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EARTH PHYSICS

THE QUANTITATIVE EVIDENCE OF THE SOIL NONLINEAR BEHAVIOR DURING OF STRONG VRANCEA EARTHQUAKES IN REAL / NONLINEAR SEISMOLOGY

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Abstract. Nonlinear effects in ground motion during large earthquakes have long been a controversial issue between seismologists and geotechnical engineers. Laboratory tests made by using resonant columns consistently show the reduction in shear modulus (G) and increase in damping ratio (D) with increasing shear strain (γ), *i.e.*, $G = G(\gamma)$, respectively, $D = D(\gamma)$, therefore nonlinear viscoelastic constitutive laws are required.Aki [1] wrote: „Nonlinear amplification at sediments sites appears to be more pervasive than seismologists used to think…Any attempt at seismic zonation must take into account the local site condition and this nonlinear amplification”. In other words, the seismological detection of the nonlinear site effects requires a simultaneous understanding of the effects of earthquake source, propagation path and local geological site conditions. The difficulty for seismologists in demonstrating the nonlinear site effects has been due to the effect being overshadowed by the overall patterns of shock generation and propagation. The authors, in order to make evidence of nonlinear effects, introduced the spectral amplification factor (SAF) as ratio between maximum spectral absolute acceleration (S_a), relative velocity (S_v), relative displacement (S_d) and peak values of acceleration ($a_{\max}$), velocity ($v_{\max}$) and displacement ($d_{\max}$), respectively, from processed strong motion record. The evidence for nonlinearity at least for thick Romanian Plain Quaternary sediments is a systematic decrease in the variability of peak ground acceleration with the increasing earthquake magnitude.

Key words: seismic hazard, nonlinear seismology, nonlinear behavior of soils, spectral amplification factors, seismic risk.

1. INTRODUCTION

The model of linear elastic response of the Earth to earthquakes has been almost universally used in seismology to model teleseismic, weak, and also strong earthquakes. For teleseismic and weak ground motions, there is no reason to doubt that this model is acceptable, but for strong ground motions, particularly when recorded on soils, the consequences of nonlinear soil behavior have to be seriously considered. Laboratory tests made by using resonant columns consistently show the reduction in shear modulus (*G*) and increase in damping ratio (*D*) with increasing shear strain (γ), *i.e*, $G = G(\gamma)$, respectively, $D[\%] = D(\gamma)$, therefore nonlinear viscoelastic constitutive laws are required (Fig.1). On the other hand, the nonlinear behavior of the soil has to be separated into two portions. The „primary nonlinearity" is attributed to the seismic excitation alone. It is nonlinear soil behavior associated with the state of deformation induced by the free-field ground motion. The „secondary nonlinearity" is due to the soil-structure interaction process. It is associated with the soil deformations caused by structural vibrations, and can, in a sense, be thought of as a perturbation of the primary nonlinearity.

Aki [1] wrote: "Nonlinear amplification at sediments sites appears to be more pervasive than seismologists used to think… Any attempt at seismic zonation must take into account the local site condition and this nonlinear amplification".

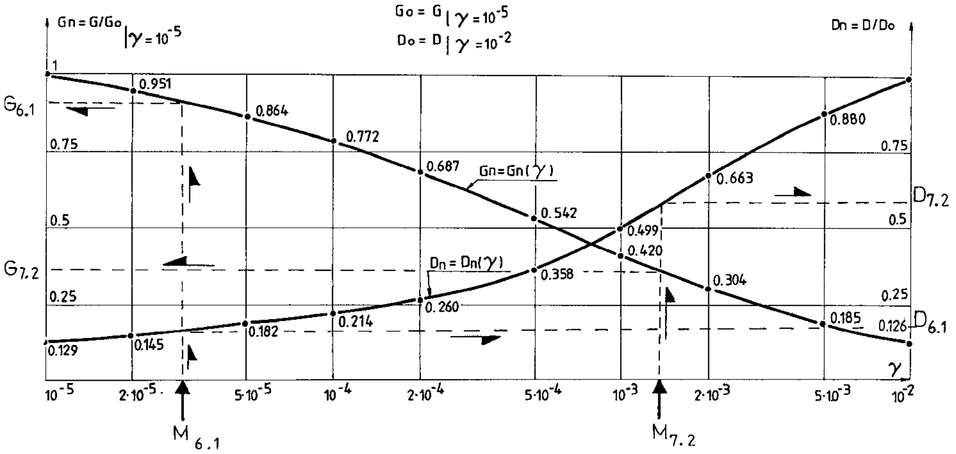


Fig.1 – Normalized curves for sand with gravel from NIEP resonant columns [7].

