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ANALYSIS OF THE LOW FREQUENCY CONTENT IN STRONG MOTION RECORDS

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ABSTRACT

The standard methodology adopted by ENEA for strong motion record processing allows to preserve the main frequency content of seismic event, which interest the structural engineers. In order to investigate low frequency content, a new methodology will be proposed in this paper, based on both time and frequency domain analysis. The importance of studying low frequency content in strong motion records is related to diffusion of structures characterized by a high fundamental period of vibration. Among these are not only long-span bridges and high rise buildings, but also base isolated structures, which seem to be very suitable to support earthquake actions.
Low frequency content is hidden by various types of noise, due to background and sensor. Time domain analysis requires the study of accelerometric records filtered in the interval of interest. Frequency domain analysis is based also on the calculation of the corner frequency. On the base of the position of corner frequency, the band-pass filtering interval, evaluated by using the standard methodology, can be changed.
Some results obtained on strong motion records from European data bank are shown.

KEYWORDS

Seismic input; low frequencies content; filtering; strong motion data acquisition; base isolation; structural control; signal to noise ratio; strong motion data processing.

INTRODUCTION

The diffusion of structures characterized by high fundamental periods is the reason of the interest about the low frequency content of strong motion records. Structures as long-span bridges, off-shore platform, tall buildings are often judged to be less vulnerable to earthquake effects, because their fundamental frequency of vibration is out of the frequency range, in which earthquake energy is strongest. From this consideration started the idea of designing flexible buildings, in order to reduce their first natural frequency. The required flexibility is achieved at the foundation level by means of base isolation system. Base isolated buildings may show very large displacements. Flexibility can cause problems, especially in the wind and under seismic actions if low frequency content is important. Therefore a more accurate analysis is necessary.

Low frequency content is often hidden by various types of noise that seriously affect the reliability of the low frequency content in the interval of interest (Trifunac and Brady 1971, Rinaldis and Bongiovanni 1989). Our capability in correcting strong motion data depends on the reliability of the reference trace used to determine the noise. In order to perform the low frequency analysis of strong motion records, the standard methodology for processing strong motion data has been revised. In this paper a new methodology will be proposed. The main results of a large investigation, carried out on European data bank, will also be shown.

ACQUISITION AND PROCESSING OF STRONG MOTION DATA

The time histories of most of data bank records were obtained on photographic films, by means of recording with analogic accelerograph (Hudson 1979). The three components of the motion and the fixed trace or the time-mark were recorded. Fixed trace or linearized time-mark represent the noise of process (Berardi et al. 1991). In the standard processing methodology adopted by ENEA (Rinaldis 1985 and 1988) data are processed in the frequency domain. In particular the band-pass filtering of uncorrected signal is based on signal to noise ratio (SNR) computation between the Fourier Amplitude Spectrum of the selected acceleration component and the Fourier Amplitude Spectrum of the reference trace.

Filter is defined by the roll-off (f_{RL}) and the cut-off (f_{CL}) frequencies at low frequencies and by the roll-off (f_{RH}) and the cut-off (f_{CH}) frequencies at high frequencies. It is $f_{RL} < f_{CL} < f_{CH} < f_{RH}$. The frequency components included in the interval $[f_{CL}, f_{CH}]$ are entirely considered. Data between each roll-off frequency and the corresponding cut-off frequency, called roll-off intervals, are tapered by using an half cosine function. Fig. 1 shows the filtering window. Selection of roll-off and cut-off frequencies is made on the basis of SNR. Two different algorithms are used. The first one, starting from the minimum frequency (equal to inverse of time history duration), assumes as f_{RL1} (f_{RL} computed by using algorithm 1) the minimum value of frequency for which SNR $\geq$ 10 dB. Analogously, the minimum value of frequency for which SNR $\geq$ 20 dB is assumed as f_{CL1}. Both f_{RL1} and f_{CL1} must be less than 2.0 Hz. The second algorithm, starting from the value of frequency 2.0 Hz and going backwards, searches for the first frequency interval of 10 points width, for which

$$\int_{f_a}^{f_b} SNR \cdot df \leq (f_b - f_a) \cdot 10dB$$

It assumes $f_{RL2}=f_a$ and $f_{CL2}=f_b$ Finally, roll-off and cut-off frequencies are selected as follows:

$$f_{RL} = \max(f_{RL1}, f_{RL2}) \qquad\qquad f_{CL} = \max(f_{CL1}, f_{CL2})$$

In such way the selected roll-off interval at low frequencies will certainly avoid most of the noise components. The pass-band filter is then multiplied by the theoretical inverse transfer function of the recording sensor. FAS of corrected acceleration is obtained by multiplying FAS of uncorrected data by the filter. Filtered velocity and displacement spectra are calculated from the acceleration spectrum. The inverse FFT of corrected spectra produce the corrected acceleration, velocity and displacement time histories.

