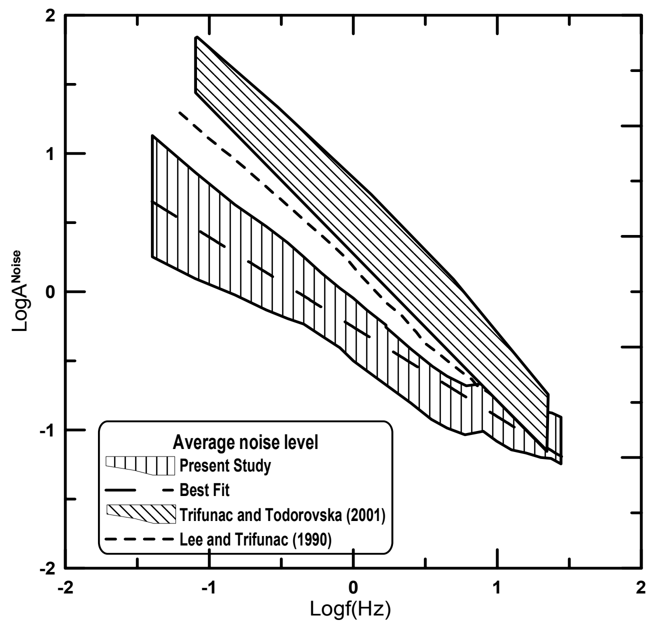


Figure 5: Mean spectral noise curves derived in the present work and comparison with the corresponding curves of Lee and Trifunac (1990) and Trifunac and Todorovska (2001)

The comparison of the curve derived from this work with the corresponding curves of Lee and Trifunac, Trifunac and Todorovska shows that the noise level introduced from the digitization and processing of the records in this work is lower than the other two corresponding levels. This can be partly attributed to the fact that all records used follow the ITSAK's criteria mentioned before, so the accelerations of these records are big enough they are hardly affected from noise level. Also all the records were scanned with scanning resolution 600dpi, which is a critical factor for the minimization of noise introduced in the digitization procedure. The importance of the obtained noise curve shown in Figure 5 is clear if we consider the fact, that a large number of the accelerographs, which are in operation now in Greece, do not record fixed traces and/or time marks, hence the noise level cannot be obtained with the previous procedure. In such cases the comparison with the average determined using all the records noise level of ITSAK's strong motion recording network, facilitates the procedure of determining the appropriate frequencies for the filtering of the uncorrected data.

CALCULATION OF THE HIGHPASS CUT-OFF AND ROLL-OFF FREQUENCIES AS A FUNCTION OF MAGNITUDE AND DISTANCE

The final stage of the processing of the strong motion data is the calculation of equations associate the cut-off frequency of the high and low filters with the hypocentral distance and the magnitude of the earthquake that the record comes from. These equations are calculated for the average spectrum of the two horizontal components as well as the spectrum of the vertical component of the records.

For the estimation of these equations the following procedure described below was adopted: After plotting and graphical examination of the data, a linear function of the form $logf_c=aM+blogD+c$, was considered relating the values previously referred. In this function f_c is the cut-off frequency, M is the earthquake magnitude and $D=(\Delta^2+H^2)^{1/2}$ is the hypocentral distance. Δ is the epicentral distance and H is the <<effective>> depth, (mean depth of energy release) of the earthquakes, which is considered stable and equal to 5 Km for Greece [18]. The calculation of the coefficients a, b and c was performed using least squares. The linear fit that relates f_c, M and D has been selected testing different functions including functions of higher order, with a proper statistic test (F-test) for the best fit of the data. The following equations were calculated for the low cut-off frequencies f_c (derived for a signal to noise ratio 2:1) for the horizontal (L and T) and the vertical (V) components.

$$\begin{aligned} \log f_{C_{LT}} &= 0.14115 * \log D - 0.32316 * M + 1.36245 \\ \log f_{C_V} &= 0.22606 * \log D - 0.32215 * M + 1.39508 \end{aligned} \quad (3)$$

