Influence of processing on the short-period spectral ordinates prediction

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SUMMARY:
This study aims at investigating the influence of the application of low pass acausal Butterworth filters on the derived GMPEs at short periods. To this end, the original time-histories of the Cauzzi and Faccioli (2008), CF08, database, with no correction at high frequency, are used. Four sets of GMPEs are derived after the application of a low-pass Butterworth filter of (a) order, *N*, 2 and a corner frequency, f_c, of 15 Hz, (b) of *N*=4 and f_c =15 Hz, (c) *N*=4 and f_c =20 Hz and (d) *N*=4 and f_c =30 Hz. Results showed decreases up to a 30% in the spectral acceleration ordinates w.r.t. the original values at 0.05 s, that do not appear fully reliable. Hence, when the processing is unnecessary, as for instance for most of digital recordings, the use of the filters may alter the derived GMPEs in an unrealistic way, and should be avoided.

Keywords: High-cut filter, short-period predictions, ground motion prediction equations

1. INTRODUCTION

The ground-motion prediction plays a crucial role in several applications of engineering seismology and earthquake engineering, such as seismic hazard analyses and earthquake loss estimation. Generally, this is performed using empirical ground-motion models (GMPEs) that describe the distribution of expected ground motion measures as a function of a few independent parameters, such as magnitude, source-to-site distance and site classification. The starting point to generate such relationships is the assemblage of a database of a sufficient number of records that can be then regressed in order to predict the ground motion parameters of interest. Since analogue and digital records may be affected by noise both at high and at low frequencies, and, consequently, the parameters can be erroneously estimated, a well-processed ground-motion data set, including reliable information on its usable period range, is an a pre-requisite for developing reliable GMPEs.
Filtering is the most popular processing procedure for removing the short- and long-period noise from the raw ground-motion data to obtain reliable waveforms. Ideally, the application of a filter should remove the noise-contaminated part of the frequency content from the record and should not alter the important features of the ground motion for a pre-determined frequency band. Although the filtering techniques are well defined, the choice of main filter parameters can strongly affect the computed velocity, displacements and response spectral ordinates. Several types of filters exist: Ormsby, elliptic, Butterworth and Chebyshev filters. However, the more significant difference is about the use of causal and acausal filters. Generally, a causal filter will produce no precursory motion when applied to a time series, but will distort the phase of the signals, affecting the spectral values. On the other hand, the phase shifts for the acausal filters are zero, but the zero padding is required. Acausal filters and hence padding and tapering, are currently preferred to causal ones (Boore, 2005; Boore and Akkar, 2003), especially for digital data with pre-event windows.
The aim of this study is to evaluate the influence of some processing schemes on the GMPEs at short periods, in particular when a fully digital database is adopted. In fact, as commented by Boore et al. (2009) and Cauzzi and Faccioli (2008), when digital data are used, the standard deviation ("sigma") associated to the mean GMPE predictions at short periods is larger than usually expected. This is obviously crucial, because the value of standard deviation plays a fundamental role in seismic hazard

analysis and consequently also in the earthquake loss estimations. To this end, the database of Cauzzi and Faccioli (2008), consisting at 99.9% of digital records, is herein used.

2. PROCESSING OF SHORT PERIOD ORDINATES

2.1. The database of Cauzzi and Faccioli (2008)

The database adopted in this study is that assembled by Cauzzi and Faccioli (2008), (hereinafter referred to as CF08). The objective of CF08 was to obtain reliable empirical prediction equations of simple analytical form for the displacement response spectra over a broad range of periods (0-20s), for moment magnitude in the $5.0 \leq M_W \leq 7.2$ range and hypocentral distances shorter than 150 km. Due to this need, the database was assembled by including almost exclusively digital records, most of which from the Japanese network, K-net (84 %), because of the high quality of the available accelerograms and the detailed information provided for each recording site. The only exception was for the few accelerograms of the 1980 Irpinia (Italy) M_W 6.9 earthquake, recorded by analog instruments and introduced in the database after a careful scrutiny of their long period characteristics. All the data were entered in the database in the form of uncorrected acceleration time histories. The correction procedure adopted by the authors followed the findings by Paolucci et al. (2008), who showed that the physically unrealistic trends of the velocity or displacement traces only slightly influence the accuracy of the computed long period spectral displacements. Moreover, according to their results, high-pass filtering the digital acceleration record to suppress baseline drifts on the displacement waveform appeared to be in most cases too conservative, losing reliable information on long-period spectral ordinates. Hence, the recordings of the CF08 database were originally corrected by removing unphysical trends in the baseline and, when necessary, by applying a high pass Butterworth filter with a corner frequency of 0.05 Hz (T=20 s). The CF08 time histories, TH, have not been corrected in the high frequency range.

