LEMA_DES equivalent signals derived from the accelerometric records of the European database

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SUMMARY
The Leveled Energy Multifrequential Analysis for Deriving Equivalent Signals (LEMA_DES) was applied at the accelerometric records of the European database integrated with records from K-NET and COSMOS databases. More than 6500 equivalent signals were obtained, among which about 88% of middle to high reliability. The comparison among natural reference accelerograms and LEMA_DES derived ones demonstrate that the differences of Arias intensity values and PGAs are within one order of magnitude. The computed relative errors are generally in the range 10%-100%, without bias in its distribution. The equivalent cycles resulting for the LEMA_DES signal vs. epicentral distances show regularly increase from 2 up to 9 for magnitude varying in the range 5-7. These findings encourage the use of the LEMA_DES derived signals for laboratory testing and numerical modeling as well as for drawing up a catalogue based on the European accelerometric one.

Keywords: Dynamic equivalent signals, European accelerometric catalogue, reliability analysis

1. INTRODUCTION

An equivalent accelerometric signal can be regarded as an acceleration time history, inferred from a reference accelerometric record which can be defined in different ways on the basis of equivalence criteria and type of reference accelerometric signal.

As their definition suggests, equivalent signals are full-fledged analogue tools for modelling natural processes (real prototypes) as physical analogues (equivalent prototypes). In particular, the equivalent signals may be employed in technical-scientific applications (i.e. laboratory testing on soil samples, modelling at shaking table, dynamic modelling at centrifuge device) when common theoretical approaches or instrumental devices can hardly manage the whole complexity of the actual accelerometric signals. A first definition of equivalent accelerometric signal to be used in geotechnical applications was proposed by Seed and Idriss (1969; 1971). Subsequently, this concept was used as part of a methodology to study the potential liquefaction of sandy soils under seismic shaking (Ishihara 1977; Seed 1979a; 1979b; Seed et al., 1983). In particular, the Authors proposed the use of a monofrequential sinusoidal accelerogram, which was derived from a reference seismometric record by assuming: i) an equivalent amplitude (amax), equal to 65% of the peak ground acceleration (PGA) of the reference accelerogram; ii) a maximum expected shear stress (τ_{max}), depending on ground motion amplitude and soil depth; iii) a number of equivalent (or characteristic) cycles (n_c) of the monofrequential sinusoidal signal, which is an empirical function of the reference earthquake moment magnitude.

The same Authors suggest a correction factor (r_d) for scaling the expected ground motion as a function of depth, considering the seismic motion amplification at the surface; more recently, revisions for this scaling factor have been proposed by some Authors (Iwasaki,1986; Cetin and Seed, 2004), taking into account further correlations based on empirical data.

Alternative approaches consist in generating synthetic accelerometric signals (Boore 1983; Saragoni and Hart 1974; Gupta and Trifunac 1997; Boore 2000; Cascone and Rampello 2003), which are consistent with local seismic ground motion response spectra. Many of these approaches generally require a random phase spectrum function (Shinokuza 1970; Sabetta and Pugliese 1996) to be associated with the spectral amplitudes that characterise the artificial signal to be obtained; the spectral amplitudes are best fitted to the selected response spectrum. The signal resulting by combining the spectral amplitudes and the phase function is sized on the basis of the duration and the PGA of the reference earthquake. Even though, the so obtained synthetic signals can be regarded as comparable with real accelerometric time histories in terms of physical complexity (i.e. amplitude and phase spectra, duration, time-variable intensity of the signal), this last one represents their limit for many numerical modelling and laboratory experiments.

An alternative procedure for deriving levelled energy multifrequential dynamic signals (LEMA_DES), equivalent to reference accelerograms was recently implemented by Lenti & Martino (2010). The resulting multifrequential dynamic equivalent signal *E(t)* satisfies all the considered convergence criteria, i.e. spectral, kinematic (in terms of PGA) and energy.

