

# Frequency bandwidth of Vrancea earthquakes and the 1991 edition of seismic Code of Romania

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**ABSTRACT:** Using the theory of stochastic processes, the analysis of the Vrancea earthquake records in 1977, 1986, and 1990 has proved both narrow and wide frequency band motions. The recordings in epicentral area are wide frequency band processes. The seismic motions, filtered through soil layers, show in Bucharest a quite particular spectral composition characterised by 1.4-1.6 sec predominant period. The response spectra and dynamic amplification factors of the recorded motions have been analysed considering mean values and values with different probabilities of exceedance. These results ground the adoption of new design response spectra in Romanian Code for Seismic Design adopted in 1991. Seismic risk for the new structures built up in Bucharest is analysed based on the statistics of their dynamic characteristics. The stochastic analysis of floor acceleration response of rigid and flexible multistory buildings clearly reflects the differences between the filtering of wide versus narrow frequency band motions from base to the roof of the structures.

## 1 DATA BASE AND APPROACH

The city of Bucharest has been shaken in the last fifteen years by three strong earthquakes: March 4, 1977 (M=7.2 and mean return period  $\bar{T}=60$  yr), August 31, 1986 (M=7 and  $\bar{T}=40$  yr) and May 30, 1990 (M=6.9 and  $\bar{T}=30$  yr).

For the first time, the great number of recordings of the Vrancea earthquake on Aug.31, 1986 made possible the knowledge of the characteristics of the ground motions in Romania, especially for Bucharest and epicentral areas. Unfortunately, the Vrancea earthquake on March 4, 1977 was recorded only in one spot in Bucharest.

The analysis of spectral content of seismic motions was performed on stochastic models, power spectra  $S(\omega)$  and autocorrelation functions  $R(\tau)$  being used:

$$R(\tau) = \int_{-\infty}^{\infty} S(\omega) e^{i\omega\tau} d\omega$$

$$S(\omega) = (1/2\pi) \int_{-\infty}^{\infty} R(\tau) e^{-i\omega\tau} d\tau$$

The duration of strong shaking of motion was selected within the fractions of 5% and 95% of the total process energy, E:

$$E = \int_0^{\max} [\ddot{y}_g(t)]^2 dt$$

The function  $R(\tau)$  is calculated for  $\tau_{max} < s/5$  where  $s$  is the selected duration of the accelerogram.

Normalised values of function  $s(\omega)$  and  $R(\tau)$  were obtained dividing the original functions by variance  $\sigma^2$  of the acceleration process:

$$s(\omega) = S(\omega)/\sigma^2$$

$$\rho(\tau) = R(\tau)/\sigma^2$$

The frequency bandwidths of the process is characterised by spectral measures:  $\epsilon$  (Longuet-Higgins) and  $q$  (Vanmarcke), defined by the moments of spectral density functions:

$$\lambda_1 = \int_{-\infty}^{\infty} \omega^1 S(\omega) d\omega$$

$$\epsilon = (1 - \lambda_2^2 / \lambda_0 \lambda_4)^{1/2}$$

$$q = (1 - \lambda_1^2 / \lambda_0 \lambda_2)^{1/2}$$

The evaluation of stationary stochastic linear response of a structure subjected to earthquake acceleration requires the determination of response autocorrelation and spectral density functions. Then, the maximum relative displacement, relative velocity and absolute acceleration of the masses could be determined by multiplying the standard deviation of these quantities with appropriate peak factors. Based on the Ang procedure, the linear response autocorrelation function of the  $j$ -th component of the solution vector for a  $n$ -th degrees of freedom structure:

$$y_j(\tau) = \sum_{k=1}^n \gamma_k \varphi_k(j) \int_0^{\tau} \ddot{y}_g(\tau) h_k(t-\tau) dt$$

subjected to base acceleration process  $y_g(t)$  is:

$$R_{y_j}(\tau) = \sum_{k=1}^n \sum_{l=1}^n \gamma_k \varphi_k(j) \gamma_l \varphi_l(j) \int_{-\infty}^{\infty} H_k(\omega) H_l^*(\omega) \frac{S_{y_g}(\omega)}{\gamma_g} e^{i\omega\tau} d\omega$$

where:

$\gamma_k$  - participation factor of mode  $k$

$\varphi_k(j)$  -  $j$ -th component of the  $k$ -th modal shape

$H_k(\omega)$  - the complex frequency response function for mode  $k$

$H_k^*(\omega)$  - the complex conjugate of  $H_k(\omega)$ .