2.2 Processing of data adopted in this study

In this study, the high frequency (short period) ordinates are of interest, and the correction procedure adopted was the application of high-cut frequency filters. Low-pass acausal Butterworth filters are applied. Moreover, the input data were processed in both the forward and reverse directions in order to obtain a zero-phase digital filtering. The response of the filter for f < f_c is as flat as mathematically possible, while the slope of the amplitude response outside the band is defined by the order of the filter (N). The actual decay of the filter starts at a frequency lower than f_c: the actual value is of about 0.45 fc when a low corner frequency (e.g. 15 Hz) is used together with low N (e.g. 2), and increases to values around 0.7-0.8 fc when a higher order (e.g. 4) and a larger f_c is adopted. Tests were made to evaluate the appropriate order N and corner frequency f_c of the adopted filter.
Preliminary investigations comparing the short-period spectral accelerations obtained through the pseudo spectral relation and through the Newmark's numerical integration method showed negligible differences (herein the average acceleration method, unconditionally stable, for which γ=1/2 and β=1/4, was adopted). Thus, since the Newmark's method is much more time-consuming, the pseudo-spectral acceleration (PSA) ordinates were computed. Moreover, the requirement of tapering in order to smooth the transition between pads and record, e.g. with a half cosine function, was also tested and no differences are found between the response spectra derived with and without the taper.
Finally, the recent work by Douglas and Boore (2011) was adopted in order to have a preliminary evaluation of the high frequency noise included in the time histories (TH) of the CF08 database. The authors, based on results obtained with real and simulated data, suggest that a useful parameter for the determination of the probable error at high frequency (HF) PSAs is the ratio of the Fourier Amplitude Spectrum (FAS) near the peak portion of the Fourier spectrum and that near the noise floor. According to their study, "if the ratio is greater than ten, the error in PSA will be less than about 15% even without filtering". Thus, such ratios have been computed for the THs of the CF08 database and the results are shown in **Figure 1**. Note that the logarithm (base 10) of the ratio is plotted, for graphical purposes. The symbols represent the value of the logarithm of the ratio for the EW (black circles) and NS (grey triangles) components, while the dashed line represents the limit suggested by Douglas and

Boore (2011). All the values are greater than 1, which leads to assume that the THs contain a low level of noise and no filtering is necessary to obtain correct PSA ordinates. Hence, herein, we assume as the "true" spectral ordinates, those derived directly from the CF08 database, hereafter named "original".

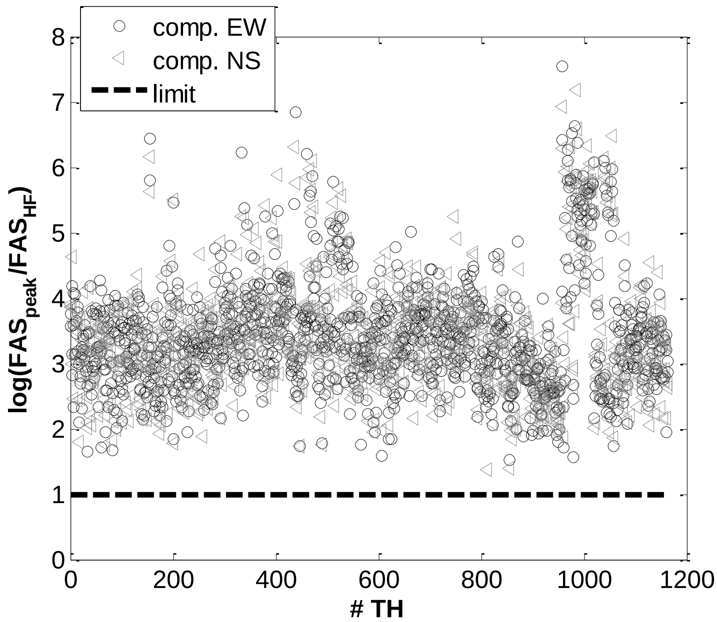

Figure 1. Ratios (in log10) of the Fourier Amplitude Spectrum (FAS) near the peak portion of the spectrum and that near the noise floor (HF), for the 1164 acceleration time-histories (TH) of the CF08 database. The limit suggested by Douglas and Boore (2011) of 10 (1 in log) is also displayed.

Different kinds of filters and adjustments were selected and applied uniformly to the CF08 THs. In particular, after the "zero-padding" required by the application of acausal filters, the records of the database were:

(a) low-pass filtered with a Butterworth filter of order 2 with a corner frequency fc=15 Hz.
(b) Ditto with N=4 and f_c=15 Hz.
(c) Ditto with N=4 and f_c=20 Hz.
(d) Ditto with N=4 and f_c=30 Hz.
(e) Ditto with N=4 and f_c=40 Hz.

The effect of the previous procedures on the PSA was analysed by comparing the PSA obtained with THs. For the sake of brevity, herein the comparisons are shown only for 3 recordings on soil type A of Eurocode 8 (CEN, 2003) with different magnitudes (#1066, #1041 and #1029), see Table 1.