At this aim, the LEMA_DES procedure consists in the generation of a sequence of functions and signals, which are summarised in the following processing steps:

step 1 - selection of the characteristic frequencies and deriving of the *harmonic functions* corresponding to monofrequential cyclical functions whose frequencies are equal to those selected from the smoothed Fourier spectrum of the reference accelerogram (FFT_{rif}), with a null phase and an amplitude proportional to the corresponding spectral densities of FFT_{rif};

step 2 - deriving of the *sum signal* $S(t)$ by algebraically summing the *adding functions* which result from the merge of a sinusoid and a null function. Each sinusoid has the same amplitude of the corresponding *harmonic function* and a duration $T_i=n_c/f_i$ (n_c=number of equivalent cycles and f_i=frequency value of the corresponding *harmonic function*), which is in general significantly shorter than the one of the natural input;

step 3 - deriving of the *shape signal* $T(t)$ from the *sum signal* by a mathematical processing, in order to derive i) a null integral over its entire duration, ii) a Fourier spectrum whose spectral density at frequencies lower than the minimum frequency selected from FFT_{rif} is negligible, iii) amplitude values null for $t>T_{end}$;

step 4 - deriving of the *preliminary equivalent signal* $E'(t)$, consisting in a multifrequential dynamic signal which is energy-equivalent to the reference accelerograms in terms of integral of the square of the filtered reference velocigram (V_{filt}), pass-band filtered in the range of the selected frequencies, but not yet best fitted in terms of *PGA*;

step 5 - deriving of the *resulting equivalent signal* $E(t)$ consisting in a multifrequential dynamic signal which is energy-equivalent to the reference accelerogram and best fitted in terms of *PGA* by the use of an iterative procedure; the goodness of the fit is evaluated by computing a convergence error (CRE%). The CRE% is used to attribute a reliability level to the derived input as follow: HIGH RELIABILITY (=CRE≤10%); MIDDLE RELIABILITY (=10%<CRE≤50%); LOW RELIABILITY (=CRE>50%).

The reliability of the LEMA_DES signals was up to now tested for: i) reproducing the Irpinia earthquake scenario (Lenti & Martino, 2010) by processing and analysing 48 records from the Italian accelerometric network; ii) numerical modelling was recently proved by using them for performing dynamic slope stability analyses (Bozzano et al., 2011; Lenti & Martino, 2011). Moreover, some tests on the use of the LEMA_DES signals for laboratory-scaled models have being processed on both shaking table and centrifuge devices.

2. DATA PROCESSING

For the present study the LEMA_DES approach was applied to process 6850 accelerometric records of earthquakes including 1387 record from the European Strong Motion database (Ambraseys et al., 2004), 903 records from the ITACA (ITalian ACcelerometric Archive) on-line database referred to the

2009 L'Aquila seismic sequence and 4560 records form the K-NET on-line database.
The records include both horizontal and vertical components of the ground motion and they correspond to the distribution of focal mechanisms reported in the graph of Fig.1.
The reliability of the LEMA_DES derived signal are reported in Fig.2; as it results, the 5% only of all the processed records do not give a convergence while the 88% give a convergence with middle to high reliability.

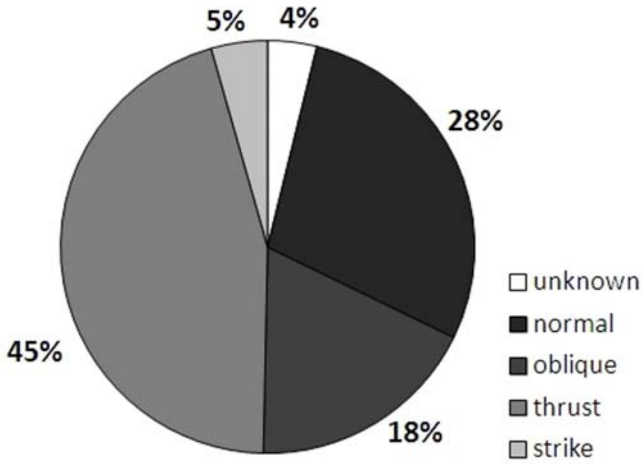

Figure 1. Percentage distribution of the focal mechanisms for the here considered dataset of earthquakes.