The peak factor  $r_p$  by which the response standard deviation must be multiplied to predict the extreme response with probability of nonexceedence  $p$  during the time interval  $t$  was evaluated with Vanmarcke procedure:

$$r_p = 2 \ln[2n(1 - \exp(-\delta_e \sqrt{\pi \ln 2n}))]^{1/2} > 2^{1/2}$$

where:

$$n = (\Omega_y t / 2\pi) (-\ln p)^{-1}$$

$$\Omega_y = (\lambda_2 / \lambda_0)^{1/2} \quad \delta_e = q^{1.2}$$

The required autocorrelation, standard deviation and peak factors for secondary system response can be obtained with the same procedure as for the primary structure.

## 2 FREQUENCY BANDWIDTH OF SEISMIC PROCESSES IN ROMANIA

The power spectra of epicentral strong motions recorded in 1986 ( $PGA \leq 3m/sec^2$ ) identify these motions as wide frequency band processes - white noise type - between corner frequencies (periods) of 2.5 rad/sec (2.5 sec), and 30 rad/sec (0.21 sec), Fig.1.

The mean power spectrum for 20 components recorded in the same earthquake in Bucharest area show that the maximum acceleration variances for longer periods (1.4 - 1.6 sec) are almost double compared to those corresponding to shorter periods and that the whole spectrum is slightly moved to lower frequencies. The power density spectrum peak of Bucharest area thus depicts the predominant period of ground vibration in Bucharest and Romanian Plain:  $T_g = 1.4 - 1.6$  sec.

In fact, the Bucharest mean power spectrum in Fig.1 is obtained from seismic motions classified according to their spectral content as follows, Fig.2:

- 5 components with narrow frequency band showing the maximum power peak around predominant period of 1.4 - 1.6 sec, characterised by  $\epsilon_{med} = 0.82$  and  $q_{med} = 0.67$ ;
  - 8 components with wide frequency band limited by corner frequency 17.5 - 25 rad/sec (0.25 - 0.36 sec) characterised by  $\epsilon_{med} = 0.65$  and  $q_{med} = 0.54$ ;
  - 7 components of transition between the previous types.
- Note that for each recording site in Bucharest the two orthogonal components have significant differences in bandwidth: one of them being wider and the other one narrower.

The narrowest frequency band motion available in Bucharest from Vrancea earthquakes is the unique NS component recorded in the South-East of the town in March 4, 1977 earthquake.

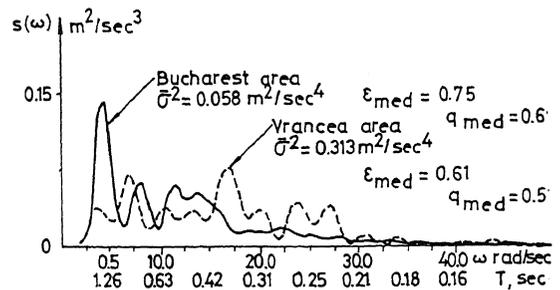


Figure 1. Mean normalised power spectra in Bucharest and in epicentral area for the 1986 earthquake.

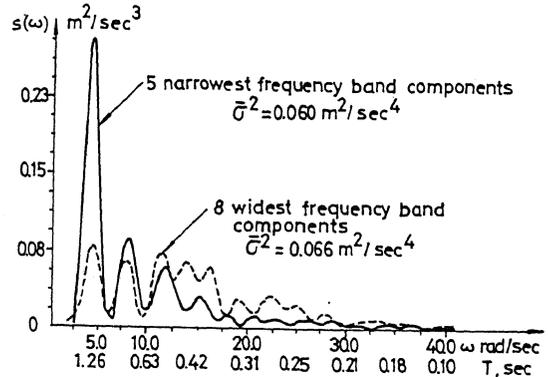


Figure 2. Mean normalised power spectra in Bucharest for the narrowest and the widest frequency band components recorded in the 1986 earthquake.