Table 1. Recordings of the CF08 database used in the comparisons of spectral acceleration ordinates.

#	Date	Name of the event	Soil type	R_{hyp} (km)	M_W
1066	3 April 1998	Umbria Marche (aftershock)	A	12.5	5.1
1041	17 June 2000	South Iceland	A	15.8	6.5
1029	12 November 1999	Duzce	A	26.9	7.2

Figure 2 shows the effect of N when a corner frequency of 15 Hz (i.e. corner period T_c=0.067 s) is used. Note that a lower order (N=2) leads to lower spectral ordinates and also causes Moreover, with N=2, the effect of the filter begins much before f_c, and the spectral ordinates are affected up to $T \approx 0.15$ s, double than the chosen corner period. Based on this result, N=4 was adopted in the following analyses.

Figure 3 illustrates the effect of the selected corner frequency of the low-pass filter. Four corner frequencies have been selected: f_c=15 Hz (T=0.067 s), f_c =20 Hz (T=0.05 s), f_c =30 Hz (T=0.033 s) and f_c =40 Hz (T=0.025 s). For T>0.1 s the effect of the filter is almost negligible in all the cases, while, as expected, the smaller the corner frequency, the larger the influence of the filter at short periods. In particular, no relevant differences are found between the spectra obtained by filtering with f_c =40 Hz and those original, and therefore, procedure (e) was not used in the following analyses. The effect of f_c is more significant at 0.05 s, leading to variation up to about 25%.

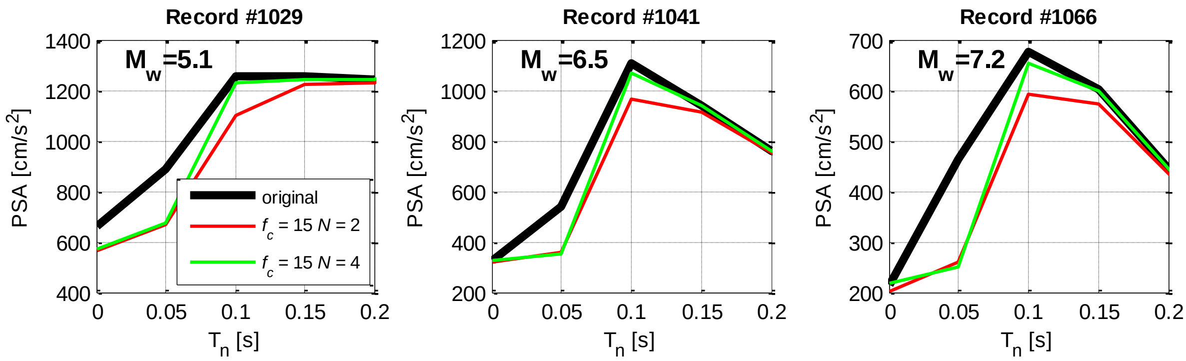

Figure 2. Effect of the order of the Butterworth filter on the spectral acceleration ordinates of 3 selected recordings of events with different magnitudes (M_W=5.1, 6.5 and 7.2) of the CF08 database.

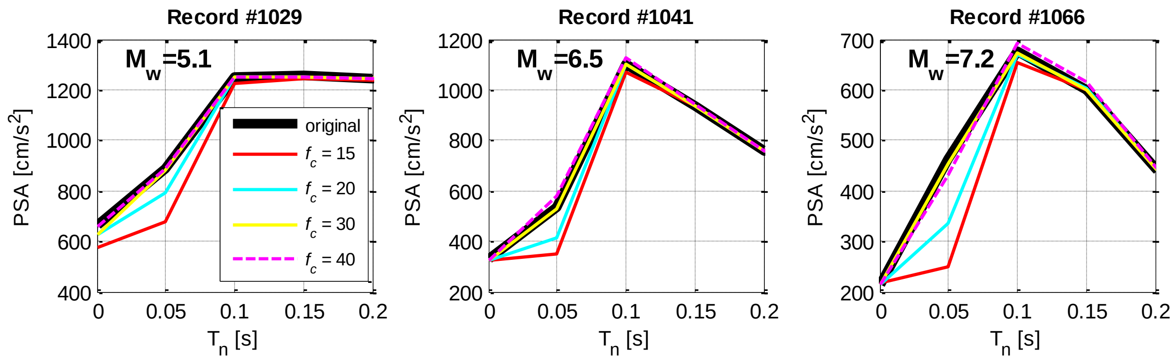

Figure 3. Effect of the corner frequency of the Butterworth filter on the spectral acceleration ordinates of 3 selected recordings of events with different magnitudes (M_W=5.1, 6.5 and 7.2) of the CF08 database.