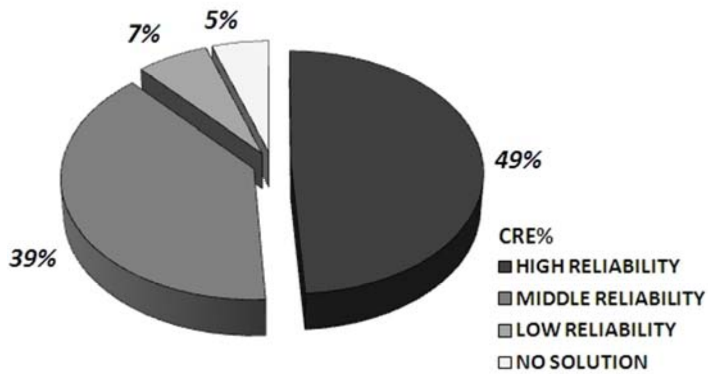

Figure 2. Percentage distribution of the LEMA_DES signal convergence.

3. LEMA_DES DERIVED EQUIVALENT SIGNALS

The distribution of the percentage error resulting from the convergence process and referred to the Arias intensity and to the PGA demonstrates that these errors are within the class 10%-100% (i.e. less than double values of the relative parameters) for more than the 50% of all the derived signals (Fig.3).
As shown by Fig.4 no bias exists in the error distributions; moreover, the high quality of the convergence between the LEMA_DES signals and the reference natural ones is demonstrated by the graphs of Fig.4 showing the linear co-relations existing on a bi-logarithmic scale between equivalent and natural parameters, in the case of Arias and PGA.

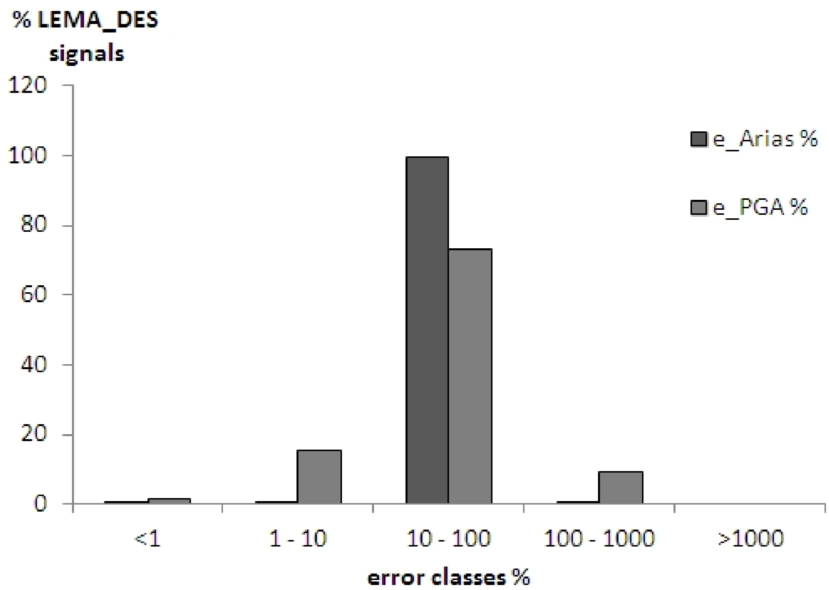

Figure 3. Percentage distribution of relative errors related to the characteristic parameters of the signals (Arias, PGA and Tm).

