# An Assessment of the Relevance of Parameters Used for Ground Motion Frequency Content Characterization with Application to Vrancea Subcrustal Earthquakes

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**SUMMARY:**
The paper presents new results from a detailed study, involving an analysis of several deterministic and stochastic indices computed for over 100 tri-axial accelerograms recorded during four strong Vrancea seismic events with moment magnitude, $M_w$, larger than 6. The study aims to better reveal the spectral characteristics of the analyzed ground motions. Various analytical estimators of the predominant period, such as those based on power spectral density, Fourier amplitude spectrum, response spectra etc. are computed and compared. Additionally, a number of bandwidth measures are used in the assessment. The variability of the analyzed period-type parameters from one event to another is pointed out, as well as, when relevant, their spatial variability. Observations are correlated with available information on local site conditions, geology etc., in order to investigate the influence of different factors on the frequency content of the analyzed motions.

*Keywords: frequency content, Vrancea earthquakes, predominant period*

## 1. INTRODUCTION

The characterization of the frequency content of ground motions by a single synthetic parameter provides a straightforward criterion for their classification. During the last decades, several proposals have been made to this end. However, the relevance of proposed parameters depends on different factors and, at present, a unique solution has not yet been found.

The study presented in this paper continues a research initiated by Lungu et al. in the early nineties (Lungu et al, 1992, Dubină and Lungu, 2003). The aim of the study is to investigate the relevance of the analyzed estimators for describing the ground motions frequency content. A set of improved ground motion digitisations is used, together with newly developed software. The first results, concerning correlations existing between various parameters, have been discussed in (Craifaleanu, 2011a, 2011b). Some new findings are presented in the following, including observations concerning the spatial distribution of the most significant parameters for each event. Considerations are made, as well, on the relevance of computed parameters for different types of ground motions and different geological site conditions.

## 2. PREREQUISITES OF THE STUDY

### 2.1. Parameters used in the study for assessing the frequency content of ground motions

A relatively large number of parameters are used in the literature to characterize the frequency content of earthquake ground motions. New and improved expressions of the scalar definitions of the frequency content, expressed as period values, were proposed in the last few years by different authors (Rathje, Abrahamson and Bray, 1998; Rathje, Faraj, Russell and Bray, 2004; Bommer, Hancock and

Alarcon, 2006; Ruiz-Garcia and Miranda, 2005). A number of bandwidth measures and related parameters are used as well (JCSS, 2001).

For the study, three categories of parameters were computed: (a) parameters based on power spectral density and on the Fourier spectrum, (b) parameters based on response spectra and (c) parameters based on peak ground motion values.

(a) Parameters based on power spectral density and on Fourier amplitude spectrum

1. The frequencies $f_1$, $f_2$ and $f_3$, corresponding to the first three peaks, in order of their amplitude, of the PSD (JCSS, 2001). In the paper, $T_{1(PSD)} = 1/f_1$ is used.
2. The $f_{10}$, $f_{50}$ and $f_{90}$ fractile frequencies below which 10%, 50% and 90%, respectively, of the total cumulative power of PSD occur (JCSS, 2001).
3. The central frequency, $\Omega$ (Vanmarcke, 1976)
4. The mean frequency, $\overline{\varpi}$ (Thrainsson, Kiremidjan and Winterstein, 2000), with its inverse, the mean period, denoted in the following by $T_{mean}$.
5. The shape factor, $q$ (Vanmarcke, 1976)
6. The $\varepsilon$ frequency bandwidth parameter (Cartwright and Longuet-Higgins, 1956)
7. The $\xi$ frequency bandwidth parameter (Boore, 2003)
8. The mean square period, $T_{ms}$ (Rathje, Abrahamson and Bray, 1998).