3. REGRESSION AND RESULTS

Consistently with CF08, the coefficients of the GMPEs have been computed in this study through the two-stage maximum-likelihood method of Joyner and Boore (1993, 1994), where the distance dependence and the site coefficients were determined within the first stage of the regression, and the magnitude dependence and the constant term in the second step. The adopted functional form is the same as the original CF08, i.e.:

$$\log DRS(T,\varsigma) = a_1 + a_2 M_w + a_3 \log R + a_B S_B + a_C S_C + a_D S_D \quad (1)$$

Four sets of response spectra obtained from the same dataset after the application of procedure (a)-to-(d) of Sect. 2, are used for deriving the coefficients of the attenuation equations.

Figure 4 compares the results in terms of the coefficients a_i of eq. (1). Note that for T> 0.1-0.2 s the coefficients are the same, while differences can be found at shorter periods, in particular for the coefficients of the site terms when a filter with a f_c< 30 Hz is used. The influence of the filters is more evident in terms of total standard error, displayed in **Figure 5**. As a matter of fact, the standard errors of the predictions obtained from the filtered response spectra are different for periods lower than 0.1-0.2 s, in particular, the error decreases with decreasing corner frequency of the filter as one would expect. However, σ is slightly different from the original total standard error of CF08 over the whole range of periods: a slight decrease of the sigma is apparent between 0.3 and 1 s and for T>1.5 s.

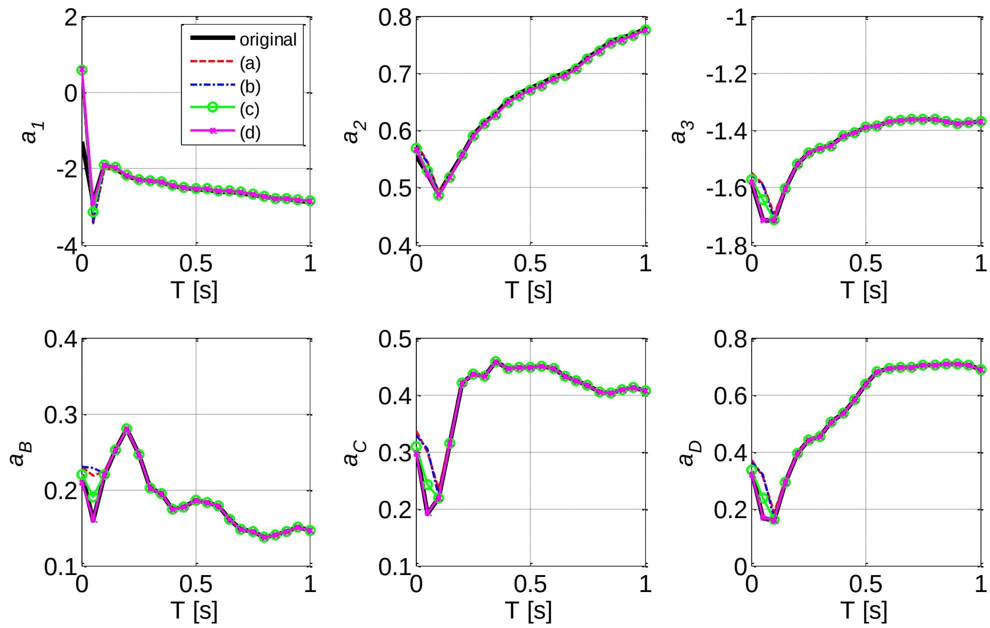

Figure 4. Coefficients of eq. (1), obtained with the regression technique of Joyner and Boore (1993 and 1994, two-stage method) applied to the response spectra obtained after the application of a low-pass Butterworth filter of (a) order 2 with a corner frequency of 15 Hz, (b) order 4 with a corner frequency of 15 Hz, (c) order 4 with a corner frequency of 20 Hz and finally (d) order 4 with a corner frequency of 30 Hz.