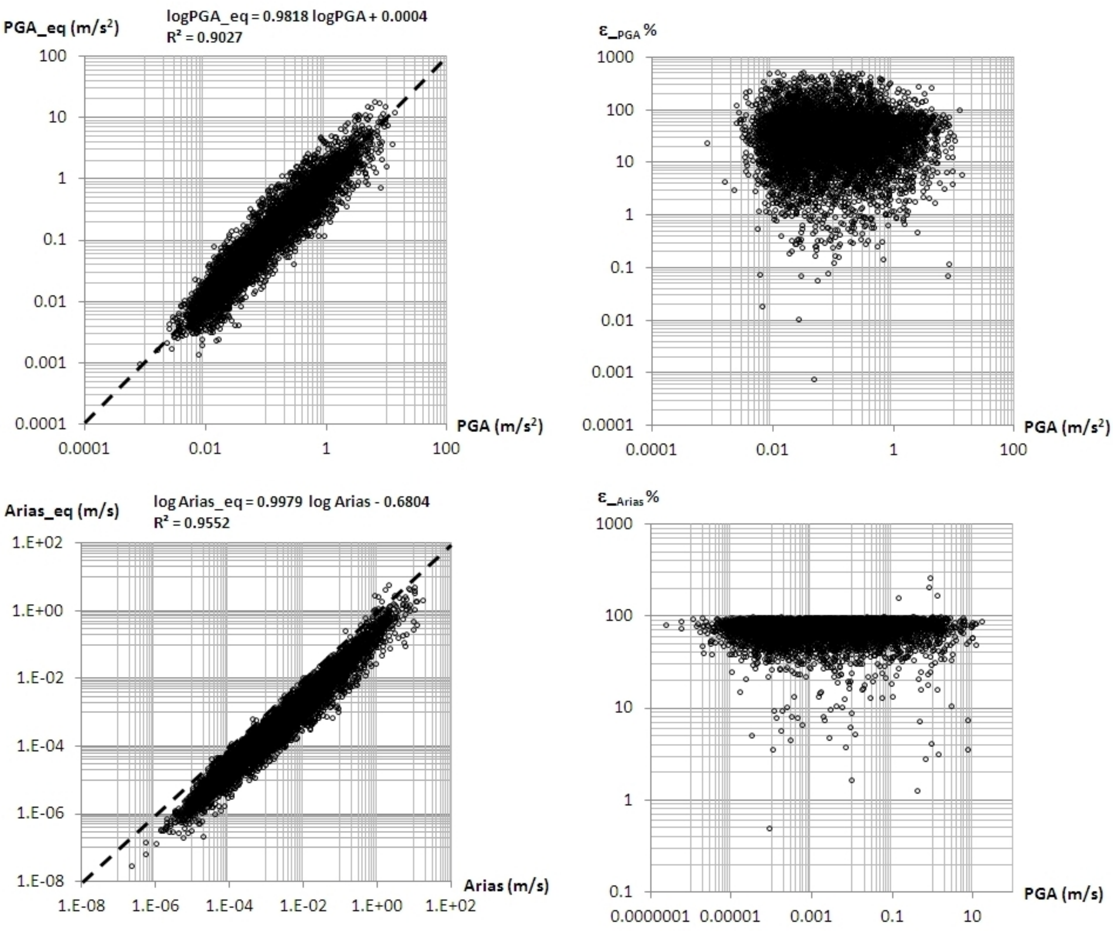

Figure 4. Left column - correlations between the characteristic parameters of the equivalent signals and of the natural reference records. Right column - distribution of relative errors related to the Arias and to the PGA of the signals with respect to the parameter values.

Nevertheless, it is worth noting that the definition of Tm (given for natural earthquake records by other Authors (Xiang and Li, 2000; Baykal et al., 2008; Bray & Rathje, 1998; Yongfeng and Gengshu, 2009) is not adequate for LEMA_DES equivalent signals since the procedure itself starts from the selection of a finite set of characteristic frequencies from the Fourier spectrum of the reference accelerometric record to define multifrequential signals.. Moreover, as these signals are characterized by a very short time duration (i.e, generally lower than few seconds) the related Fast Fourier Transforms have not the resolution needed for applying the proposed equation for computing Tm values.

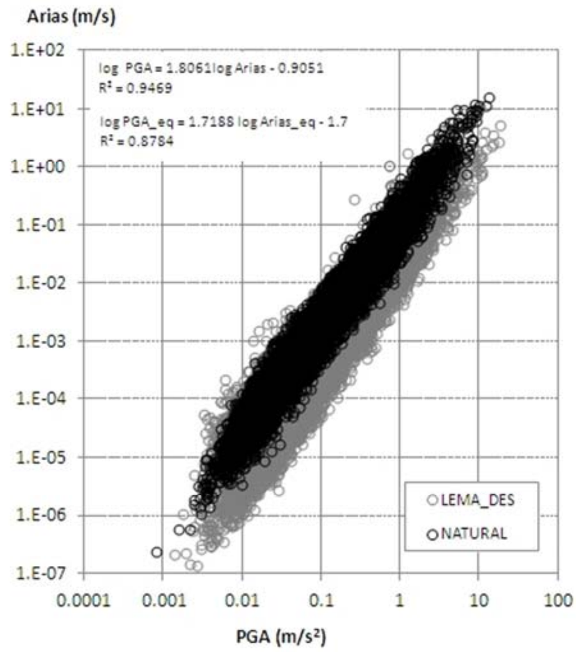

Figure 5. Correlations between the derived characteristic parameters (*PGA* and Arias intensity) of the equivalent signals and of the natural reference records.