The normalised autocorrelation and spectral density functions of this component are compared with the corresponding functions of the same component recorded in the same spot in Aug.31, 1986 earthquake, Fig.3. The results prove that:

- (i) the autocorrelation functions as well as the power spectra are almost identical, indicating typical narrow frequency band processes characterised by  $\epsilon = 0.9$  (1977) and  $\epsilon = 0.85$  (1986);
- (ii) compared to the power spectrum peak of 1986 earthquake, at 1.4 sec, the power spectrum peak of 1977 earthquake at 1.6 sec denotes the tendency of moving towards longer predominant periods, which occurs in stronger earthquakes.

The Vrancea 1986 earthquake has proved that Japanese theories about predominant periods of earthquake motions are true: "as the epicentral distance increased, the predominant period has a tendency to become shorter" (Kanai, 1983) or: "in the cases of small earthquakes and great earthquakes the predominant periods of ground vibrations may be different" (Okamoto, 1984).

The soil profile which is responsible for the 1.4 - 1.6 sec predominant period of the earthquake motion recorded in the South-East of Bucharest is described in Fig.4.

### 3 DYNAMIC AMPLIFICATION FACTORS AND THE ROMANIAN SEISMIC DESIGN CODE

The acceleration response spectra with maximum peaks in the short periods range reflect wide frequency band motions.

To the narrow frequency band motions correspond acceleration response spectra having peaks in the long periods range; the ordinates of these peaks are higher or at least similar to those peaks situated in short period range.

The available earthquake records were classified according to geographical area position and to their spectral content. Statistical analysis of the deterministic response spectra for sets of records was performed and the response spectra for normalised absolute acceleration, i.e. Dynamic Amplification Factor (DAF) spectra are presented in terms of: the average spectra and the average plus one standard deviation spectra, corresponding to about 15% exceedance probability, Fig.5.

In epicentral area and in the East of Carpathian Mountains (Moldova), characterised by wide frequency band seismic motions, the DAF spectra have maximum ordinates for periods < 0.6 sec. This ordinates surpass 2.5 for mean DAF and 3.0 for DAF with 15% probability of exceedance.

In Bucharest area, in Romanian Plain, the establishing of DAF were taken into account:

- (i) the maximum spectral peaks in long periods range ( $T > 1.0$  sec), specific to narrow frequency band seismic motions;
- (ii) the maximum spectral peaks in short periods range ( $T < 0.6$  sec), specific to wide frequency band seismic motions.

The mean DAF and DAF with 15% probability of exceedance are presented in Fig.5 for:

- 5 components having the narrowest frequency band in Bucharest area in 1986, and the unique narrowest band NS component recorded in 1977;
- 8 components having the widest frequency band recorded in Bucharest area in 1986.

The statistic results for both long periods and short periods range, lead to mean DAF=2.5 and to DAF with 15% probability of exceedance=3.0.

This values should be extended - straight lines - up to  $T=1.6$  sec because the power spectra for narrow frequency band motion in Bucharest area reach the maximum at 1.4 - 1.6 sec.

The mean DAF could be selected for ordinary buildings and structures and the DAF with 15% probability of exceedance for structures of special interest.

Based on these results, the proposed DAF and the DAF adopted by the 1991 edition of the Romanian Code for Seismic Design are also presented in Fig.5. They must be connected with the map in Fig.6.