(b) Parameters based on response spectra

1. The predominant period based on acceleration spectrum, $T_{gSA}$ (Rathje, Abrahamson and Bray, 1998), defined as the period at which the maximum ordinate of an acceleration response spectrum computed for 5% damping occurs.
2. Analogously, the predominant period based on velocity spectrum, $T_{gSV}$ (Miranda, 1993a; Ruiz-Garcia and Miranda, 2005) and the predominant period based on input energy spectrum, $T_{gSEI}$ (Miranda, 1993b).
3. The characteristic period, $T_1^*$, defined as the period at the transition between the constant-acceleration and the constant-velocity segments of a 5% damped elastic spectrum, and given by

$$T_1^* = 2\pi \frac{(S_v)_{\max}}{(S_a)_{\max}} \tag{2.1}$$

where $(S_v)_{\max}$ and $(S_a)_{\max}$ are the maximum ordinates of the pseudo-velocity and pseudo-acceleration response spectra, computed for 5% damping.

An alternate definition of the characteristic period, proposed by Lungu et al. in 1997 (cited in Dubină and Lungu, 2003), is used in this paper, i.e.:

$$T_C = 2\pi \, EPV/EPA \tag{2.2}$$

with

$$EPV = (S_v, \text{ averaged on } 0.4\text{s})_{\max}/2.5 \tag{2.3}$$

$$EPA = (S_a, \text{ averaged on } 0.4\text{s})_{\max}/2.5 \tag{2.4}$$

In Eqns. (3.3) and (3.4), $(S_{v, \text{ averaged on } 0.4\text{s}})_{\max}$ and $(S_{a, \text{ averaged on } 0.4\text{s}})_{\max}$ are the maximum values of velocity and acceleration response spectra, respectively, averaged on a 0.4 s period mobile window.

Ruiz-Garcia and Miranda (2005) have proposed modified definitions of the spectral moments, computed from the squared values of the velocity spectra, for elastic SDOF systems with damping ratios of 5%. Based on the above definitions, they computed a modified spectral characteristic period,

$$T_c^* = \left( \sum_{i=1}^{n} T_i \cdot S_{v,i}^2 \cdot \Delta T \right) \bigg/ \left( \sum_{i=1}^{n} S_{v,i}^2 \cdot \Delta T \right) \tag{2.5}$$

and a modified central period

$$T_{cen}^* = \sqrt{\left( \sum_{i=1}^{n} T_i^2 \cdot S_{v,i}^2 \cdot \Delta T \right) \bigg/ \left( \sum_{i=1}^{n} S_{v,i}^2 \cdot \Delta T \right)} \tag{2.6}$$

where $n$ is the number of periods in the velocity spectra, $S_v$ is the spectral velocity and $\Delta T$ is the period interval on the spectrum abscissa. Analogously to the Vanmarcke shape factor, $q$, the cited authors also computed a frequency bandwidth parameter, $\Omega$, also based on modified spectral moments. Smaller values of this parameters are associated with narrow band signals (e.g. $\Omega < 0.5$ is considered a narrow band ground motion).

To avoid confusion with Vanmarcke's $\Omega$ parameter, the modified shape factor of Ruiz-Garcia and Miranda is denoted, in this paper, by $q^*$. For the same reason and also due to its analogy to $T_{mean}$, the modified spectral characteristic period, $T_c^*$, is denoted by $T_{mean}^*$.

(c) Parameters based on peak ground motion values

A single parameter is considered in this category, i.e. the characteristic period of the ground motion, computed based on an empirical relationship, suggested by Heidebrecht in 1987 (cited in Fajfar, Vidic and Fischinger, 1990):

$$T_{4.3} = 4.3 \frac{PGV}{PGA} \tag{2.7}$$

In the above equation, PGV is the peak ground velocity and PGA is the peak ground acceleration. This period was used to define the lower bound of the medium period region, i.e. the period range where the smoothed pseudo-velocity spectrum reaches its maximum values.

## 2.2. Ground motion database

The study was performed by using ground motions recorded during the four strong subcrustal seismic events with moment magnitude, $M_w$, larger than 6, generated by the Vrancea seismogenic source during the past 35 years. The seismic events considered in the analysis were: March 4, 1977 (moment magnitude $M_w$ = 7.4, focal depth $h$ = 94 km), August 30, 1986 ($M_w$ = 7.1, $h$ = 131 km), May 30, 1990 ($M_w$ = 6.9, $h$ = 91 km) and May 31, 1990 ($M_w$ = 6.4, $h$ = 87 km).