Analysis of records, selected from European data bank, was carried out by plotting the roll-off filtering frequencies for the three acceleration components versus the peak ground acceleration (PGA) and the epicentral distance. Linear regression for events of the same magnitude was also done. As already shown for Italian strong motion records (Rinaldis and al. 1994) the roll-off frequency values are very dispersed. Anyway the following properties can be stated: f_{RL} increases with the epicentral distance and decreases when Peak Ground Acceleration or magnitude get higher.

In the case of digital records, there is no reference trace. So the noise should be better evaluated in absence of earthquake motion. On the base of the knowledge of earthquake characteristics, the values of f_{RL}, f_{CL}, f_{CH} and f_{RH} can be chosen by using a probabilistic approach (Rinaldis at al. 1996).

BRUNE MODEL AND CORNER FREQUENCY

According to Brune model the displacement is simultaneous along the whole fault. As a result the far field Fourier Amplitude Spectrum of displacements can be approximated by two straight lines, joined at the so called corner frequency f_c (Fig. 2). A rough estimation of f_c can be obtained by the relation-ship (Boore 1983)

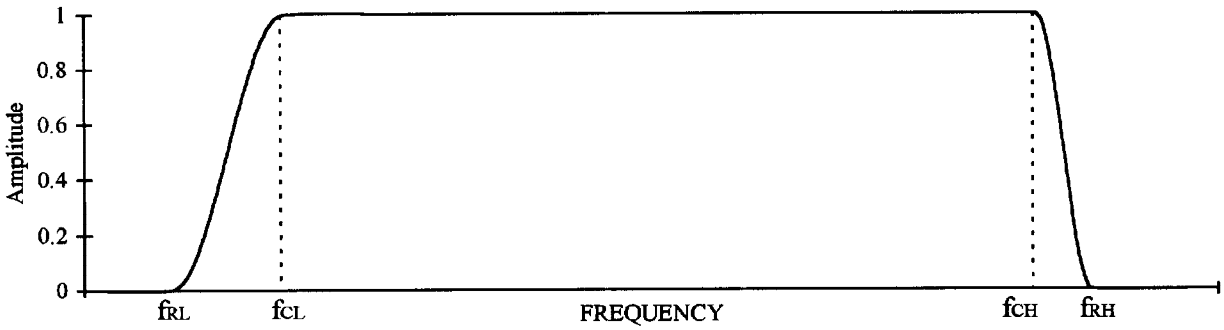

Fig. 1 Filtering window in the standard methodology

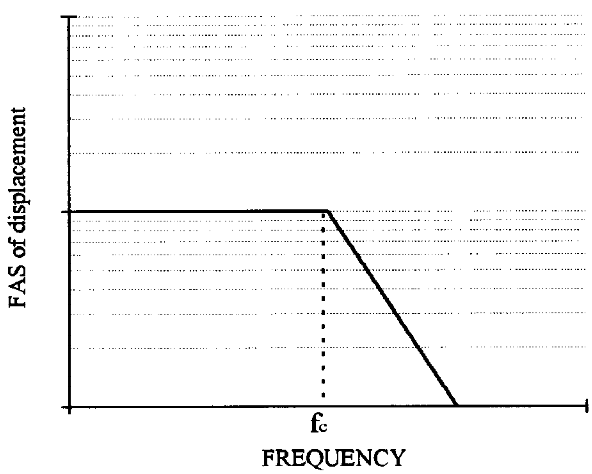

Fig. 2 FAS of displacement in Brune model

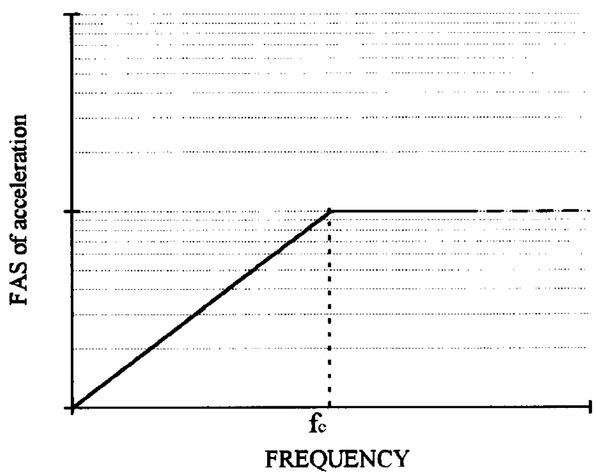

Fig. 3 FAS of acceleration in Brune model

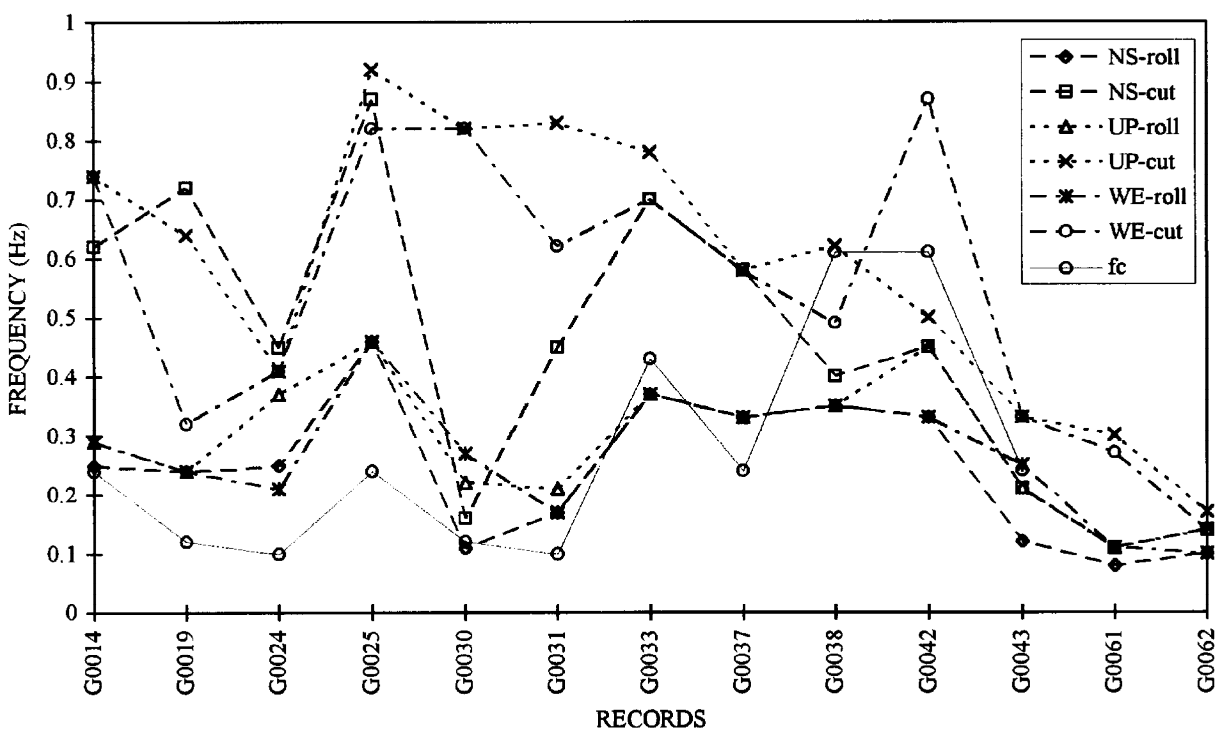

Fig. 4 Seismic events from European data bank - Roll-off and cut-off frequencies

$$f_c = 4.9 \cdot 10^6 \cdot \beta \cdot \sqrt[3]{\Delta\sigma / M_0}$$

where β is the wave velocity (Km/s), $\Delta\sigma$ is the static stress drop (bar) and M_0 is the moment magnitude, related to magnitude M_s through the relation-ship

$$log\, M_0 = 3/2 \cdot (M_s + 10.7)$$

The corresponding Fourier Amplitude Spectrum of acceleration is plotted in Fig. 3, f_c being the corner frequency. The theoretical horizontal line is usually substituted, for high values of f, by a f^{-1} decreasing law. The meaning of f_c is clear. The frequency content for $f < f_c$ may be lost in accelerometric recording, especially in far field. Frequency content for $f > f_c$ give negligible contribution in terms of displacement.