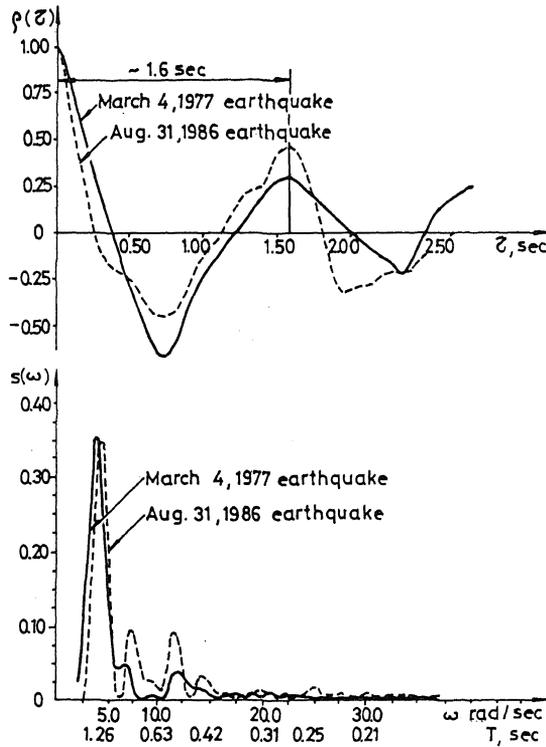


Figure 3. Normalised autocorrelation and power density functions for the NS components of the 1977 and 1986 earthquakes recorded in the South-East of Bucharest.

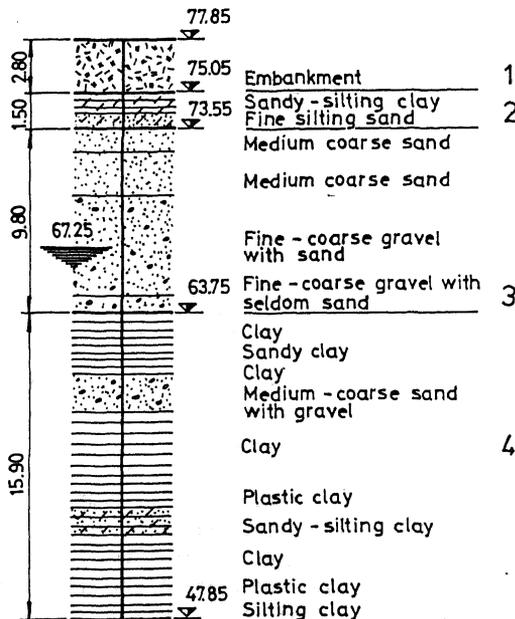


Figure 4. Soil-layers in the South-East of Bucharest.

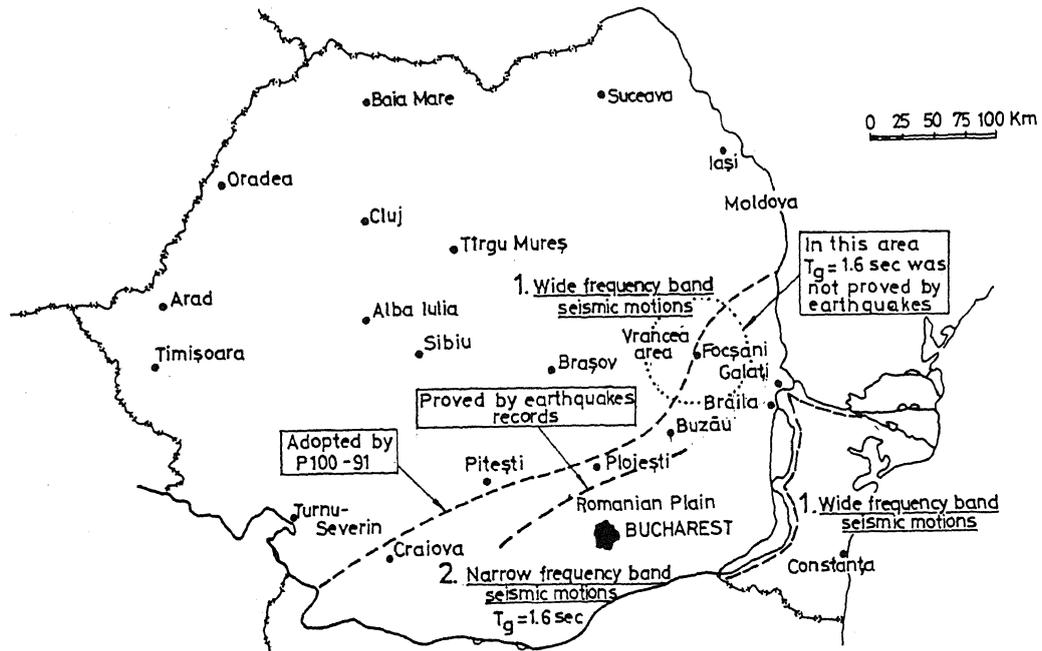


Figure 6. Wide and narrow frequency band seismic motions recorded in Romania.