On the contrary, a very good convergence between the LEMA_DES equivalent signals and the natural reference records exists in terms of PGA and Arias intensity; in this regard it is worth noting that the energy convergence in the LEMA_DES procedure is directly guarantees by the integral of the square of the filtered reference velocigram (V_{filt}) (i.e. which is physically better related to the kinetic energy of the ground motion) and not by the Arias intensity itself.

The distributions of the derived characteristic parameters of the equivalent signals ($Arias_{eq}$ vs. PGA_{eq}), i.e. not fixed by the LEMA_DES procedure but resulting from a-priori selections or iterations, as well as of the real accelerometric records (Arias vs. *PGA*) are linearly correlated on a bi-logarithmic scale (Fig.5). The obtained co-relations demonstrate the parallelism between the two regression lines according to the previously discussed effect on the energy values of the equivalent signals, due to the filtering processing.

All the obtained correlations suggest that, in the case of the here considered dataset, the LEMA-DES approach proposed for deriving multifrequential dynamic equivalent signals: i) guarantees the energy equivalence of the derived signals (*E(t)*) in terms of Arias Intensity, except for a half order of magnitude, and ii) guarantees the equivalence of *PGA* values with relative errors below 500%. In this regard, it is worth noting that PGA and Arias Intensity are both parameters that may be not able to represent in a complete way the various types of acceleration records. There are many example of events of low magnitude generating large PGA but small duration, e.g. Ancona Earthquake of 1972 (Rocca PGA = 0.6 g strong-phase duration 4 seconds, Ml=4.9), Sicilia Orientale Earthquake of 1990 (Catania PGA = 0.25 g, strong-phase duration 3 seconds, Mw=5.3) and conversely events of large magnitude generating similar PGA e.g. Campano-Lucano Earthquake of 1980 (Calitri PGA = 0.2 g but strong-phase duration of 30 seconds at list). So to carry-out a better correlation between equivalent signals and natural ones, some other strong-motion parameters should be selected as spectral values, by means of response spectra at selected periods, and the Housner Intensity evaluated at some period intervals.

4. ANALYSIS OF THE DISTRIBUTION OF THE EQUIVALENT CYCLES

In order to point out possible co-relations among the number of equivalent cycles (n_c) derived by the LEMA_DES approach, of earthquake magnitude (Mw) and the epicentral distance a class distribution was obtained by considering the average value of n_c per classes of magnitude and epicentral distance. At this aim, the frequency distribution of the here considered classes was maintained within 50 and 300 signals per class (i.e. within 1% and 10% of the total number of signals) by randomly reducing the number of signals of the most numerous classes which resulted by considering the complete dataset.

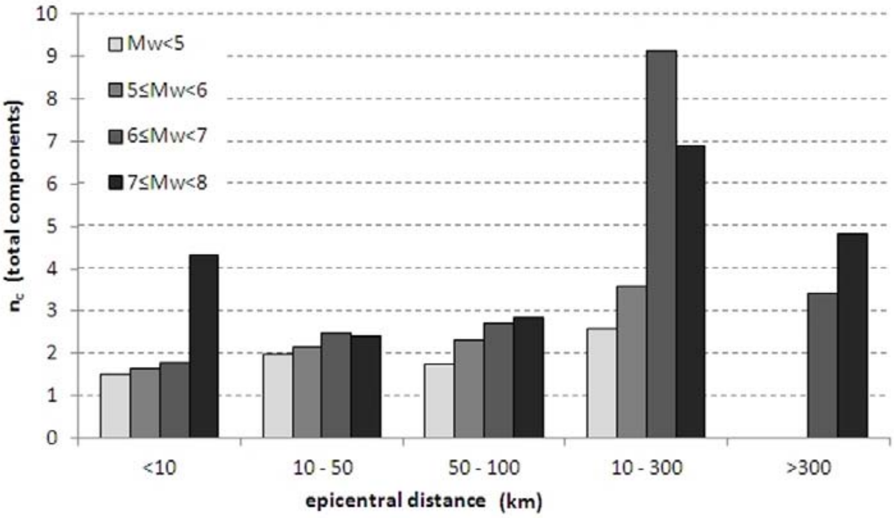

Figure 6. Distribution of n_c per classes of magnitude (Mw) and epicentral distance, obtained by considering all the ground motion components.