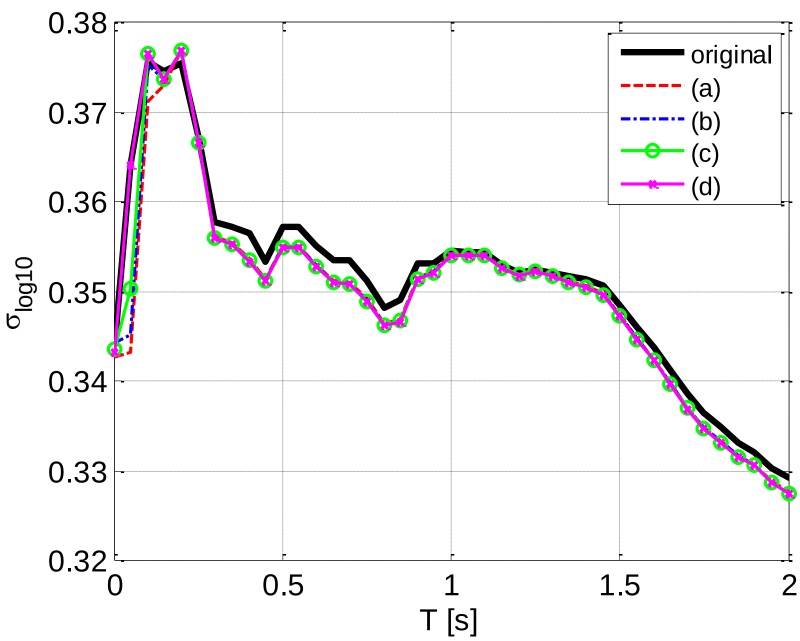

Figure 5. Total standard error of the predictions, σ_{log10}, as a function of the vibration period T . The four curves in color represent the standard errors related to the predictions obtained after the application of the low-pass Butterworth filters ((a) N=2 and f_c= 15 Hz, (b) N=4 and f_c= 15 Hz, (c) N=4 and f_c= 20 Hz and finally (d) N=4 and f_c=30 Hz) while the thick black curve is the original standard error of the Cauzzi and Faccioli (2008) predictions.

Figure 6 illustrates the results in terms of median acceleration response spectra and band of deviations for different magnitudes and hypocentral distances for rock sites. The shape of the spectra slightly varies giving rise to broad spectra for increasing magnitudes and distances. Note that the influence of the filters is more evident for the 84-percentile levels due to the total standard errors variations.

However, modifications of the spectrum are also present at the 50- and, to a lesser extent, also at the 16-percentile levels.

The same comments apply when different soil conditions are considered (**Figure 7**). Note that, in particular at the 84-percentile level, the influence of the filters in the predictions is evident at short periods. In particular, the peaks are reduced and smoothed. The values of the maximum ground acceleration on soil sites vary by about 10-19% for soil type B, about 7-15% for soil type C and about 8-13% for soil type D. For periods longer than 0.1 s the changes due to the filters are negligible.

SOIL TYPE A:

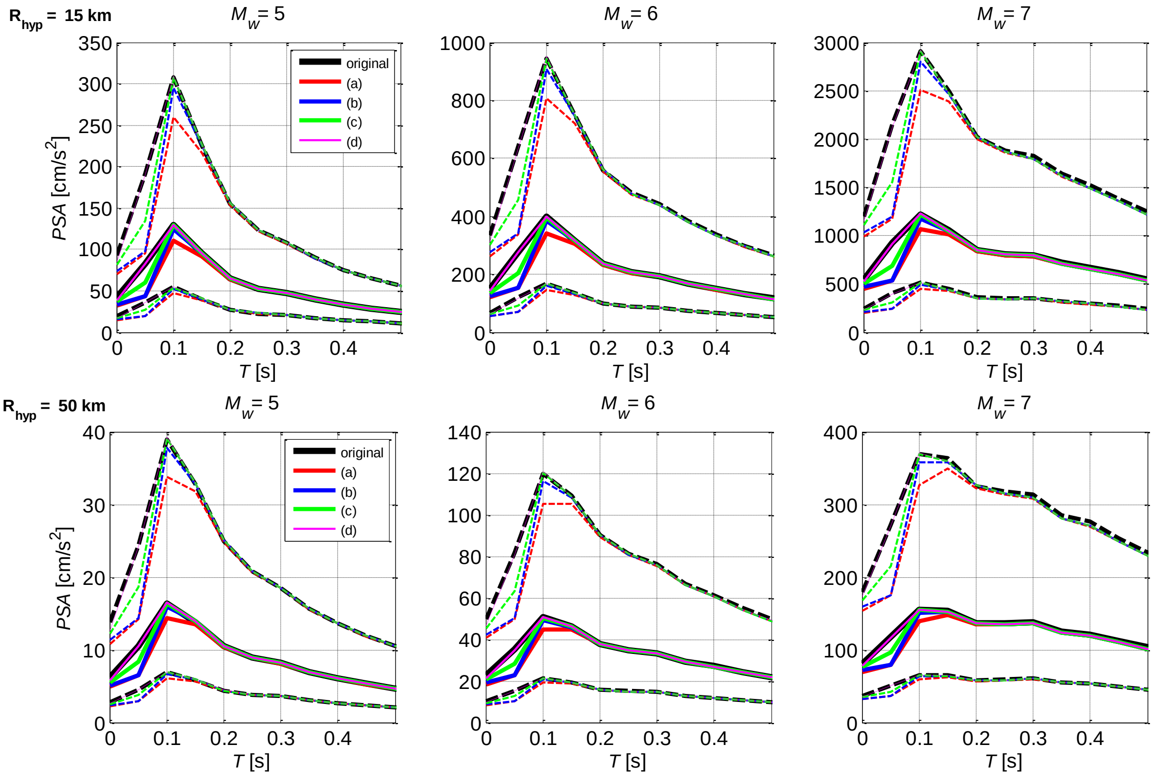

Figure 6. Acceleration response spectra derived from the 4 attenuation equations computed from the database corrected with different low-pass Butterworth filters ((a) N=2 and f_c= 15 Hz, (b) N=4 and f_c= 15 Hz, (c) N=4 and f_c= 20 Hz and finally (d) N=4 and f_c=30 Hz) at different magnitudes and at 15 km of hypocentral distance (top panels) and at 50 km (bottom panels) on rock sites. The dashed curves are the 16- and 84-percentile of the estimates.