#### 4 DYNAMIC CHARACTERISTICS OF NEW BUILDINGS IN BUCHAREST

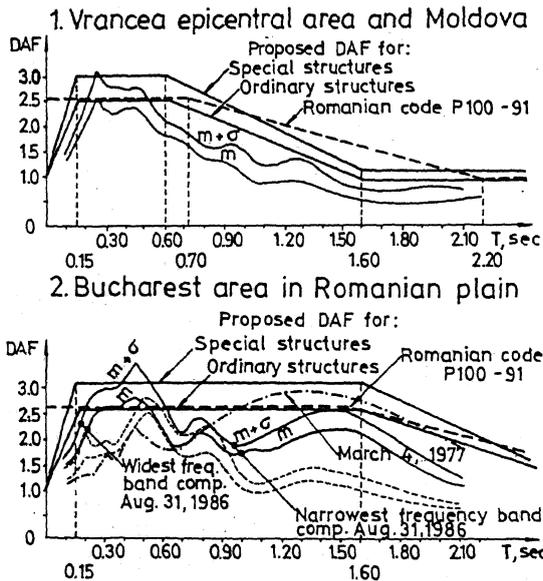


Figure 5. Dynamic amplification factors for Vrancea seismic motions in Romania.

It should be mentioned that for the same spectral composition the greatest values of DAF are associated with lower values of peak ground acceleration and viceversa.

The majority of buildings built up in Bucharest city in the last years has been based on typified design.

The new buildings, with known structural characteristics, make possible a general evaluation of their dynamic behaviour to earthquakes recorded in the city.

The structure fundamental period, on cross and longitudinal directions, was selected as classification parameter for the reinforced concrete multistory structures in the city, Fig.7. In figure are shown too, significant response spectra illustrating the predominant periods for Bucharest area.

We must stress too, some mobility of the periods in histogram of Fig.7 to become longer due to degradation of structure stiffness by the previous earthquakes as well as due to soil-structure interaction. The increase of the structure period in Fig.7 could be over 50%.

The remarks concerning the data in Fig.7 are:

- 1) the apartments in flexible buildings (frames with > 8 stories) having structure period in the proximity of 1.2 - 1.6 sec spectral peak put in light by the strong 1977 Vrancea earthquake, but also by the moderate one in 1986, represent only few percents from all apartments;
- 2) the apartments in structures with period situated in the proximity of 0.45 sec spectral peak (shear-wall structures with 8 stories) represent about 2/3 from all of them;
- 3) the apartments in prefabricated shear-wall structures of five stories represent about 1/6 from all of them and they are, with periods  $\approx$  0.3 sec, out of city spectral peaks.