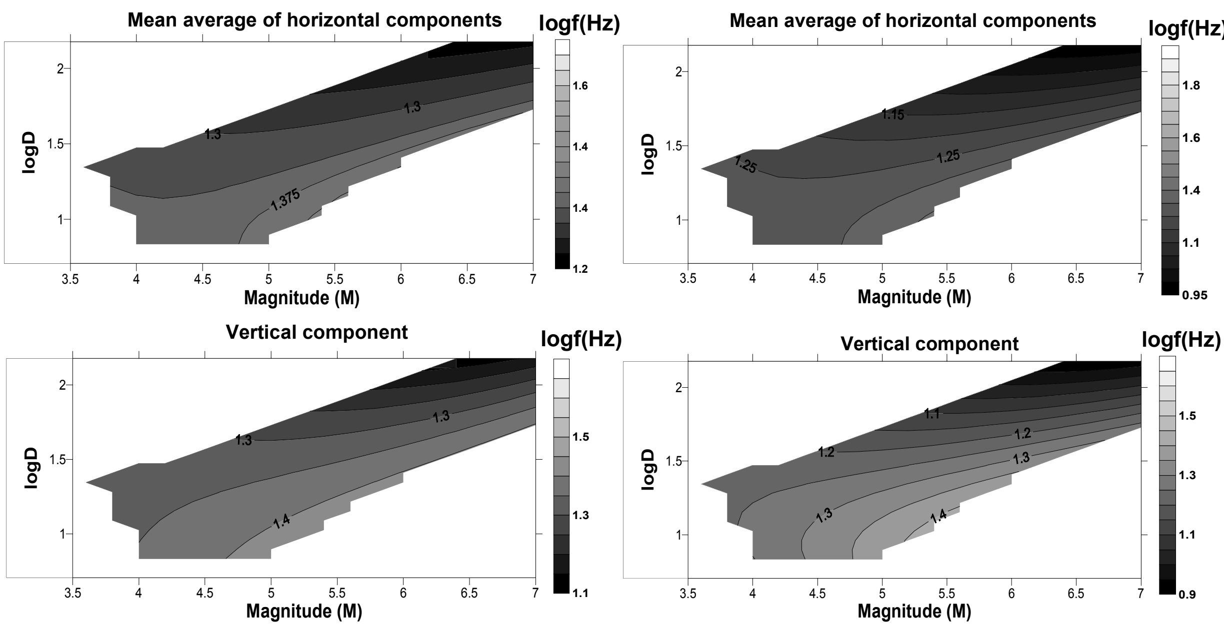
The root mean square (RMS) error of the cut-off frequencies for the two horizontal and the vertical components (signal to noise ratio 2:1) is $RMS_{f_{C_{LT}}} = 0.238$ and $RMS_{f_{C_V}} = 0.244$ respectively. For the low roll-off frequency f_r (signal to noise ratio 3:1) equations estimated are:

$$\begin{aligned} \log f_{C_{LT}} &= 0.14763 * \log D - 0.30083 * M + 1.35360 \\ \log f_{C_V} &= 0.19943 * \log D - 0.31103 * M + 1.49118 \end{aligned} \quad (4)$$

The corresponding values for the RMS error are $RMS_{f_{C_{LT}}} = 0.221$ and $RMS_{f_{C_V}} = 0.251$. By the examination of Eqs (3) and (4) is easily shown that high cut-off and roll-off frequencies (noisy records) are estimated for earthquakes with small magnitude recorded at large distances. Also earthquakes with large magnitudes recorded in small distances have relatively low cut-off frequencies allowing a larger portion of the spectrum to be studied. This behavior is expected due to the attenuation of the seismic energy with distance and the reduction of the energy for small earthquakes.

It is also interesting to compare the cut-off frequencies of the mean average of the two horizontal components of the record with the corresponding vertical component. It is evident that the cut-off frequency of the vertical component shows higher values for the same magnitude and distance i.e. vertical component is more sensitive to noise than the two horizontal components. This is expected because of the smaller amplitude of the S waves recorded at the vertical component. Similar conclusions are derived from the comparison of Eqs (4). Because of the adequate number of data used for the derivation of Eqs (3) and (4), the estimation of the cut-off frequency from these equations can be considered to be reliable and the results can be used for similar purposes.

The technique followed for the estimation of the equations of the high-pass cut-of and roll-off frequencies was applied also for the case of the low-pass cut-off and roll-off frequencies. In this case however a linear relation wasn't found to apply for the variables used for the high-pass frequencies function. This result occurred because most of the records used in this paper have a cut-off frequency larger than 25Hz, which is imposed by the characteristics of the recording instrument. For this reason curves of equal frequencies were calculated for signal to noise ratio 2:1 and 3:1, for the average spectrum of the two horizontal components and the vertical one. The corresponding figures are shown in Figures 6a and 6b, respectively. Blanked areas where equal frequency curves are not shown correspond to regions for which records were not available.



Figures 6a and 6b: Equal frequency curves for the average of the two horizontal and the vertical component as a function of the logarithm of the hypocentral distance and earthquake magnitude. Figure 6a (left figure) shows the frequency curves plotted for signal to noise ratio 2:1 and 6b (right figure) for signal to noise ratio 3:1 respectively

CONCLUTIONS

The processing of the strong motion records with the technique applied at this paper can contribute to the solution of several problems related to analog strong motion data processing. The processing described previously minimizes significantly the average processing time of the records and the noise introduced from the digitization and processing of the accelerograms. Also a significant result of the homogenous processing of the records is the calculation of mean curve of the spectrum noise for the Greek strong motion records, which constitutes a reliable solution to the calculation of the filtering limits of the accelerograms for which fixed traces or time marks are not available. Finally appropriate relations are proposed for the calculation of the high-pass cut-off and roll-off frequencies in relation to the earthquake magnitude and the epicentral distance, as well as corresponding equal frequency plots for the behavior of the low-pass cut-off and roll-off frequencies.

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