A database of 313 ground motions, recorded during the four above-mentioned earthquakes, was used (Fig. 2.1).

The records were classified according to their frequency bandwidth, by using the criteria in Table 2.1, which are to some extent similar to those used by Lungu et al. in (Dubina and Lungu, 2003). All the criteria in a row needed to be satisfied for a record to be classified as "narrow bandwidth" or "broad bandwidth".

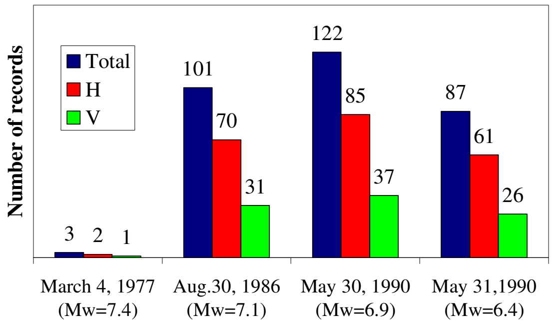



**Figure 2.1.** Number of ground motion records used in the study

**Table 2.1.** Criteria used in the study for the classification of ground motion records according to their bandwidth

| **Bandwidth** | **ε** | $f_{50}$ | $T_C$ |
|---|---|---|---|
| Narrow | ≥ 0.95 | ≤ 2.0Hz | ≥ 0.95s |
| Intermediate | | all other records | |
| Broad | ≤ 0.85 | ≥ 3.0Hz | ≤ 0.75s |

By using the criteria in Table 2.1, from the total of 218 horizontal ground motion records, 21 were identified as narrow band records, 151 as intermediate band records and 46 as broad band records.

## 2.3. Peculiarities of Vrancea earthquakes related to the determination of the predominant period of ground motions

According to the literature (Sandi et al., 2004; Sandi and Borcia, 2011), the radiation directivity is differentiated between the four seismic events considered in the study. While, for the 1977 and 1986 earthquakes, radiation was quite similar, i.e. approximately NE-SW, for the May 30, 1990 and May 31, 1990 earthquakes, N-S and S-E directivity was observed, respectively.

By investigating the influence of local site conditions on the frequency content of ground motions, it was shown that, for a large proportion of the area affected by Vrancea earthquakes, it is difficult to identify the depth of base rock, due to the particular geological conditions (Sandi et al., 2004a). The reason is the absence of an interface where an obvious contrast can be identified in the shear wave propagation velocity, i.e. a significant increase with depth of this parameter.

Based on parametric studies performed on the transfer function of superficial soil deposits for two characteristic sites, the cited reference concludes that sites can be classified according to two distinct situations:

a) a strong increase of shear wave propagation velocity at shallow depths;
b) a gradual increase with depth of the shear wave propagation velocities, proportional with the number of soil layers taken into account in the analysis.

In the first case, local site conditions have a significant influence, and a stability tendency of the predominant periods of ground motions is observed. In the second case, a tendency of variability of the frequency content is found, and it is considered that the determinant influences are, most probably, those of the focal mechanism and of the radiation / long distance attenuation characteristics.

A typical site from the first category is that of the "Cernavodă Municipality" seismic station, located in the south-eastern part of Romania, while one of the most important sites in the second category is the site of INCERC, in Bucharest, where the narrowest frequency band motions were recorded, during the strong Vrancea earthquakes of March 4, 1977 and of August 30, 1986.

A research based on a different approach, performed by Lungu et al. (Dubină and Lungu, 2003) has obtained, for the same site of INCERC, results that generally confirm the above observations. The shear wave propagation velocities and soil layer characteristics were measured in a 128 meters-deep borehole. By using this data, the fundamental period for the site was determined and compared with predominant periods computed based on the power spectral density and the autocorrelation function, for the local records of the March 4, 1977 and August 30, 1986. The predominant periods of vibration computed for the two earthquakes were, for the NS components, 1.6 s and 1.4 s, respectively. Similar values were obtained, based on borehole data, only by considering the entire soil profile (128 m).