For smaller earthquakes, the strains are smaller and we are in the left-hand side of Fig.1: for strong earthquakes, the strains are larger and we are in the right-hand side of Fig. 1. Consequently the responses of a system of nonlinear viscoelastic materials (clays, marls, gravel, sands etc.) subjected, for example to vertically traveling shear waves are far away from being linear and generating large discrepancies. In this case, in the wave equation:

$$G\frac{\partial^2 u_2(x_1,t)}{\partial x_1^{\,2}} + \eta\frac{\partial^3 u_2(x_1,t)}{\partial t\partial x_1^{\,2}} = \rho\frac{\partial^2 u_2(x_1,t)}{\partial t^2}, \qquad \textbf{(1)}$$

where G[daN/cm^2] is the dynamic torsion modulus function and D[%] is the torsion damping function; both of them are functions of shear strains (γ), frequency (ω), confining pressure (σ), depth (h), temperature (t), void ratio (v) etc., that is: $G = G(\gamma, \omega, \sigma, h, t, v,\ldots)$ and $D = D(\gamma, \omega, \sigma, h, t, v,\ldots)$.

In order to find the quantitative characteristics of the nonlinear soil behavior and nonlinear site response, authors [4, 5] introduced so-called “the spectral (seismic) amplification factor”.

2. THE QUANTITATIVE EVIDENCE OF NONLINEAR EFFECTS BY USING SPECTRAL AMPLIFICATION FACTORS (SAF)

2.1. THE DEFINITION AND THE THEORETICAL SUPPORT OF THE SAF

If we have a single degree of freedom linear oscillator of mass m, stiffness k, fraction of critical damping β [%], subjected to base acceleration $\ddot{a}(t)$, or absolute motion of the ground $a(t)$, the relative displacement $x(t)$ of the mass m can be computed from Duhamel integral. For zero initial conditions, the expression for $x(t)$ takes the form:

$$x(t) = \frac{-1}{\omega\sqrt{1-\beta^2}} \int_0^t \ddot{a}(\tau)\mathrm{e}^{-\beta\omega(t-\tau)} \sin\omega\sqrt{1-\beta^2}(t-\tau)\mathrm{d}\tau, \tag{2}$$

where the natural frequency ω and the fraction of critical damping β[%] are defined as follows:

$$\omega^2 = k / m \qquad \text{and} \quad \beta = \frac{\xi}{2\sqrt{km}}. \tag{3}$$

The exact value of the relative velocity $\dot{x}(t)$ follows from (2):

$$\begin{aligned}\dot{x}(t) = &-\int_0^t \ddot{a}(\tau)\mathrm{e}^{-\beta\omega(t-\tau)} \cos\omega\sqrt{1-\beta^2}(t-\tau)\mathrm{d}\tau + \\ &\frac{\beta}{\sqrt{1-\beta^2}} \int_0^t \ddot{a}(\tau)\mathrm{e}^{-\beta\omega(t-\tau)} \sin\omega\sqrt{1-\beta^2}(t-\tau)\mathrm{d}\tau.\end{aligned} \tag{4}$$

The absolute acceleration $\ddot{y}(t)$ of the mass m is obtained by further differentiation of $\dot{x}(t)$ and noting that $\ddot{y}(t) = \ddot{x}(t) + \ddot{a}(t)$ is given by the expression:

$$\begin{aligned}\ddot{y}(t) = &\,\omega\frac{1-2\beta^2}{\sqrt{1-\beta^2}} \int_0^t \ddot{a}(\tau)\mathrm{e}^{-\beta\omega(t-\tau)} \sin\omega\sqrt{1-\beta^2}(t-\tau)\mathrm{d}\tau + \\ &+2\omega\beta\int_0^t \ddot{a}(\tau)\mathrm{e}^{-\beta\omega(t-\tau)} \cos\omega\sqrt{1-\beta^2}(t-\tau)\mathrm{d}\tau.\end{aligned} \tag{5}$$

The maximum absolute values of the quantities $x(t)$, $\dot{x}(t)$ and $\ddot{y}(t)$ experienced during the earthquake response are commonly defined as follows:

$$S_d = |x(t)|_{\max} \; ; \qquad S_v = |\dot{x}(t)|_{\max} \; ; \qquad S_a = |\ddot{y}(t)|_{\max} \tag{6}$$

and plots of S_a, S_v and S_d versus the un-damped natural period of vibration $T = 2\pi/\omega$ for various fractions of critical damping (β=0%, 2%, 5%, 10%, 20% etc.) are called earthquake response spectra. The ratio between maximum spectral values of S_a, S_v, S_d from response spectra for a fraction of critical damping (β) and peak values of $\ddot{y}(t)$, $\dot{x}(t)$, respectively, $x(t)$ from processed acceleration record is called the spectral amplification factor for absolute acceleration, relative velocity, respectively, relative displacement, that is:

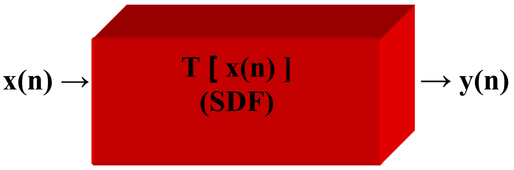
$$\mathrm{SAF_a} = S_a^{\max}/a_{\max} \; ; \quad \mathrm{SAF_v} = S_v^{\max}/v_{\max} \; ; \quad \mathrm{SAF_d} = S_d^{\max}/d_{\max},$$

where :

$$a_{\max} = \ddot{y}(t)_{\max} \; ; \qquad v_{\max} = \dot{x}(t)_{\max} \quad \text{and} \quad d_{\max} = x(t)_{\max} \, . \tag{7}$$

As is known a linear SDF system (*Single Degree of Freedom*) is essentially an algorithm which transforms a sequence of input $x(n)$ to an output sequence $y(n)$ as follows:

$$y(n) = T\,[\,x(n)\,] \tag{8}$$



and there is the following relation of superposition:

$$T\,[\,a\,x_1\,(n) + b\,x_2\,(n)\,] = a\,T\,[\,x_1\,(n)\,] + b\,T\,[\,x_2\,(n)],\tag{9}$$

where a and b are arbitrary constants. For $x(n)$ sequence we have:

$$x(n) = \sum x(k)\,\delta_0\,(n-k).\tag{10}$$

On the other hand an arbitrary sequence could be wrote as a weight sum of tardy unitary impulses (10) and by using the linearity of the system, we have:

$$y(n) = T\,[\sum x(k)\,\delta_0\,(n-k)\,] = \sum x(k)\,T\,[\delta_0\,(n-k)\,].\tag{11}$$

If we introduce the notation:

$$h_k\,(n) = T\,[\delta_0\,(n-k)\,],\tag{12}$$

where the sequence h_k is the system response to tardy unitary impulse with k periods, we have:

$$y(n)= \sum x(k)\ h_k\ (n). \qquad (13)$$

For time invariable systems there are the properties:

$$y(n)= T\,[x(n)] \rightarrow y(n{-}k)=T\,[x(n{-}k)],\ \ h_k\ (n) =h(n{-}k) \qquad (14)$$

and from Equation (13) we have:

$$y(n) = \sum x(k)\ h(n{-}k) = [x \times h\ ]\ (n) \qquad (15)$$

and this equation is named sum of convolution and it could be write in this last compact form.

Finally we have:

$$y(n)= [x \times h\ ]\ (n) = [h \times x\ ]\ (n). \qquad (16)$$

Consequently, knowing the output sequence h to unit impulse δ_0 there is the possibility to find the response of the linear system, invariant in time, to any sequence by using the convolution summation (15). This is the theoretical support to spectral amplification factor approach which is used in classical theory of linear systems.

2.2. SPECTRAL AMPLIFICATION FACTORS FOR LAST STRONG VRANCEA EARTHQUAKES

The last Vrancea strong earthquakes on August 31,1986 (H=21:28:37; N=45.53N, 8=26.47E; h=133 km and M_W =7.1), on May 30,1990 (H=10:40:06; N=45.82N; 8=26.90E; h=90 km and M_W =6.9) and on May 31,1990 (H=00:17:41; N=45.83N; 8=26.89E; h=79 km and M_W =6.3) were recorded at 11 seismic stations of the National Institute for Earth Physics and to other 5 seismic stations which belongs to ISPH Bucharest. Also, the earthquake on March 4,1977 (H=21:21:54; N=45.77N, 8=26.49E; h=94 km and M_W =7.4**)** recorded at INCERC Seismic Station by SMAC-B. The processing of the records was made by using CALTECH and Kinematrics procedures and the results are given in papers (2) and (3) where we can find the peak values of $a_{\max}$, $v_{\max}$ and $d_{\max}$. Also, in paper (2) and (3) are given the spectral amplification factors for fraction of critical damping (β[%]) of 2%, 5%, 10% and 20% , the median values (50%) and one sigma cumulative probability level (1F) values [4, 5, 7].

In Tables 1, 2, 3, 4 and 5 are given spectral amplification factors for absolute accelerations at 5% fraction of critical damping (β=5%) at five seismic stations: Bucharest-INCERC(soft soils, quaternary layers with a total thickness of 700 m); Bucharest-Măgurele (sand, loess – 350m); Cernavoda-NPP (marl, loess, limestone-270m), Bacău (gravel, loess –20 m) and Iaşi (loess, sand, clay, gravel-20÷60m) for last four Vrancea strong earthquakes: March, 4, 1977 (M_W=7.4); August, 30, 1986 (M_W=7.1); May, 30, 1990 (M_W=6.9) and May, 31, 1990 (M_W=6.3) [4, 5, 7].

