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NONLINEAR SEISMOLOGY A REALITY. THE QUANTITATIVE DATA*

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Motto: The *nonlinear* seismology is the rule,
The *linear* seismology is the exception !
Paraphrasing Tullio Levi-Civita…

Abstract. The central point of the discussion in last 10–15 years was whether soil amplification is function of earthquake magnitude. Laboratory tests made by using Hardin or Drnevich resonant columns consistently show the decreasing of dynamic torsion function (G) and increasing of torsion damping function (D%) with shear strains (γ) induced by deep strong Vrancea earthquakes; $G = G(\gamma)$, 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". The difficulty to seismologists in demonstrating the nonlinear site effects has been due to the effect being overshadowed by the overall patterns of shock generation and propagation. 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 authors, in order to make evidence of nonlinear effects, introduced the spectral amplification factor (SAF) as ratio between maximum spectral absolute acceleration (Sa), 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 Bucharest and extra-Carpathian area is given by a systematic relative decrease in the variability of peak ground acceleration with the increasing earthquake magnitude. The researches made in this paper show that using real spectral amplification factors, amplifications showing local effects, have values which differ totally from those of crustal earthquake from USA, Europe, Asia etc.

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

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1. INTRODUCTION

Most cities and villages are located on alluvial deposits/sediments, on Quaternary layers in river valleys [8]. The central question of the discussion is whether soil amplification is amplitude dependent. The dependence of soil response on strain amplitude become a standard assumption in the geotechnical field and engineering seismology.

From the geological point of view, Bucharest City is located in the central part of the Moesia Platform in the Romanian Plain [8], at about 140 km far from Vrancea area. Above a Cretaceous and a Miocene deposit (with the bottom at roundly 1,400 m of depth), a Pliocene shallow water deposit (~ 700m thick) was settled (Fig. 1). The surface geology consists mainly of Quaternary alluvial deposits.

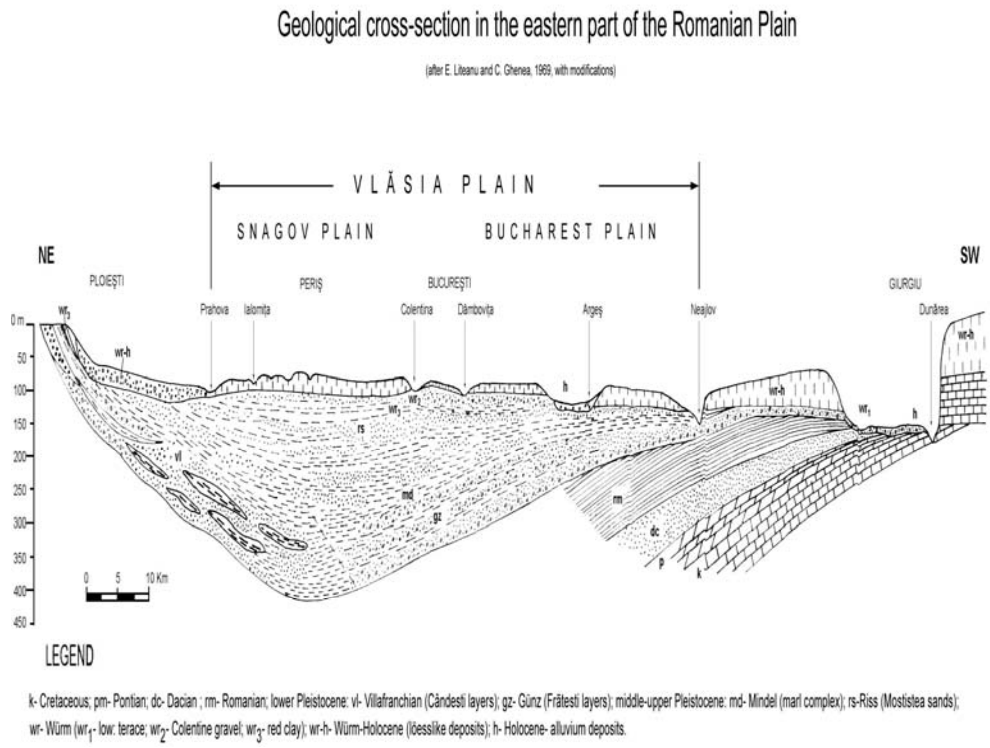

Fig. 1 – Geological cross-section in the eastern part of the Romanian Plain (NE - SW) (Vrancea-Ploiesti-Bucharest- Giurgiu-Danube river).