## 3. CORRELATION STUDIES

Detailed results of correlation analyses performed for the parameters described in Section 2.1 have been presented in (Craifaleanu, 2011a; b). Some results are briefly summarized below.

Table 3.1 shows the correlation coefficients, $R^2$, computed for the horizontal components of the ground motions in the database. It was assumed that the relationship between two parameters is given by a linear function, of the form $y = a \cdot x + b$.

**Table 3.1.** Correlation coefficients ($R^2$) between the analyzed ground motion frequency content and bandwidth parameters (assumed relationship: $y=a{\cdot}x+b$). Horizontal components for all seismic events

| | $T_{ms}$ | $T_{1(PSD)}$ | $T_{mean}$ | $T_{cen}$ | $T_{gSA}$ | $T_{gSV}$ | $T_{gSEI}$ | $T_C$ | $T_{mean}^*$ | $T_{cen}^*$ | $T_{4.3}$ | $q$ | $q^*$ | $\varepsilon$ | $\xi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $T_{ms}$ | **1.000** | **0.531** | **0.763** | **0.570** | *0.441* | *0.285* | *0.417* | **0.831** | *0.330* | *0.235* | **0.759** | **0.515** | **0.574** | *0.445* | **0.551** |
| $T_{1(PSD)}$ | **0.531** | **1.000** | *0.384* | *0.261* | *0.227* | *0.189* | *0.358* | *0.468* | *0.242* | *0.182* | *0.378* | *0.324* | *0.375* | *0.161* | *0.201* |
| $T_{mean}$ | **0.763** | *0.384* | **1.000** | **0.921** | **0.543** | *0.127* | *0.204* | **0.512** | *0.111* | 0.066 | **0.559** | *0.272* | *0.267* | *0.481* | **0.588** |
| $T_{cen}$ | **0.570** | *0.261* | **0.921** | **1.000** | *0.443* | 0.071 | *0.126* | *0.341* | 0.048 | 0.023 | *0.410* | 0.098 | *0.149* | *0.420* | *0.491* |
| $T_{gSA}$ | *0.441* | *0.227* | **0.543** | *0.443* | **1.000** | 0.030 | 0.064 | *0.276* | 0.023 | 0.007 | *0.307* | *0.196* | *0.108* | *0.356* | *0.435* |
| $T_{gSV}$ | *0.285* | *0.189* | *0.127* | 0.071 | 0.030 | **1.000** | *0.417* | *0.366* | **0.627** | **0.574** | *0.266* | *0.253* | **0.565** | *0.127* | *0.133* |
| $T_{gSEI}$ | *0.417* | *0.358* | *0.204* | *0.126* | 0.064 | 0.417 | **1.000** | *0.426* | *0.403* | *0.338* | *0.318* | *0.258* | *0.474* | *0.111* | *0.127* |
| $T_C$ | **0.831** | *0.468* | **0.512** | *0.341* | *0.276* | *0.366* | *0.426* | **1.000** | *0.401* | *0.290* | **0.715** | *0.442* | **0.673** | *0.274* | *0.371* |
| $T_{mean}^*$ | *0.330* | *0.242* | *0.111* | 0.048 | 0.023 | **0.627** | *0.403* | *0.401* | **1.000** | **0.975** | *0.356* | *0.229* | **0.769** | 0.053 | 0.072 |
| $T_{cen}^*$ | *0.235* | *0.182* | 0.066 | 0.023 | 0.007 | **0.574** | *0.338* | *0.290* | **0.975** | **1.000** | *0.276* | *0.160* | **0.626** | 0.028 | 0.040 |
| $T_{4.3}$ | **0.759** | *0.378* | **0.559** | *0.410* | *0.307* | *0.266* | *0.318* | **0.715** | *0.356* | *0.276* | **1.000** | *0.379* | **0.519** | *0.310* | *0.372* |

As it can be observed from Table 3.1, in most cases (56%) correlation coefficients for the period-type parameters are in the intermediate range (0.1…0.5, values shown in italic font). In 31% of the cases the correlation coefficients exceed 0.5 (values shown in bold font), while in about 13% of the analyzed cases a weak correlation was obtained, with $R^2$ values less than 0.1 (values shown in normal font).