LOW FREQUENCY ANALYSIS BY USING THE STANDARD METHODOLOGY

The standard methodology is certainly good enough to preserve the main frequency content of the record. On the other hand, the frequency interval, in which the earthquake energy is strongest, contains the first natural frequencies of normal structures.

Goodness of standard methodology also depends on the method used to determine the noise. If noise is deduced from time-mark, its FAS may show strange trends, such as values higher than those of the corresponding FAS of uncorrected acceleration components, or a valley which is not in the FAS of the uncorrected acceleration. In fact, noise deduced from time-mark processing may be very different from the noise present in the acceleration record, because of the distance between the two traces on the photographic film. This behaviour was already pointed out (Rinaldis et al. 1994) in records of Italian seismic events and has also been found in other records from European data bank. These occurrences may influence the selection of roll-off interval. When fixed trace is available, standard data processing is more reliable.

Anyway, if the frequency interval, which has been selected by using the standard methodology, contains the interval of interest, no signal component of interest have been lost. In this case the usual method could be too conservative. If the interval of interest is not included in the selected one, a more accurate analysis is necessary.

Fig. 4 shows the selected roll-off and cut-off frequencies obtained by applying the standard methodology for records from the Greek data bank. The values of f_c obtained by assuming $\beta = 3$ Km/s and $\Delta\sigma = 100$ bars are also shown.

NEW METHODOLOGY FOR LOW FREQUENCY ANALYSIS

In order to analyze the effectiveness of the standard methodology to select the roll-off interval, pass-band filtering of all the selected time-histories in the frequency interval [0.2, 0.5] Hz can be undertaken. So "non stationary" trends associated to a seismic event can be checked for. Moreover, the filtered ground acceleration, velocity and displacement time-histories can be compared with those of the reference trace, its integral and double integral respectively, filtered in the same frequency interval. If the time history shows PGA, PGV and PGD higher than a fixed value (the minimum reliable value of PGA, 2 or 3 gals, is obtained taking into account the limits of the A/D conversion equipment and the accelerograph characteristics: 1 g full scale and 2 cm/g sensibility - Rinaldis 1988), the detected signal is probably associated to a seismic event.

It is important to distinguish the following cases:

A) the filtered time-history shows a digitizing duration of the same order of the strong phase duration;
B) the filtered time-history shows a low frequency feature, which duration is much lower than the digitized duration.

In fact, the low frequency energy content due to the signal may be lost if it is present only in a short interval

of the time history. In case A, the standard methodology will certainly work and the low frequency content will be recovered. In case B more information are necessary to establish the presence of a seismic event in the signal.
In particular, in case B, the selected band-pass frequency interval may or not contain the interval of interest ([0.2, 0.5] Hz). In the first case the standard methodology works correctly for our purposes, the signal being totally preserved. Vice versa, if the interval of interest is external to the selected one, a more detailed analysis has to be carried out. In this case the corner frequency may be useful. In fact, its position with respect to the roll-off interval at low frequencies is a measure of the reliability of the standard methodology to preserve the frequency content of the recorded event.

If $f_c \geq f_{CL}$, the low frequency content has been individualized by using the standard methodology.

If $f_c \leq f_{RL}$, part of the low frequency content could be lost. If FAS of acceleration is comparable to FAS of noise, the missed frequency content is not recoverable from the signal. This may occurs in far field records because of the attenuation with the distance from the epicentre. If the level of the noise is much smaller than the level of the signal, the roll-off interval should be re-evaluated in order to recover the missed frequency content. In this case the choice of the new roll-off interval can be carried out in the same way of the following case.

If $f_{RL} < f_c < f_{CL}$ then the selected roll-off interval has to be revised. When the noise figure is deduced from the fixed trace, we assume $f_{CL} = f_c$. In this way no signal component will be lost. If noise is determined by using time-mark, which is less reliable than the fixed trace, we assume $f_{RL} = f_{CL} - 2\,(f_{CL} - f_c)$. As a result the selected interval is certainly conservative.