Table 1

Bucharest-Măgurele Seismic Station (E-W Component)

Earthquake	$a_{\max}(g)$ (recorded)	$S_a^{\max}(g)$ (β=5%)	$S_a^{\max}/a_{\max}$ (SAF)	c	$S_a^{*}(g)$ (β=5%)	$a^{*}(g)$	%
08.30,1986	0.116	0.313	2.6982	1.3294	0.4160	0.1542	**32.94**
05.30,1990	0.092	0.330	3.5869	**1.0000**	3.5869	0.0920	**-**

Table 2

Bucharest-INCERC Seismic Station (N-S Component)

Earthquake	$a_{\max}(g)$ (recorded)	$S_a^{\max}(g)$ (β =5%)	$S_a^{\max}/a_{\max}$ (SAF)	c	$S_a^{*}(g)$ (β =5%)	$a^{*}(g)$	**%**
03.04,1977	0.208	0.620	2.9807	1.1386	0.7059	0.2368	**13,46**
08.30,1986	0.096	0.254	2.6458	1.2827	0.3258	0.1231	**28.27**
05.30,1990	0.066	0.224	3.3939	**1.0000**	0.224	0.0660	-

Table 3

Cernavoda NPPlant Seismic Station (N-S Component)

Earthquake	$a_{\max}(g)$ (recorded)	$S_a^{\max}(g)$ (β =5%)	$S_a^{\max}/a_{\max}$ (SAF)	c	$S_a^{*}(g)$ (β =5%)	$a^{*}(g)$	**%**
08.30,1986	0.0640	0.2610	4.0781	**1.4185**	**0.3702**	**0.0907**	**41.72**
05.30,1990	0.1020	0.4850	4.7549	1.2166	0.5900	0.1241	**21.66**
05.31,1990	0.0507	0.2933	5.7851	**1.0000**	0.2933	0.0507	-

Table 4

Bacău Seismic Station (N-S Component)

Earthquake	$a_{\max}(g)$ (recorded)	$S_a^{\max}(g)$ (β =5%)	$S_a^{\max}/a_{\max}$ (SAF)	c	$S_a^{*}(g)$ (β =5%)	$a^{*}(g)$	**%**
08.30,1986	0.0736	0.2980	4.0489	**1.4557**	**0.4338**	**0.1070**	**45.57**
05.30,1990	0.1350	0.6890	5.1629	1.1416	0.7957	0.1540	**14.16**
05.31,1990	0.0643	0.3790	5.8942	**1.0000**	0.3790	0.0643	-

Table 5

Iaşi Seismic Station (N-S Component)

Earthquake	$a_{\max}(g)$ (recorded)	$S_a^{\max}(g)$ (β =5%)	$S_a^{\max}/a_{\max}$ (SAF)	c	$S_a^{*}(g)$ (β =5%)	$a^{*}(g)$	**%**
08.30,1986	0.0695	0.230	3.3079	**1.2890**	**0.2966**	**0.0800**	**28.00**
05.30,1990	0.0991	0.403	4.0665	1.0490	0.4230	0.1039	**4.95**
05.31,1990	0.0504	0.215	4.2658	**1.0000**	0.2150	0.0504	-

In Tables 1, 2, 3, 4 and 5 are given the spectral amplification factors and the effects of nonlinearity. Coefficient *c* is the ration between SAF for May 31, or May 31, 1990 Vrancea earthquakes and (SAF) for each earthquake before May 1990; S_a^* (*g*) and $a^*(g)$ are the maximum spectral acceleration, respectively, maximum acceleration if the system would have a linear response (behavior) to fundamental period. Vrancea earthquake on May 31, 1990 (M_W=6.3) could be assumed that the response is still in elastic domain and then we have the possibility to compare to it.

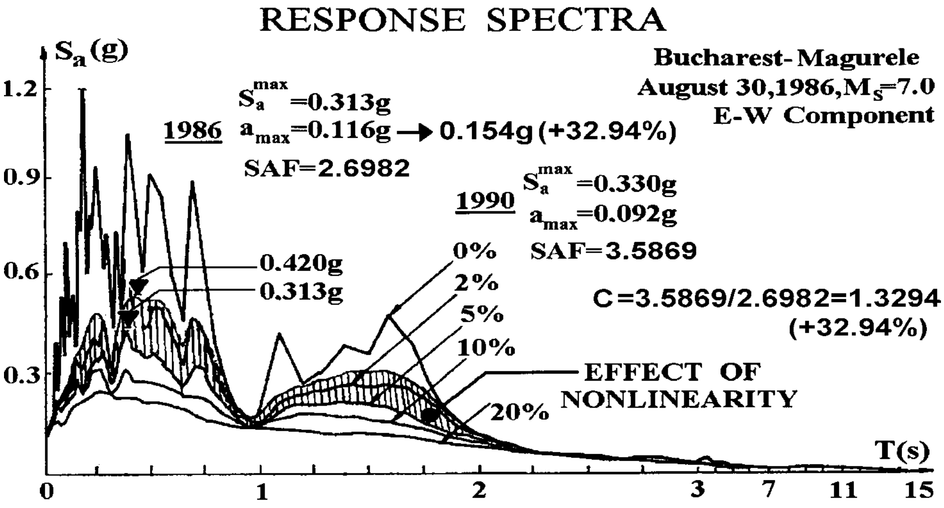


Fig. 2 – The effect of nonlinearity for Bucharest-Măgurele site (β= 5%) [5,7].