The mean square period, $T_{ms}$ shows the best correlation ($R^2 = 0.831$) with the characteristic period, $T_C$, computed with the modified definitions of effective peak ground motion values. Good correlations ($R^2 \cong 0.76$) are also observed with the mean period, $T_{mean}$, and with the characteristic period based on peak ground motion values, $T_{4.3}$. Lower correlation coefficients (0.570 and 0.531, respectively) result between $T_{ms}$ and $T_{cen}$ and between $T_{ms}$ and $T_{1(PSD)}$. The mean square period also shows a good correlation with the frequency bandwidth indicators, especially $q$, $q^*$ and $\xi$.

The period corresponding to the maximum PSD value, $T_{1(PSD)}$, is rather poorly correlated with the other analyzed parameters, except $T_{ms}$.

A preliminary evaluation made on vertical records has shown a better correlation between $T_{1(PSD)}$ and $T_{gSV}$, $T_{gSEI}$, $T_{mean}^*$ and $T_{cen}^*$, as compared with the set of horizontal records.

A selection of ground motion records according to the frequency bandwidth criteria in Table 2.1 has identified, from the total of 218 horizontal components, 21 narrow frequency band motions, recorded during the earthquakes of March 4, 1977, August 30, 1986 and May 30, 1990. The number of narrow frequency band records was considered as insufficient to obtain reliable correlation results.

The correlations were also assessed separately for the 1986 and 1990 seismic events. As an alternative hypothesis, it was assumed that the functional passes through the origin, i.e. $y=a \cdot x$. Some relevant results are summarized in Table 3.2.

**Table 3.2.** Correlations between the mean square period, $T_{ms}$, and $T_C$, $T_{mean}$ and $T_{4.3}$, respectively, for the horizontal components of the analyzed records. Assumed relationship between two parameters: $y=a \cdot x$

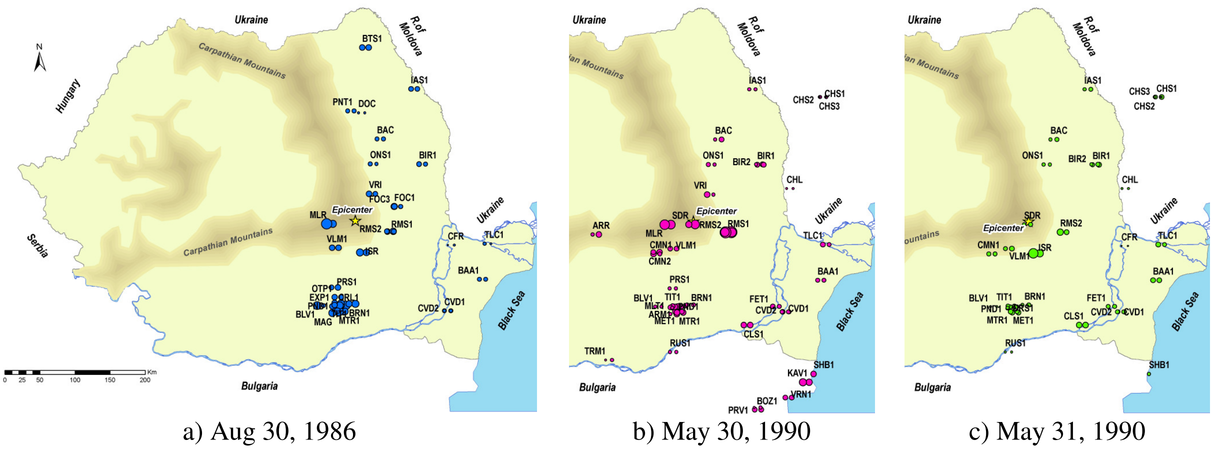
| | | **Aug 30, 1986** | **May 30, 1990** | **May 31, 1990** | **All records, including those of March 4, 1977** |
|---|---|---|---|---|---|
| $T_{ms}$ - $T_C$ | $R^2$ | 0.8122 | 0.8143 | 0.2084 | 0.7954 |
| | $a$ | 0.8006 | 0.7954 | 0.8083 | 0.8017 |
| $T_{ms}$ - $T_{mean}$ | $R^2$ | 0.7238 | 0.7723 | 0.6978 | 0.7619 |
| | $a$ | 1.5409 | 1.5304 | 1.4562 | 1.5328 |
| $T_{ms}$ - $T_{4.3}$ | $R^2$ | 0.7146 | 0.6745 | 0.6137 | 0.7216 |
| | $a$ | 1.2008 | 1.1049 | 1.1705 | 1.1508 |