LOW FREQUENCY CONTENT IN EUROPEAN STRONG MOTION RECORDS

The proposed methodology allowed to analyze the low frequency content of records from European data bank. In this paper the analysis carried out on recent seismic events in Greece will be shown. The main characteristics of selected records are summarized in Tab. 1

Table 1 - Selected events from European data bank

Event	Station	Record Number	Magnitude	Epic. Distance (Km)
Jan. 17th, 1983	Lefkada	G0024	7.0	105
Jan . 17th, 1983	Argostoli	G0031	7.0	33
March 23rd, 1986	Zakynthos	G0014	6.2	68
Sept. 13th, 1986	Kalamata	G0043	6.2	1

In Fig. 5b the time histories of the WE acceleration, velocity and displacement components recorded at Lefkada, filtered in the frequency interval [0.2, 0.5] Hz, are plotted. The comparison between the acceleration component and the corresponding fixed trace (Fig. 5a) allows to detect the presence of a seismic event distributed over the whole time length. In this case, the standard methodology is good in selecting the roll-off interval. The interval of interest is in part included in the filtering window. It is $f_c < f_{RL}$ (Fig. 5d). It is also $f_c < 0.2$ Hz and therefore out of the interval of interest. For low frequency, FAS of acceleration is lower than FAS of noise.

Filtered time histories of acceleration, velocity and displacement of WE component recorded at Argostoli are shown in Fig. 6b. The time domain analysis shows that the signal is present only in a portion of the digitizing interval. The values of roll-off and cut-off frequencies selected by using the standard methodology are influenced by a valley in the FAS of noise. It is $f_c < f_{RL}$ (Fig. 6d). The low frequency content is not recoverable, FAS of noise having the same amplitude of FAS of acceleration component (Fig. 6c).