3.1 Implications on seismic hazard analysis

In this section, a test is performed to evaluate the consequences of using the GMPEs developed in this study in a probabilistic seismic hazard analysis (PSHA). The scenario is described in the left panel of **Figure 8**. The uniform hazard (UH) PSA were computed with CRISIS2007 (Ordaz *et al.*, 1991) for two sites, for return periods, *RP*, of 475 and 975 yr. **Figure 8**, right panel, shows the computed UH spectra up to 0.2 s, since for longer period no discrepancies are found. The differences at short periods (T<0.2 s) are similar to those found in the deterministic response spectra: the smaller the corner frequency ($f_{c(a)}= f_{c(b)}< f_{c(c)}< f_{c(d)}$) used for filtering, the smaller the spectral ordinates. Also the order of the filter affects the results and in particular the peak of the spectra derived with a GMPE filtered with order 2, (a), is reduced by about 15% compared with that found with the GMPEs filtered with a Butterworth of order 4, (b), with the same corner frequency ($f_{c(a)}= f_{c(b)}$=15 Hz).

The error made when the UH spectra are derived from a filtered database with respect to the original PSA, considered "correct" since a very low level of noise has been found in the THs, has been computed as:

$$error(T) = \frac{PSA(T)_{orig} - PSA(T)_{filter}}{PSA(T)_{orig}} \times 100 \qquad (2).$$

The results, illustrated in **Figure 9**, highlight the significant effect of the filter at short periods. The results show that the application of filters can lead to errors in the estimations of the short-period ordinates, which play an important role in the seismic hazard estimations leading to underestimate the actual value up to 50% at *T*=0.05s when a fc=15 Hz and of about 30% when f_c=20 Hz. Even neglecting the strong influence of the filters at 0.05, the error made in the estimation of the ordinate at *T*=0 s is still large (more than 20% for filters with corner frequency of 15 Hz and of about 10% with f_c=20 Hz). Moreover also the peak ordinate at about 0.1 s is affected by the filter. The due observation is that a uniform filtering procedure applied over all the THs of a database should be avoided in order to obtain reliable estimates of the spectral ordinates at short periods.