The effect on nonlinearity is very large. For example, if we keep the same amplification factor (SAF= 5.8942) as for relatively strong earthquake on May 31, 1990 with magnitude M_W=6.3 then at Bacău seismic station for earthquake on May 30, 1990 (M_W =6.9) the peak acceleration has to be $a^*_{\max}$ =0.154*g* (+14.16%) and the actual recorded was only, $a_{\max}$ =0.135g. Also, for Vrancea earthquake on August 30, 1986, the peak acceleration has to be $a^*_{\max}$=0.107g (+45,57%) instead of real value of 0.0736 g recorded at Bacău seismic station.

3. THE QUANTITATIVE NONLINEAR DEPENDECE OF SAF OF EARTHQUAKE MAGNITUDE AND FREQUENCY

3.1. DEPENDENCE OF SAF OF VRANCEA EARTHQUAKE MAGNITUDE

The spectral amplification factors and, in fact, the nonlinearity, are function of earthquake magnitude. From Tables 1, 2, 3, 4, 5 and 6 and Fig. 3 we can see that there is a strong nonlinear dependence of the spectral amplification factors of earthquake magnitude. The median values of the spectral amplification factors of the last strong Vrancea earthquakes for damping 5% are: 4.16; 3.63 and 3.26 corresponding to May 31, 1990 Vrancea earthquake (M_W=6.3), May 30, 1990 Vrancea earthquake (M_W=6.9), respectively, August 30,1986 Vrancea one (M_W=7.1). At the same seismic station, for example at Bacău, for 5% damping, SAF for accelerations is 5.22 for May 31, 1990 earthquake (M_W =6.3); 4.32 for May 30, 1990 earthquake (M_W=6.79) and 3.94 for August 30, 1986 one (M_W=7.1**).**

Table 6

The median values of the spectral amplification factors of the last strong Vrancea earthquakes

Damping	08.30.1986 (M_w=7.1)		05.30.1990 (M_w=6,9)		05.31.1990 (M_w=6,3)	
β [%]	S_a^{max}/a_{max}	S_v^{max}/v_{max}	S_a^{max}/a_{max}	S_v^{max}/v_{max}	S_a^{max}/a_{max}	S_v^{max}/v_{mav}
2%	4.74	3.61	5.58	3.72	6.22	4.84
5%	**3.26**	2.69	**3.63**	2.95	**4.16**	3.48
10%	2.43	1.99	2.56	2.14	2.92	2.69
20%	1.78	1.50	1.82	1.58	2.13	1.86

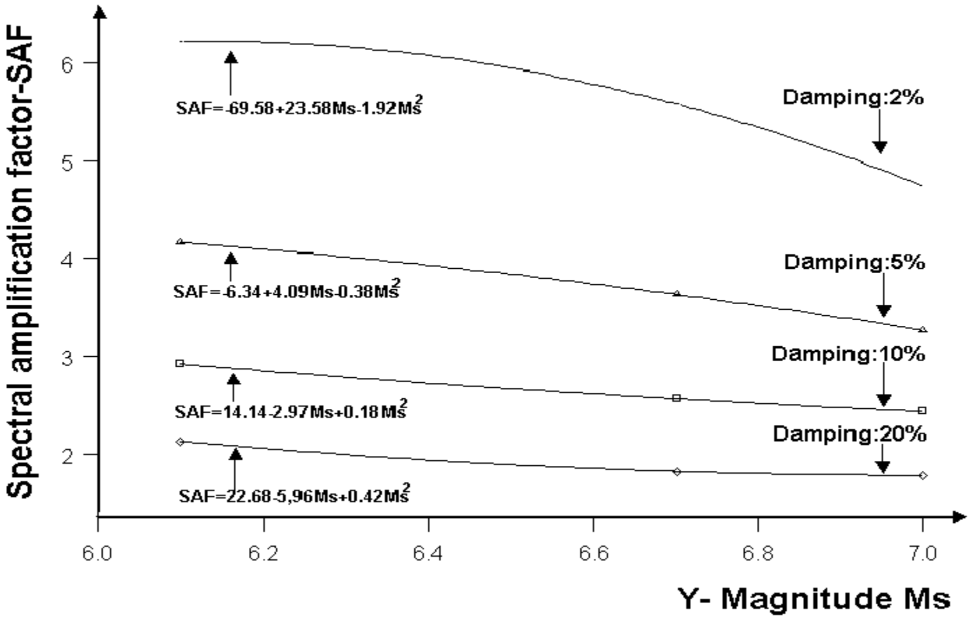


Fig. 3 – The dependence of the spectral amplification factors of strong Vrancea earthquake magnitude [5, 7].