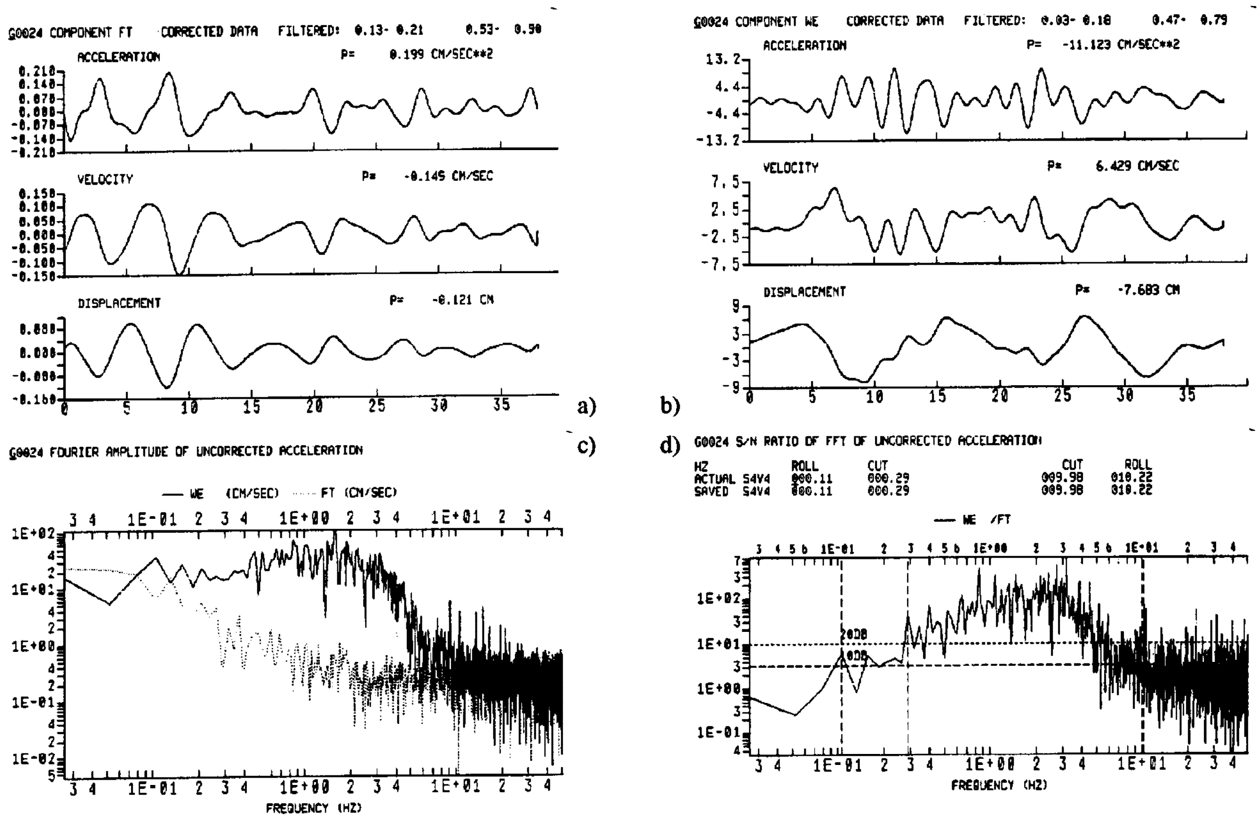

Fig. 5 Jan. 17th 1983 earthquake, recorded at Lefkada. FT and WE component. Corrected acceleration, velocity and displacement time histories (a, b). FAS and SNR of uncorrected acceleration (c,d).

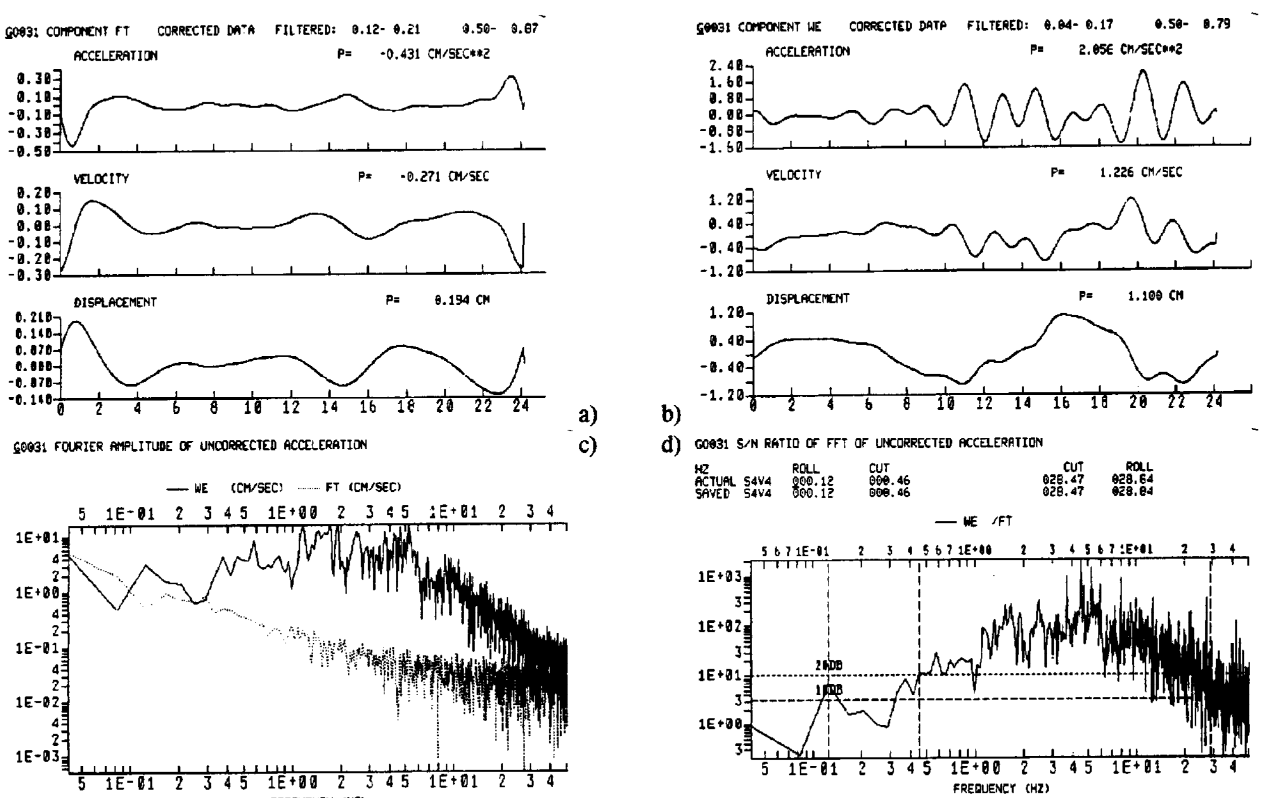

Fig. 6 Jan. 17th 1983 earthquake, recorded at Argostoli. FT and WE component. Corrected acceleration, velocity and displacement time histories (a, b). FAS and SNR of uncorrected acceleration (c,d).