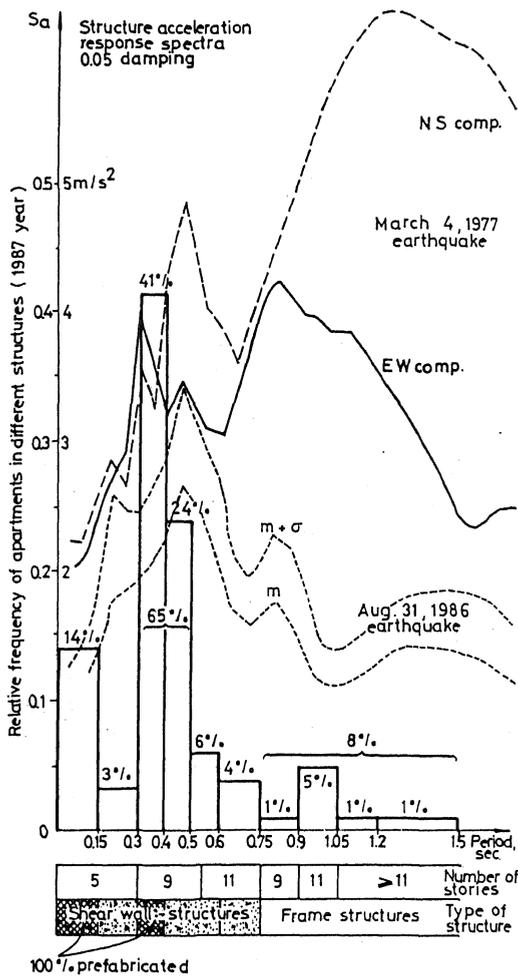


Figure 7. Seismic risk for different types of new structures in Bucharest.

## 5 FILTERING OF WIDE AND NARROW FREQUENCY BAND MOTIONS BY FLEXIBLE AND RIGID STRUCTURES

The stochastic response of two multistory buildings, typified in Romania, to three strong earthquakes of different frequency bandwidth is examined.

The selected reinforced concrete structures are:

- (i) flexible eleven stories K21 frame structure;
- (ii) rigid eight stories D11 shear-wall structure.

The first modal frequencies of that structures are:

Mode	1	2	3	4	5
K21	$\omega = 7.26$	$21.16$	$36.80$	$53.90$	$4.66$
Frame	$T = 0.865$	$0.297$	$0.171$	$0.116$	$0.084$
D11	$\omega = 18.48$	$74.82$	$156.6$	$237.7$	$312.2$
Shear-wall	$T = 0.34$	$0.084$	$0.040$	$0.026$	$0.020$

The earthquakes considered are characterised in Fig.8.

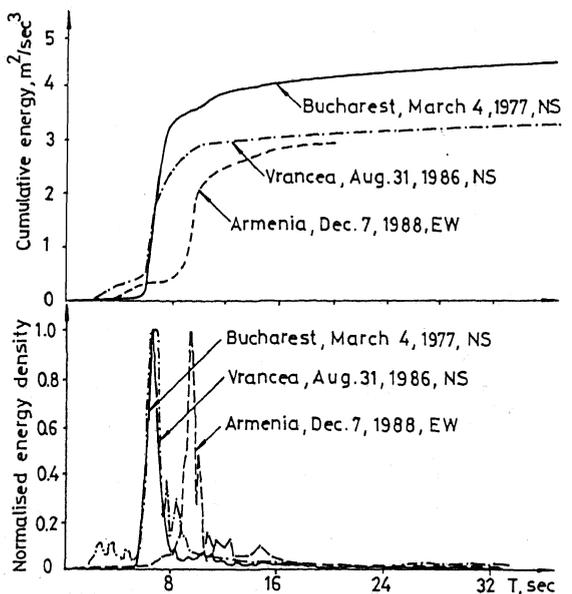
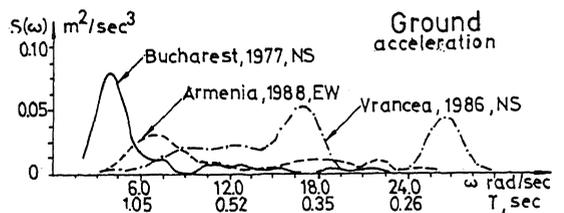


Figure 8. Intensity and energy characteristics of selected Vrancea and Armenia earthquakes.

The basic method adopted in the stochastic dynamic analysis was that of Ang.

The maximum or peak response characteristics were determined with Vanmarcke peak factors.

The validity of the maximum response determined, which is based on the stationarity assumption, has been proved for the primary structure by the deterministic time-history solution, Fig.9 (structure damping  $\xi=0.05$ ).

The filtering of the seismic motions from base to the structure roof was examined based on floor absolute acceleration response spectra concept. The floor acceleration response is represented in Fig.10 and it reflects the differences between dynamics of flexible versus rigid buildings subjected to earthquakes with opposite frequency contents.