3.2. DEPENDENCE OF SAF OF FREQUENCY

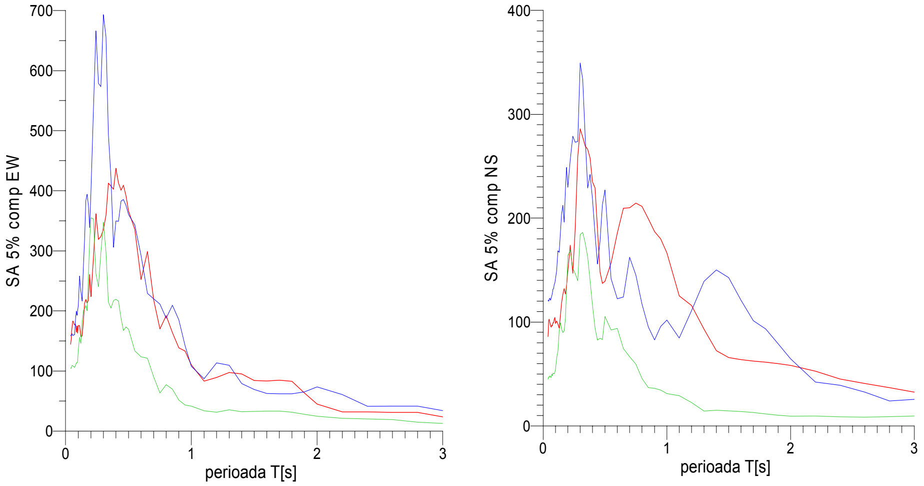
Table 7 presents the spectral amplification factors (FAS) for some intermediate depth earthquakes recorded in the epicenter area (Vrancioaia station), with unfiltered accelerations and filtered ones by using a low-pass filter (Gaussian) with cut-off frequencies of 1, 2, 5 and 10 Hz [2, 3, 7].

Table 7

The variation of SAF for some intermediate depth earthquakes recorded
in the epicenter area (Vrâncioaia)

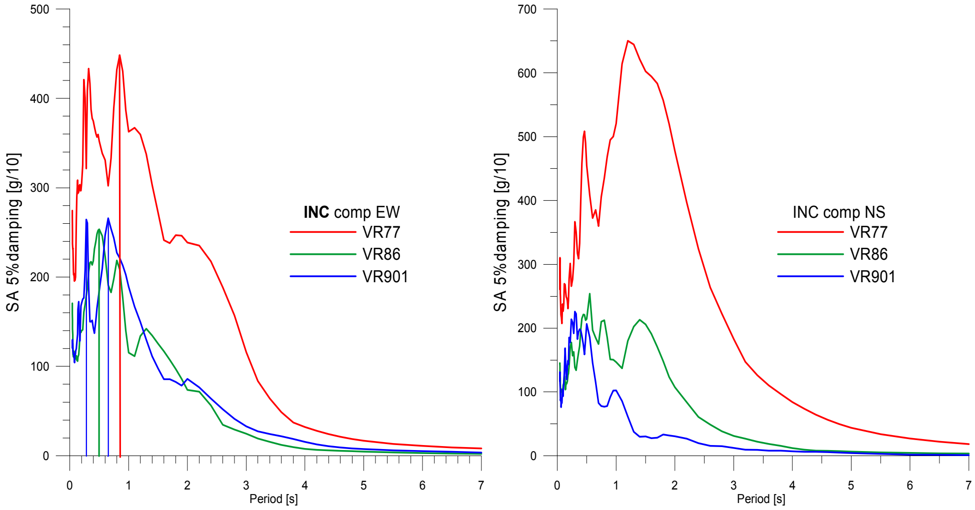
Vrancioaia station	M_W	unfiltered	1 Hz	2 Hz	5 Hz	10 Hz
August 30,1986	7.1	3.390	4.140	3.880	3.328	3.252
May 30,1990	6.9	4.190	3.899	4.096	4.359	3.541
May 31,1990	6.3	3.863	3.531	5.085	4.564	3.778
October 27,2004	6.0	3.992	3.980	6.012	4.897	3.801

The average SAF is 3.860 and can be considered as specific site. The apparent general tendency of decreasing the SAF when the earthquake magnitude increases is explained by the tendency of “saturation” of the accelerations when the magnitude is increasing which is observed for all stations located on sediments. This behavior seems not to be respected for the filtration of up to 1 Hz, due to seismic radiation directivity which is expressed not only in space but also in the frequency domain: *e.g.* May 31, 1990 recording where the maximum spectrum (Fourier) the NS component is in the range of up to 1 Hz while the EW component (maximum for this event) is in the range 1–3 Hz, as shown in Figs. 9a,b. Near-field seismic response is maximal, for short periods from 0.3 to 0.4 seconds (Figs. 9c, d), a situation that differs from that of the major remote sites, for example. Bucharest-140 km far of Vrancea epicenters.