On the other part, in 1996, it was the question: Nonlinear Soil Response – A Reality? [2]. The difficulty to seismologists in demonstrating the nonlinear site effects has been due to the effect being overshadowed by the overall patterns of shock generation and propagation.

Laboratory tests developed in Engineering Seismology Laboratory from NIEP by using resonant columns Hardin and Drnevich consistently show the decreasing of dynamic torsion function (*G*,daN/cm^2) and increasing of torsion damping function (*D*%) with shear strains (γ) induced by deep strong Vrancea earthquakes; $G = G(\gamma)$, respectively, $D\% = D(\gamma)\%$ reduction in shear modulus (*G*) and increase in damping ratio (*D*) with increasing shear strain (γ), *i.e.*, $G = G(\gamma)$, respectively, $D\% = D(\gamma)\%$ (Fig. 1).

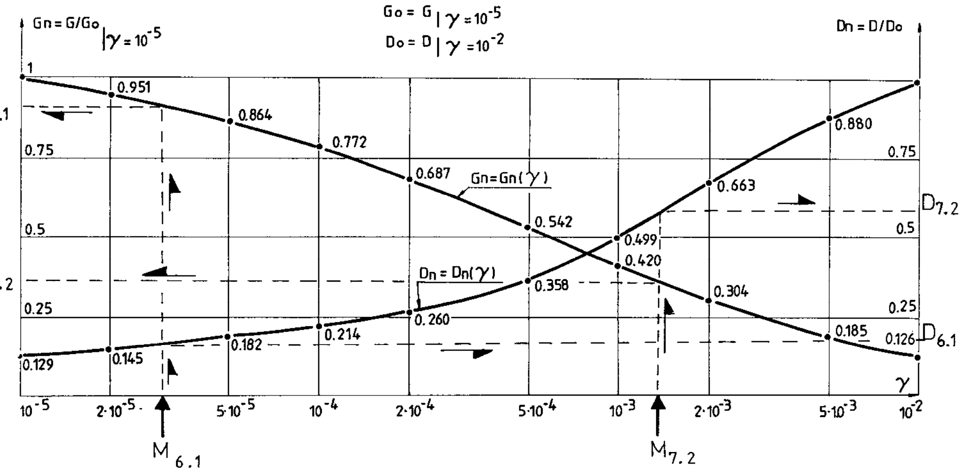

Fig. 2 – Normalized curves for sand with gravel from NIEP resonant columns [7].

For smaller earthquakes, the strains are smaller and we are in the left-hand side of Fig. 2: for strong earthquakes, the strains are larger and we are in the right-hand side of Fig. 2. 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:

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

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 main ground motion equation, ground displacement *u*(*t*) has general form:

$$u(t) = s(t)*g(t)*i(t),$$

where: $s(t)$ = source function, $g(t)$ = propagation function and, $i(t)$ = instrument recording function.

Modern seismology strives to describe mathematically each of the filters contributing to the observed displacements and seismological research efforts classically bifurcate in two major categories: (i) – studying the source terms and their associated phenomena, and, (ii) – studying propagation terms and the associated Earth structure.

The nature of elasticity allows us to treat mathematically the process of excitation, propagation, and recording of seismic waves as a sequence of linear filters that combine to produce observed seismograms. On the other hand, the difficulty to seismologists in demonstrating the nonlinear site effects has been due to the effect being overshadowed by the overall patterns of shock generation and propagation. 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.

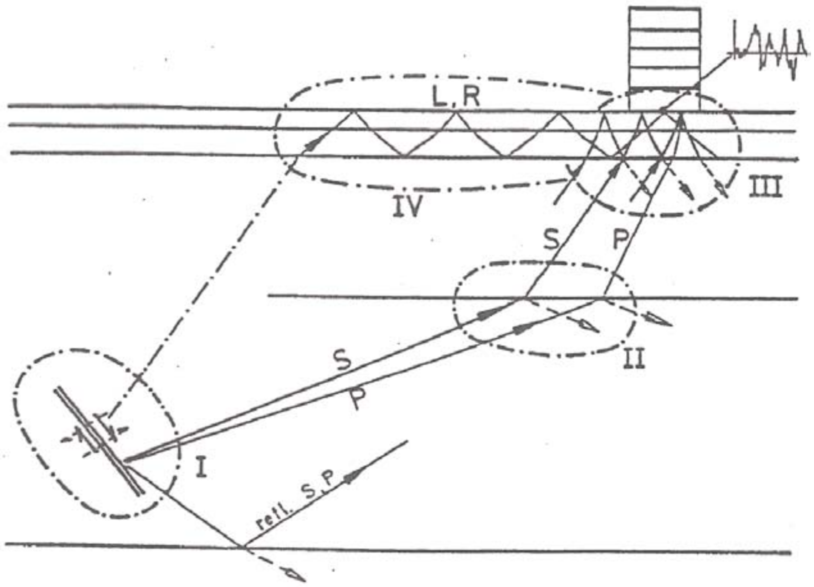

Fig. 3 – The ways of seismic waves from source to free field.