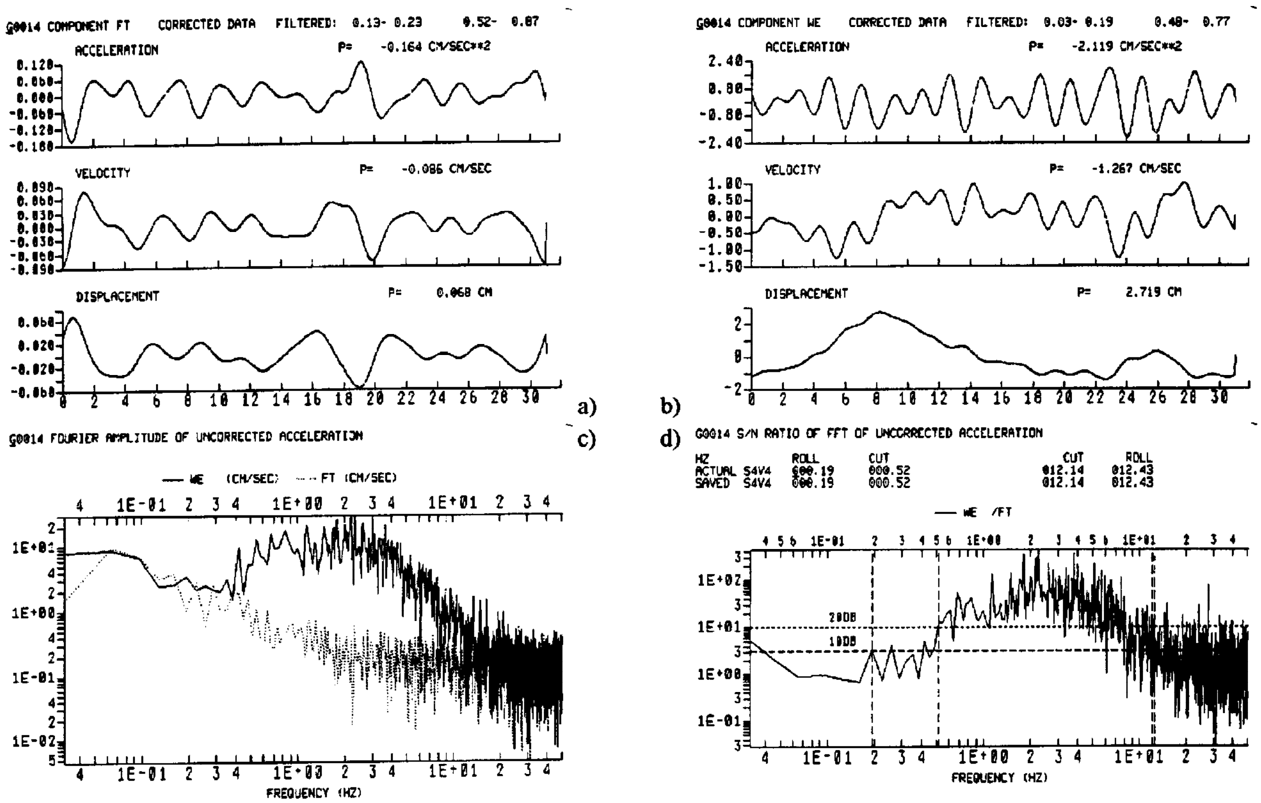

Fig. 7 March. 23th 1986 earthquake, recorded at Zakynthos. FT and WE component. Corrected acceleration, velocity and displacement time histories (a, b). FAS and SNR of uncorrected acceleration (c,d).