One can observe that, for all analyzed correlations, the values of both $R^2$ and $a$ coefficients in Table 3.2 vary very little with the considered event, which could be used for the development of empirical relationships between the above parameters. The only exception is the low $R^2$ (0.2084) resulting for the $T_{ms}$ - $T_C$ correlation, in the case of the May 31, 1990 earthquake. A possible explanation could reside in the lower magnitude of this earthquake; however, further research is needed in order to individualize each event.

## 4. SPATIAL AND TEMPORAL DISTRIBUTION OF PERIOD-TYPE PARAMETERS

The spatial distribution of the analyzed period-type parameters was analyzed, for the considered seismic events.

Taking into account the promising results obtained for $T_{ms}$ in the correlation studies, the obtained values were mapped, as shown in Fig. 4.1. Values for both components of ground motions are displayed, for each seismic station. Due to the gradual development of the seismic networks, or to the occasional malfunction of some instruments, the set of recording stations differs, to a certain extent, between the considered earthquakes.

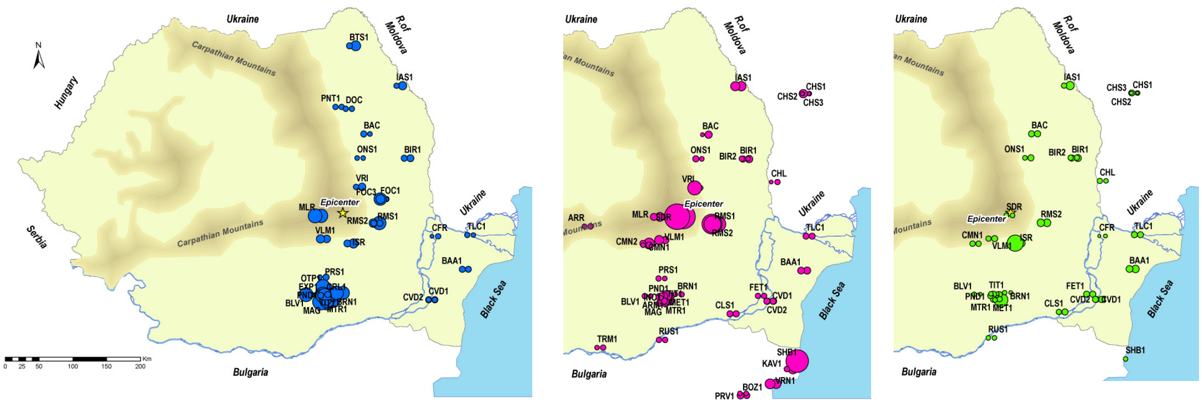



a) Aug 30, 1986 b) May 30, 1990 c) May 31, 1990

**Figure 4.1.** Maps of the mean square period, $T_{ms}$, for the 1986 and 1990 earthquakes

As it can be observed on the maps in Fig. 4.1, the variability of $T_{ms}$ values with the seismic event is different for the recording stations. While in the stations located in the north-eastern and south-eastern parts of the country the variability is small, there are stations near to the Carpathian Arc bend and in Bucharest, which exhibit larger $T_{ms}$ values for one or two of the three considered events.