Let's see the actual data from records made during of last strong and deep Vrancea earthquakes, that are: March 4, 1977 (M_W = 7.4; h = 109 km); August 30,1086 (M_W= 7.1; h = 131 km), May 30, 1990 (M_W= 6.9; h = 79 km) and May 31, 1990 (M_W= 6.4, h = 90 km).

2. RECORDED DATA ON SEISMIC STATIONS FROM EXTRA-CARPATHIAN AREA

In order to find the quantitative characteristics of the nonlinear soil behavior and nonlinear site response, the authors [4–7] introduced so-called „the spectral (seismic) amplification factor" (SAF) as ratio between maximum spectral absolute acceleration (*Sa*), relative velocity (*Sv*), relative displacement (*Sd*) and peak values of acceleration (a_{max}), velocity (v_{max}) and displacement (d_{max}), respectively, from processed strong motion record). The theoretical support to spectral amplification factor approach is given in [7].

The concept was used by us for last *STRESS TEST* asked by IAEA Vienna for Romanian Cernavoda Nuclear Power Plant after strong Japan earthquake on March 11, 2011 (M_W = 9,0). In Tables 1–19 are given the nonlinear effects function of Vrancea earthquake magnitude and site of seismic stations locations from Bucharest and other cities from extra-Carpathian area, that is, from Iasi to Craiova, records obtained by NIEP and INCERC Bucharest [3, 5]. In Tables 1–19 are given spectral amplification factors (SAF) for absolute accelerations at 5% fraction of critical damping (β = 5%) at 18 seismic stations 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 = 6.4).

Table 1

Bucharest-INCERC Seismic Station (E-W Comp.): Φ^0 = 44.442; λ^0 = 26.105

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	*c*	$S_a^*(g)$ (**β**=5%)	a^*	%
04.03,1977	188,4	440cm/s^2	2.33	1,214	1025.2	228.7	**21.4%**
08.30,1986	109.1	249cm/s^2	2.28	1.241	309.0	135.4	**24.1%**
05.30,1990	98,9	280cm/s^2	2.83	**1.000**	280.0	98.9	**-**

Table 2

Bucharest-INCERC Seismic Station (N-S Comp.): Φ^0 = 44.442; λ^0 = 26.105

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	*c*	$S_a^*(g)$ (**β**=5%)	a^*	%
04.03,1977	206,9	650cm/s^2	3.14	1,322	859.3	273.5	**32.2%**
08.30,1986	96.96	255cm/s^2	2.62	1.583	403.6	153.4	**58.3%**
05.30,1990	66,21	275cm/s^2	4.15	**1.000**	275.0	66.2	**-**

Table 3

Bucharest-Balta Albă Seismic Station (E-W Comp.): Φ^0 = 44.413; λ^0 = 26.169

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	*c*	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	89.08	345cm/s^2	3.87	1,217	419.86	104.41	**21.7%**
05.30,1990	63.13	270cm/s^2	4.27	1.103	297.81	69.63	**10.3%**
05.31,1990	15.90	75cm/s^2	4.71	**1.000**	75.00	15.90	**-**

Table 4

Bucharest-Bolintinu Vale Seismic Station (N155E Comp.): $\Phi^0 = 44.444$; $\lambda^0 = 25.757$

Earthquake	a_{max} (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	83.7 cm/s^2	295cm/s^2	3.52	1,235	364.3	103.3	**23.5%**
05.30,1990	215.0cm/s^2	800cm/s^2	3.72	1.169	935,2	251.3	**16.9%**
05.31,1990	35.6 cm/s^2	155cm/s^2	4.35	**1.000**	155.0	35.60	-

Table 5

Bucharest-Brăneşti Seismic Station (N107W Comp.): $\Phi^0 = 44.460$; $\lambda^0 = 26.329$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	89.08	345cm/s^2	3.87	1,217	419.86	104.4	**21.7%**
05.30,1990	63.13	270cm/s^2	4.27	1.103	297.81	69.6	**10.3%**
05.31,1990	15.90	75cm/s^2	4.71	**1.000**	75.00	15.9	-