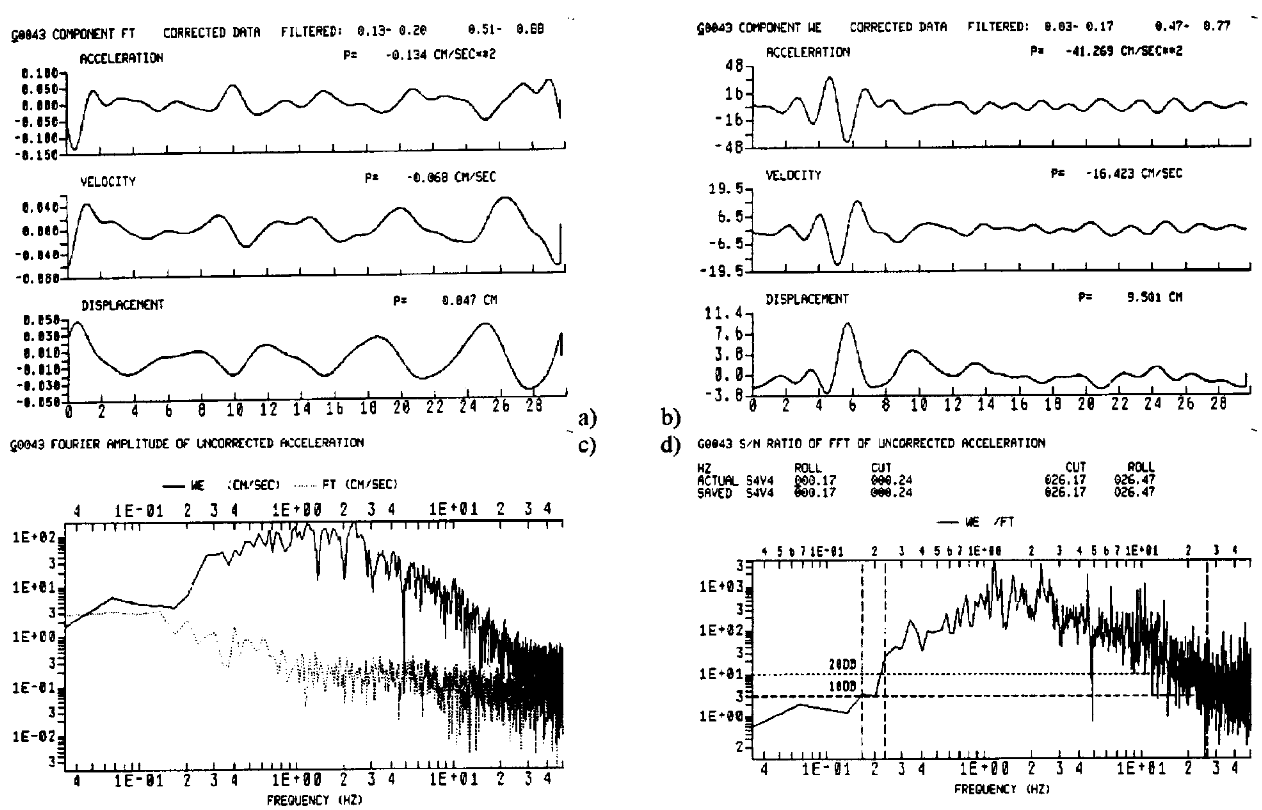

Fig. 8 Sept. 13th 1986 earthquake, recorded at Kalamata. FT and WE component. Corrected acceleration, velocity and displacement time histories (a, b). FAS and SNR of uncorrected acceleration (c,d).

Filtered WE acceleration, velocity and displacement relative to the event recorded at Zakynthos are plotted in Fig. 7b. The low frequency signal is apparent over the whole time history. It is $f_{RL} < f_c < f_{CL}$ (Fig. 7d), f_{RL} being quite low, because of the presence of a valley in the FAS of noise. Because of that, the standard methodology fail to select a reliable f_{RL}, that should be greater than f_c. FAS of noise being comparable to FAS of acceleration, the low frequency content is not recoverable.

The last event, shown in Fig. 8, was recorded at Kalamata. The significant low frequency component is apparent only in a small portion of the time history (Fig. 8b). PGA is much higher than peak of the noise. The interval of interest is included in the selected band (Fig. 8d). It is $f_c > f_{CL}$. Therefore all the low frequency content is recovered by using the standard methodology.

CONCLUSIONS

The proposed methodology, based on the corner frequency calculation, seems to be very good in preserving the low frequency content of strong motion records. The recovering of low frequency content is often not possible for the following reasons:

- FAS of acceleration may be comparable to FAS of noise;
- noise figure is not reliable because it is deduced from time-mark.

Anyway particular care should be taken in seismic input analysis, when designing base isolated structures. In fact, large displacements may occur, that cannot be supported by rubber bearings. In particular the analysis of European strong motion data pointed out records with high PGD. Taking into account the limited period of ground monitoring this result is warning for engineers dealing with design of base isolated structures. It is worth to remind (Rinaldis et al. 1994) that a displacement of 25 cm was recorded at Sturno station during Campano-Lucano earthquake in Italy.

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