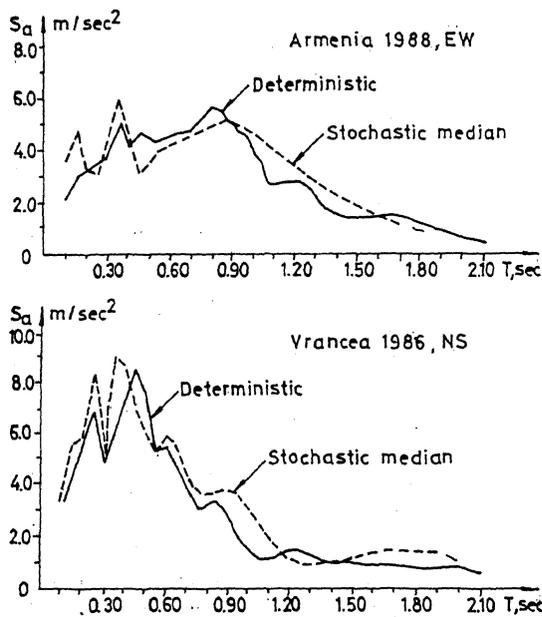


Figure 9. Deterministic versus stochastic acceleration response spectra.

## CONCLUSIONS

The recordings of Vrancea 1986 earthquake emphasize, for the first time, the spectral difference between epicentral area and Bucharest area in Romanian Plain.

The Vrancea and Moldova areas are characterised by wide frequency band power spectrum. In Bucharest, for some of the ground motion components, the stochastic analysis shows narrow band processes, having the spectral density peak at 1.4 - 1.6 sec.

The power density and autocorrelation functions for narrow band component of seismic motions recorded in Bucharest area singled out the predominant period of ground vibration:  $T_g = 1.4 - 1.6$  sec.

This result suggests that structures with fundamental periods situated in the proximity of the power density and absolute acceleration spectra peaks should be avoided in Bucharest.

For Romanian seismic records available, the maximum values of average dynamic amplification factor, DAF are greater than 2.5 and the maximum values of DAF with 15% probability of exceedance are greater than 3.0.

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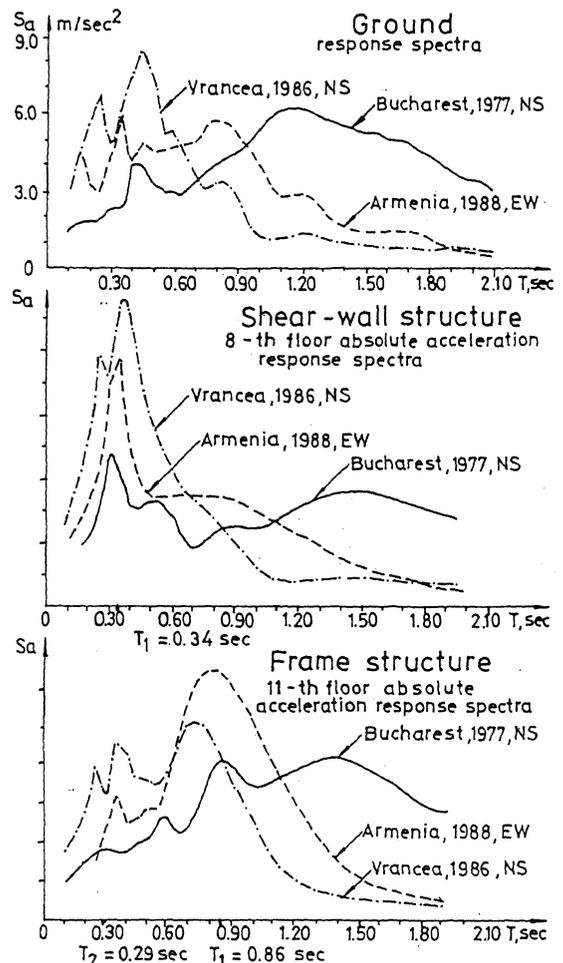


Figure 10. Ground and roof acceleration response spectra.

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