a). Vrâncioia, E-W Component b). Vrâncioaia, N-S Component

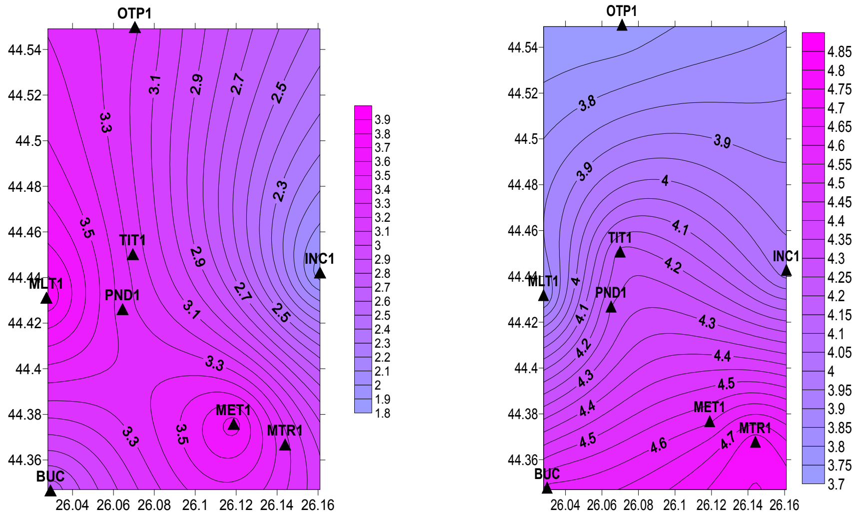
Figs. 9a,b – Accelations response spectra (β=5%) for records made at Vrâncioaia seismic station during: May 31,1990 (M_W=6.3) – green colour; May 30, 1990 (M_W=6.9) – blue colour and August 30,1986 (M_W=7.1) – red colour [2, 7] (see www.infim.ro/rrp).



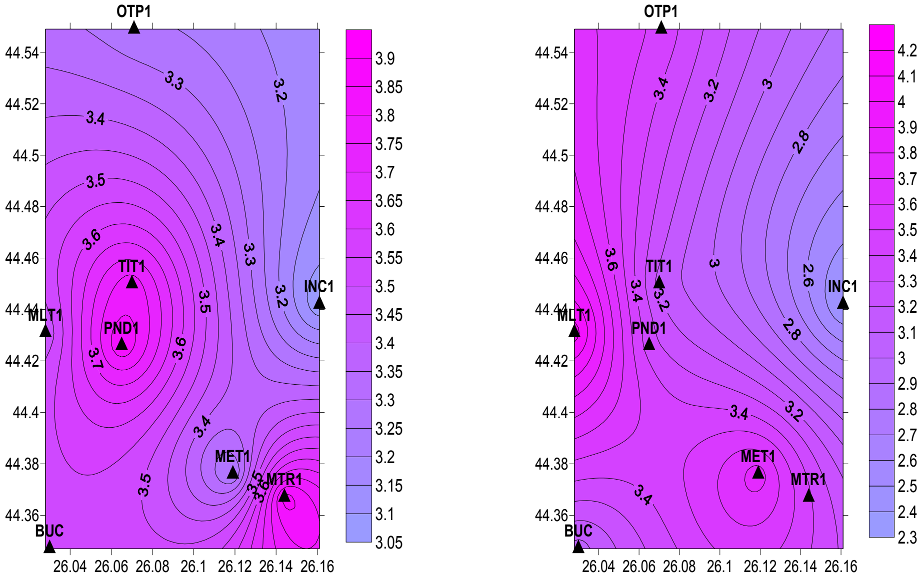
c) INCERC – E-W Component d) INCERC – N-S Component

Figs. 9c,d – Accelations response spectra (β=5%) for records made at Vrancioaia seismic station during :August 30,1986 (M_W=7.1) – green colour; May 31, 1990 (M_W=6.9) – blue colour and March 4,1977 (M_W=7.4) – red colour [2, 7] (see www.infim.ro/rrp).

The coincidence of SAF values for the filtered and unfiltered records up to 10Hz means that the main energy seismic events occur in this domain, at least for the Bucharest municipality. For each frequency range can be observed a certain stability range of values (1 Hz: 3.5 to 4.6; 2 Hz: 2.8 to 3.8) and can be used for rapid estimation of seismic response on a site (Figs.10 and 11).