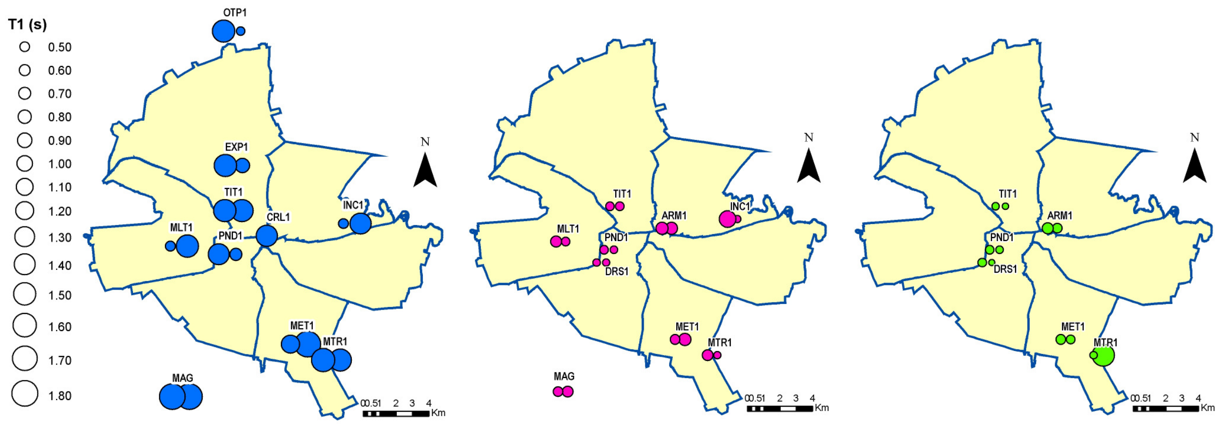
Similar observations were made by examining the maps for $T_{1(PSD)}$ displayed in Figs. 4.2 and 4.3. As in the case of $T_{ms}$, the stations located in the north-eastern and south-eastern parts of the country appear to have a smaller variability the values with the event, while other stations exhibit large $T_{1(PSD)}$ values for one or two of the three considered events and much smaller values for the other event(s). To this second category belong most of the records obtained on August 30, 1986 at the stations located in Bucharest and its surroundings (the group of stations in the south-west of the analyzed zone), at some stations near the Carpathian Arc bend (Muntele Roşu (MLR), Râmnicu Sărat (RMS1) and Focşani (FOC3) in 1986, Surduc (SDR), RMS1 and Vrâncioaia (VRI) on May 30, 1990, Istriţa (ISR) on May 31, 1990) and at station Shabla in Bulgaria, for the earthquake of May 30, 1990. Practically all the records in the second category are narrowband motions, according to the criteria in Table 2.1.




a) Aug 30, 1986 b) May 30, 1990 c) May 31, 1990

**Figure 4.2.** Maps of the period corresponding to maximum PSD, $T_{1(PSD)}$, for the 1986 and 1990 earthquakes

The above observations are also illustrated by the maps of $T_{1(PSD)}$ for Bucharest, in Fig. 4.3. As it can be seen from this figure, large values of $T_{1(PSD)}$ are characteristic for the 1986 earthquake, for one or both components of the ground motions. The situation is radically different for the other two events, with a single exception, that of the EW component at the MTR1 station, on May 31, 1990. This record does not meet all conditions in Table 2.1 for a narrowband motion; however, it has a $q$ value of 0.95.