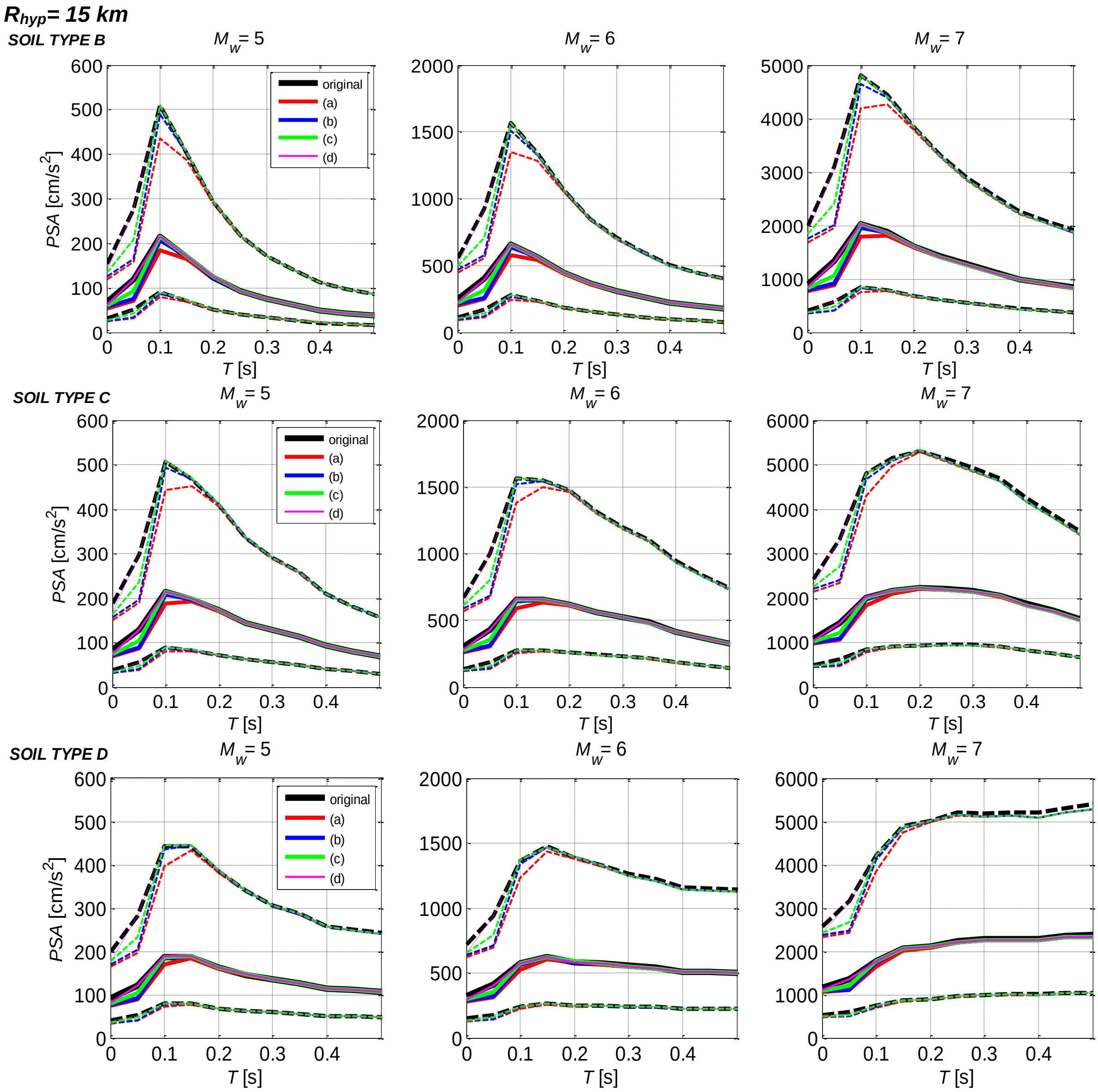

Figure 7. Acceleration response spectra derived from the 4 attenuation equations computed from the database corrected with different low-pass Butterworth filters ((a) *N*=2 and f_c= 15 Hz, (b) *N*=4 and f_c= 15 Hz, (c) *N*=4 and f_c= 20 Hz and finally (d) *N*=4 and f_c=30 Hz) at different magnitudes and at R_{hyp}=15 km for soil type B (top panel), soil type C (central panel) and soil type D (bottom panel). The dashed curves are the 16- and 84-percentile of the estimates.