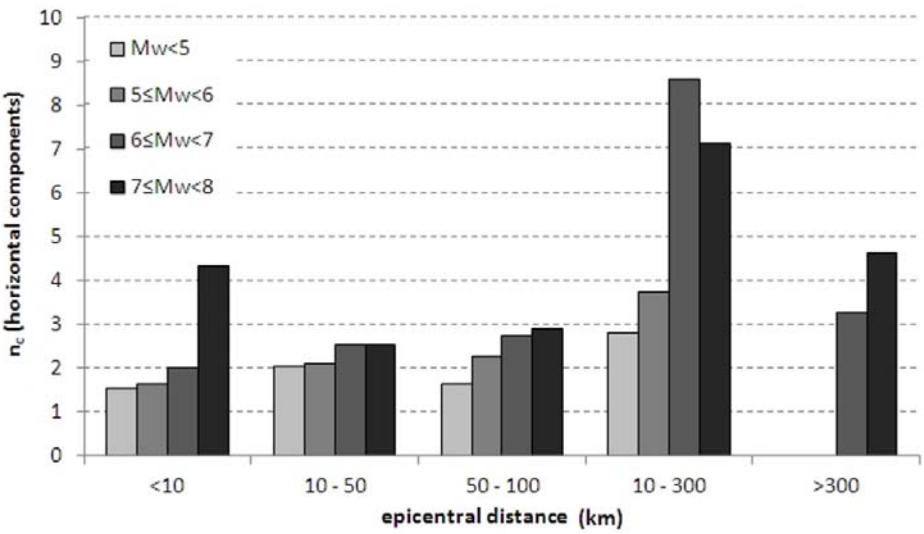

Figure 7. Distribution of n_c per classes of magnitude (Mw) and epicentral distance, obtained by considering only the horizontal components of the ground motion.

If all the ground motion components are considered (Fig.6), this distribution shows that the LEMA_DES derived n_c increase with increasing epicentral distances from 10km up to 300km for 5≤ Mw <7. More in particular, the average n_c varies from 1.5 up to 3.5 for 5≤Mw<6 and from 2 up to 9 for 6≤Mw<7 while not relevant variation of n_c results for class of magnitude <5 (i.e. the n_c values vary in the very close range 1.5 – 2.5).