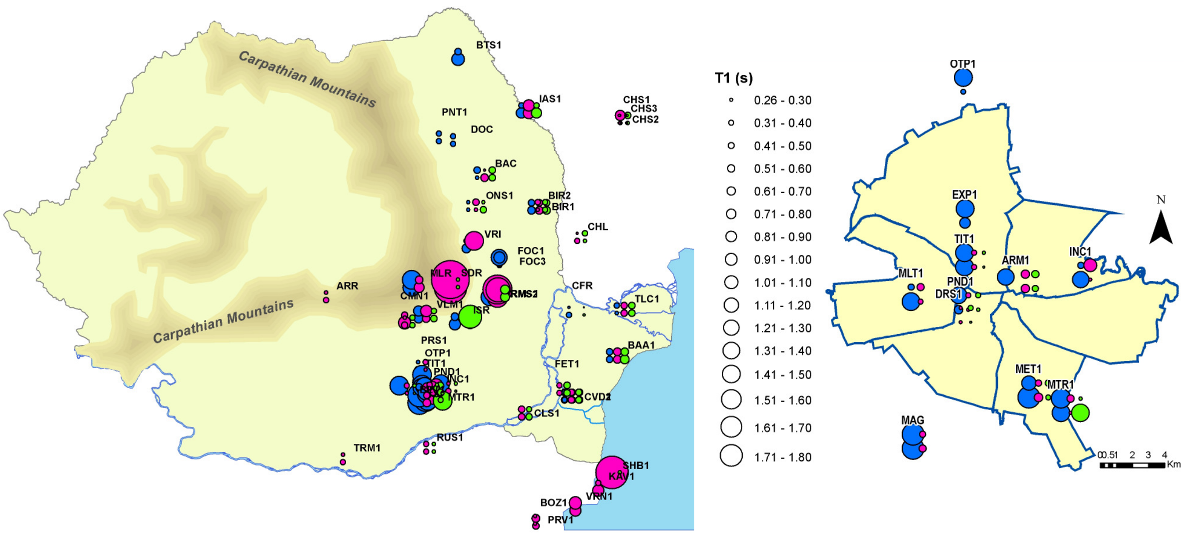

a) Aug 30, 1986 b) May 30, 1990 c) May 31, 1990

**Figure 4.3.** Bucharest: maps of the period corresponding to maximum PSD, $T_{1(PSD)}$, for the 1986 and 1990 earthquakes

The explanation of the strong contrast observed in Bucharest between the frequency content of the 1986 records and that of the 1990 records could possibly reside in the different characteristics (directivity of radiation / attenuation) of the analyzed earthquakes, discussed in Section 2.3 of the paper.

The variability of $T_{1(PSD)}$ with seismic event is summarized in Fig. 4.4. Blue circles denote the August 30, 1986 earthquake, magenta circles, the May 30, 1990 earthquake, and green circles, the May 31, 1990 earthquake. Values for both components are displayed for each station.

As it can be observed, for the stations located in the south-eastern part of Romania, the variation of $T_{1(PSD)}$ with the seismic event is small. Among these stations, it can be mentioned the "Cernavoda Municipality" seismic station (CVD1 and CVD2), mentioned in Section 2 of the paper, as well as the neighboring stations, Feteşti (FET1), Baia (BAA) and Tulcea (TLC1). Taking into account the geology of the concerned area (Dobrogea), the above results could confirm the hypotheses concerning the predominant influence, for these sites, of local soil conditions. A small variability of $T_{1(PSD)}$ values can be also observed for other stations, for instance in Bârlad (BIR1 and BIR2). Additional research is needed to further refine the identification of the site categories discussed in Section 2.




a) All seismic stations b) Stations in Bucharest

**Figure 4.4.** Bucharest: maps of the period corresponding to maximum PSD, $T_{1(PSD)}$ , for the 1986 and 1990 earthquakes

## 5. CONCLUSIONS

The capacity of eleven different scalar period-type parameters, used in the literature to describe the frequency content of ground motions, was assessed comparatively, by using a database of over 300 records obtained from the four strong earthquakes with moment magnitude, $M_w$, larger than 6, that occurred in the Vrancea region in the past 35 years. Additionally, information provided by four spectral bandwidth measures was used. Correlations between the considered parameters were determined for the entire ground motion set, as well as for subsets created by type of component (horizontal or vertical), event or frequency bandwidth. The study presented in the paper is part of a larger research, previous results being described in (Craifaleanu, 2011a; b).

Good and remarkably stable correlations were obtained between the mean square period, $T_{ms}$ (Rathje et al., 1998) and the characteristic period, $T_C$, computed with modified definitions of effective peak ground motion values (Lungu et al., 1997), the mean period, $T_{mean}$, and the characteristic period based on peak ground motion values, $T_{4.3}$ (Heidebrecht, 1987), respectively.

Based on the analysis of the spatial and temporal distributions of period-type parameters, it was concluded that the variability of these parameters with the seismic event differs substantially among the analyzed seismic stations. The first conclusions appear to confirm the hypothesis of Sandi et al. (2004) concerning the types of sites in Romania for which the influence of local site conditions on the frequency content of the ground motions prevails over other factors, as directivity, attenuation or focal mechanism.

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