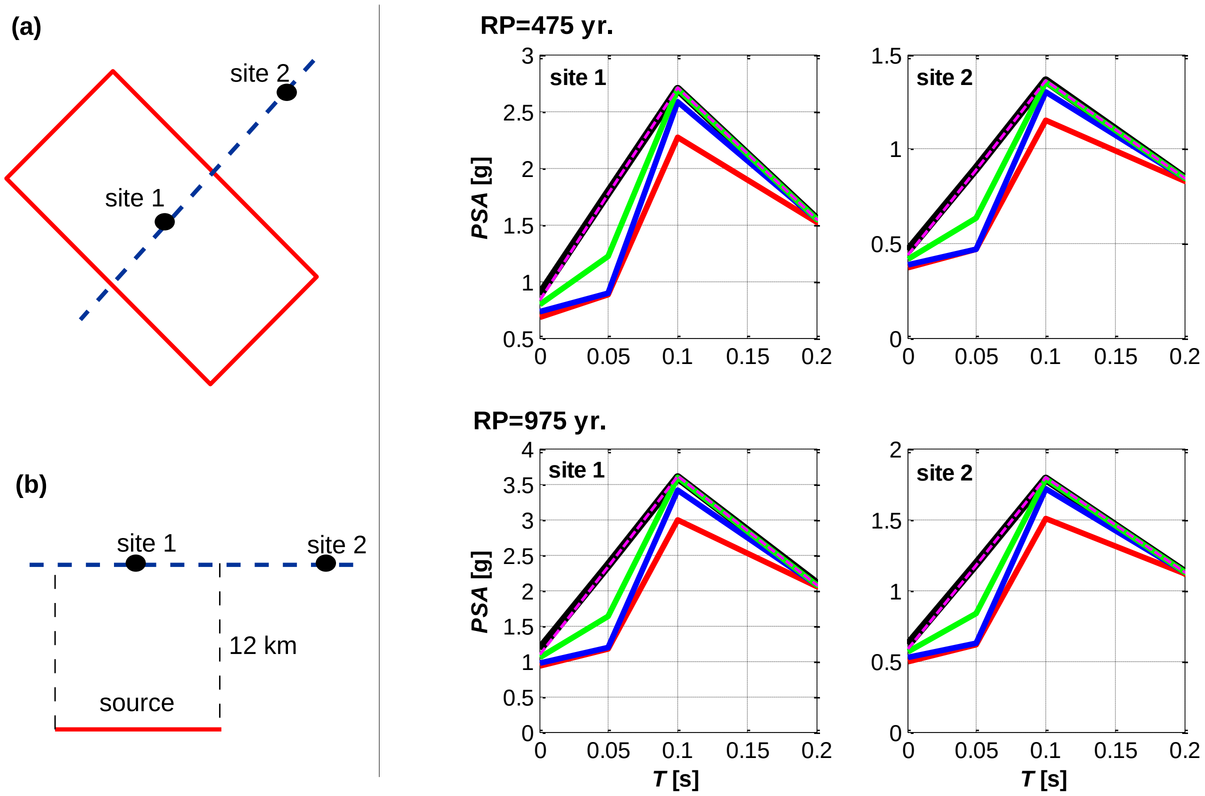

Figure 8. Left panel: Geometrical representation of the scenario used in the probabilistic analysis: (a) surface projection of the source and location of the two sites, (b) vertical cross-section. Right panel: Comparison of the uniform hazard (UH) acceleration response spectra computed at the 2 sites displayed in the left panel for return periods, RP, of 475 yr. (top panel) and 975 yr. (bottom panel) and a damping ratio of 5%. The spectra derived with the attenuation equation of CF08 (black thick curves) are compared with those derived with the GMPEs produced in this study by correcting the CF08 database records with different low-pass Butterworth filters: (a) N=2 and fc= 15 Hz, (b) N=4 and fc= 15 Hz, (c) N=4 and fc= 20 Hz and finally (d) N=4 and fc=30 Hz.

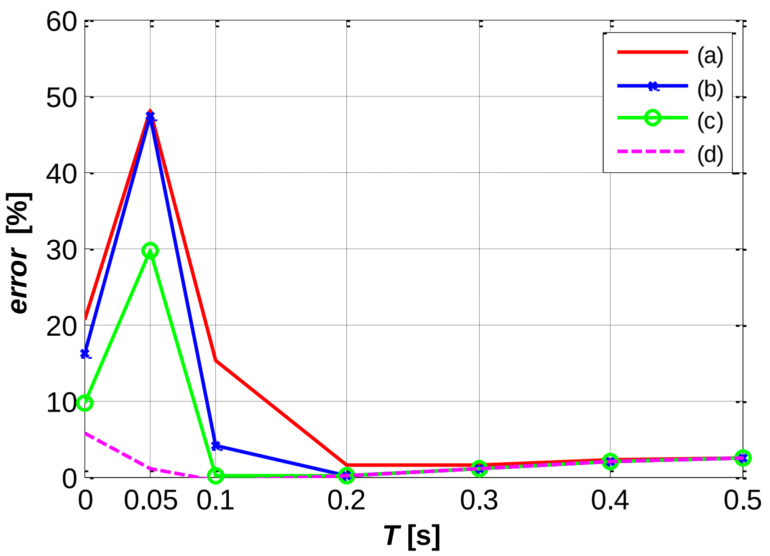

Figure 9. Comparison of the errors computed with eq. (1) made when the filters are applied to the original database of CF08.

4. CONCLUSIONS

This study aimed at evaluating the effect of a uniform correction procedure of acceleration waveforms on the spectral ordinates prediction at short periods. The original time histories of the Cauzzi and Faccioli (2008), CF08, database, with no correction at high frequency, are used to this purpose. Following the recent findings of Douglas and Boore (2011) the level of noise was approximately evaluated by computing the ratios between the FAS near the peak portion and that at high frequency. Since the ratios obtained with the CF08 database were found to be always greater than 10, according to Douglas and Boore (2011) no correction was considered necessary to compute correct PSAs. According to this criterion, in this study we considered "true" PSAs those obtained with the original THs of CF08 database.
Four set of GMPEs were derived after the uniform application of (a) a low-pass Butterworth filter of order, N, 2 and a corner frequency, f_c, of 15 Hz, (b) a low-pass Butterworth filter of N=4 and a f_c =15 Hz, (c) a low-pass Butterworth filter of N=4 and f_c =20 Hz and (d) a low-pass Butterworth filter of N=4 and f_c =30 Hz. Both in the acceleration response spectra derived from the regressions and in the uniform hazard spectra computed in a simple seismic hazard analysis with those GMPEs, the filters were found to affect the derived GMPEs leading to significant influence: the peaks of the spectra vary up to a 30% when a filter corner frequency of 20 Hz is used. An important role is played by standard error of the predictions, which, when filtering is applied, is slightly different from the original total standard error of CF08 even for periods much longer than those directly influenced by the filters. The decrease in the spectral ordinates obtained as the result of filtering does not appear realistic. Hence, when the processing is unnecessary, as for instance for most of modern digital accelerometers, the use of the filters should be carefully evaluated by estimating the signal-to-noise ratio for each TH. As a matter of fact, a correction procedure uniformly applied to all the waveforms may alter the derived GMPEs in an unrealistic way and should be avoided. This is in particular the case of those databases containing analogue records to which, generally, a uniform filter at about 25 Hz is applied (see e.g Ambraseys et al., 2005).

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