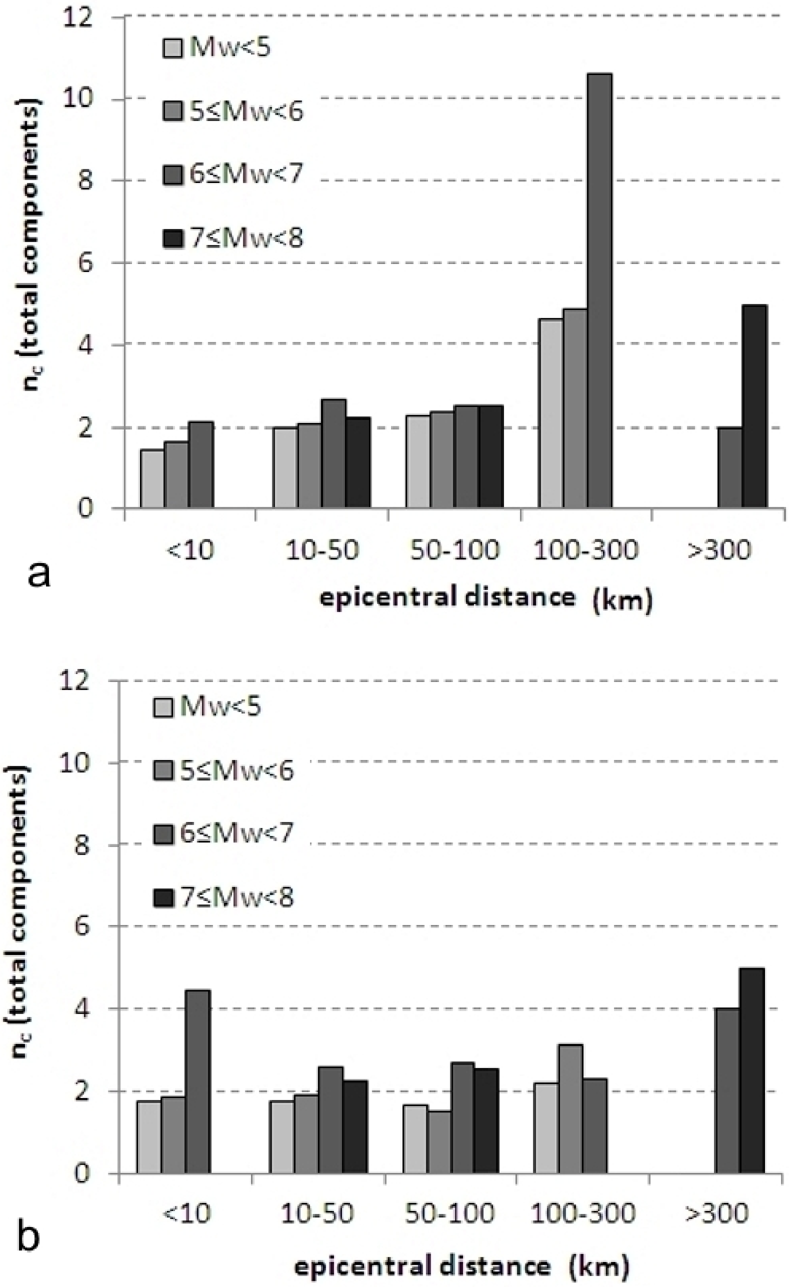

Figure 8. Distribution of n_c per classes of magnitude (Mw) and epicentral distance obtained by considering only the signals referred to normal (a) and thrust (b) fault mechanisms.

For Mw≥7 a more regular increasing of n_c from 2.5 up to 7 results for epicentral distances higher than 10km while an anomalous value of n_c results for the epicentral distance <10km; nevertheless, this value is not highly reliable since, in the here considered dataset, the reference accelerometric records for this class of magnitude/distance are referred to the Chi-Chi earthquake only (TAIWAN Accelerometric Network).Moreover, n_c values decrease for the class distance >300km with respect to the previous trend; nevertheless, for this class of epicentral distance, no data are available for Mw<6.

Fig. 7 shows that the above reported results do not significantly change if only the horizontal components of the ground motion are considered. Moreover, the n_c distribution per classes of magnitude and epicentral distance is very similar to the previous ones if only signals related to normal fault mechanisms are considered (Fig.8a) while a not significant trend results if only signals related to thrust fault mechanisms are considered (Fig.8b); in this last case, the resulting n_c irregularly vary within the range 1.5 – 5.
It is worth noting that the n_c values resulting from the LEMA_DES approach are generally lower than the ones obtained according to the Seed and Idriss (1969; 1971) approach to derive equivalent sinusoidal signals for the same classes of magnitude. More in particular, in the case of equivalent sinusoidal signals, the before mentioned Authors proposed a linear empirical co-relation between n_c and earthquake magnitude corresponding to n_c values varying from 10 up to 30 in the magnitude range 7-8.

5. CONCLUSIONS

More than 6800 accelerometric records of earthquakes were processed according to the LEMA_DES procedure to derive multifrequential dynamic equivalent signals. The records were selected from the European Accelerometric catalogues as well as from the Italian ITACA on-line catalogue and from the Japanese K-NET catalogue. The results of the processing confirmed the high reliability of the LEMA_DES approach to derive dynamic signals equivalent to the reference ones in terms of energy content and PGA since the related relative errors, computed with respect to the reference accelerometric signals, do not exceed 500% and their frequency distribution demonstrates that they are mainly included in the range 10%-100%.
On the basis of the here derived LEMA_DES equivalent signals a distribution of number of equivalent cycles n_c per classes of earthquake magnitude and epicentral distances was derived; this distribution generally shows that the average resulting n_c values do not exceed 10 and they generally increase with increasing magnitude and epicentral distances.
Nevertheless, in order to obtain more reliable results for the highest magnitude events other accelerometric records, available in the COSMOS on-line catalogue, will be processed; then evaluation of Housner Intensity to characterize the accelerometric records energy and spectral values may reduce the spread in the distribution of the PGA relative errors.

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