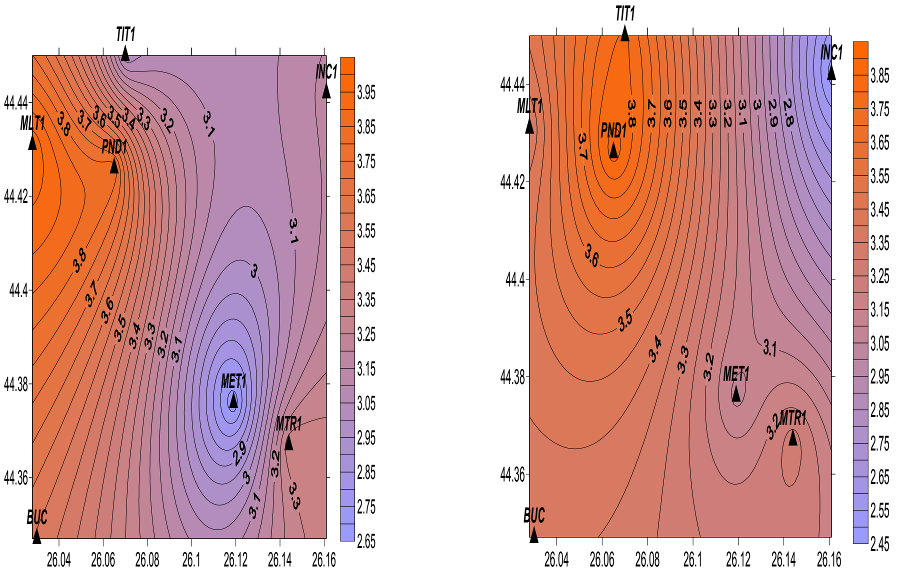


Unfiltered Otopeni Seismic Station (OTO1) **0.005-1.0 Hz**



0.05 - 2Hz OTOPENI Seismic station **0.05 - 5 Hz**

Fig. 10 – Spatial distribution of SAF in Bucharest during of August 30,1986 Vrancea earthquake (M_W=7.1) on different frequency domains (OTOPENI seismic station) [7].



0.05 - 2Hz TITAN 1 **0.05 - 5 Hz**

Fig.11 – Spatial distribution of SAF in Bucharest during of May 30, 1990 Vrancea earthquake (M_W =6.9) on different frequency domains (TITAN 1 seismic station) [7].

4. CONCLUDIND REMARKS

1. The significance of nonlinear-elastic soil response to strong earthquakes has long been a contentious matter. Soil sample behave nonlinearly in laboratory tests made on Hardin and Drnevich resonant columns at strains larger than 10^{-5} or 10^{-4}, a result that is standard in geotechnical research field. On the other hand, it is also routine in seismology to assume that soil amplification factors measured from weak motions apply to strong motions, *i.e.,* effects of nonlinearity are complete neglected;

2. The model of linear elastic response of the soils has been almost universally used by seismologists to model teleseismic, weak, and strong ground motions. Our opinion is that for teleseismic and weak ground motions, there is no reason to doubt that this model is acceptable, but for strong ground motions, particularly when recorded on thick Quaternary sediments, the consequences of nonlinear soil behavior have to be seriously considered;

3. The scope of this paper is to point out that the actual assessment of earthquake risk and the structural control of structures are incomplete without a nonlinear seismology to know the real state;

4. The spectral amplification factors (SAF) and, in fact, the nonlinearity, are function of earthquake magnitude (Fig. 3). There is a strong nonlinear dependence of the spectral amplification factors of earthquake magnitude and site conditions.

5. On the other hand, the seismological detection of the nonlinear site effects in deterministic/(neo)deterministic hazard analysis requires a simultaneous understanding of the effects of earthquake source, propagation path and local geological site conditions. The difficulty in demonstrating the nonlinearity has been due to the effect being overshadowed by the overall patterns of shock generation and propagation.

6. The spectral amplification factors decrease as the magnitude increase. This is consistent with Fig. 3 and data from Tables 1–7, which confirm that the ground accelerations tends to decrease as earthquake magnitude increase. As the excitation level increases, the response spectrum is larger for the linear case than that for the nonlinear one. This is consistent with SDF (*Single Degree of freedom*) theory (used here to introduce the concept of spectral amplification factor), since the peaks of the displacement seismograms in the linear and nonlinear cases are controlled by frequencies that are no amplified due to the nonlinearity;

7. The evidence of nonlinearity at least for thick Quaternary sediments is a systematic decrease in the variability of peak ground acceleration with increasing earthquake magnitude. The quantitative values put into evidence, based on real data from records made in Romania during last Vrancea strong earthquakes of the nonlinear effects have values between 13.46% and 45.57%;

8. We infer the conclusion that despite the fact that the seismic waves may be not characterized by critical values in the range of nonlinear effects, the specificity of major earthquakes in the Romanian Plain may induce important amplification due to nonlinear effects in the frame of directivity phenomena. We add the observation that since no third order nonlinear effects were considered, it may happen that the associated seismic risk should be increased, fact which will be subsequently analyses including also the refraction and reflection effects.

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