Table 6

Bucharest-Metalurgiei Seismic Station (N127W Comp.): $\Phi^0 = 44.376$; $\lambda^0 = 26.119$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	71.07	220cm/s^2	3.06	1,483	326.26	105,39	**48.3%**
05.30,1990	55.40	220cm/s^2	3.97	1.143	251.46	63,32	**14.3%**
05.31,1990	12.10	55cm/s^2	4.54	**1.000**	55.00	12.10	-

Table 7

Bucharest-Panduri Seismic Station (N131E Component): $\Phi^0 = 44.426$; $\lambda^0 = 26.065$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	89.4	295cm/s^2	3.29	1,513	446.33	135.26	**51.3%**
05.30,1990	131.3	590cm/s^2	4.49	1.109	654.31	145.61	**10.9%**
05.31,1990	33.0	160cm/s^2	4.98	**1.000**	160.00	33.00	-

Table 8

Bucharest-Titulescu Seismic Station (N145W Component): $\Phi^0 = 44.452$; $\lambda^0 = 26.080$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (**β**=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (**β**=5%)	a^*	%
08.30,1986	87.54	395cm/s^2	4.51	1,142	451.09	99.97	**14.2%**
05.30,1990	56.80	210cm/s^2	3.69	1.395	292,95	78.91	**39.5%**
05.31,1990	10.67	55cm/s^2	5.15	**1.000**	55.00	10.67	-

Table 9

Bucharest-Carlton Seismic Station (N75E Comp.): $\Phi^0 = 44.436$; $\lambda^0 = 26.102$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	79.60	240cm/s^2	3.015	1,276	306.24	101.64	**27.6%**
05.30,1990	114.7	305cm/s^2	2.659	1.447	210.78	165.97	**44.7%**
05.31,1990	19.48	75cm/s^2	3.850	**1.000**	75.00	19.48	-

Table 10

Galați-IPJ (GLT2) Seismic Station (N97WE Comp.): $\Phi^0 = 45.430$; $\lambda^0 = 28.058$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	69.10	220cm/s^2	3.183	1,334	293.48	92.17	**33.4%**
05.30,1990	74.23	250cm/s^2	3.368	1.260	315.00	93.53	**26.0%**
05.31,1990	47.11	200cm/s^2	4.245	**1.000**	200.00	47.11	-

Table 11

Iaşi-Centru (IAS2) Seismic Station (N-S Comp.): $\Phi^0 = 47.160$; $\lambda^0 = 27.570$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	64.10	190cm/s^2	2.964	1.363	563.16	87.36	**36.3%**
05.30,1990	109.5	390cm/s^2	3.561	1.135	442.65	124.28	**13.5%**
05.31,1990	45.76	185cm/s^2	4.042	**1.000**	185.00	45.76	-

Table 12

Iaşi-Copou (IAS2) Seismic Station (N-S Comp.): $\Phi^0 = 47.193$; $\lambda^0 = 27.562$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	68.18	225cm/s^2	3.300	1.293	290.92	88.15	**29.3%**
05.30,1990	97.22	395cm/s^2	4.063	1.050	414.75	102,08	**13.5%**
05.31,1990	49.44	211cm/s^2	4.267	**1.000**	211.00	49.44	-

Table 13

Bucharest-Măgurele Seismic Station (E-W Comp.): $\Phi^0 = 47.347$; $\lambda^0 = 26.030$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	***c***	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	113.8	307cm/s^2	2.6982	1.329	408.6	151.46	**32.9%**
05.30,1990	90.25	324cm/s^2	3.5869	**1.000**	324.0	90.25	-

Table 14

Ploieşti-(PLS) Seismic Station (N100E Comp.): $\Phi^0 = 44.930$; $\lambda^0 = 26.020$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	**c**	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	207.2	730cm/s^2	3.523	1.124	820.5	232.89	**12.4%**
05.30,1990	72.6	235cm/s^2	3.236	1.224	287.6	88.86	**22.4%**
05.31,1990	16.4	65cm/s^2	3.963	**1.000**	65.00	16.40	-

Table 15

Vaslui-(VLS1) Seismic Station (N100E Comp.): $\Phi^0 = 46.637$; $\lambda^0 = 27.733$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	**c**	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	171.3	550cm/s^2	3.210	1.275	701.25	218.40	**27.5%**
05.30,1990	130.0	440cm/s^2	3.236	1.209	531.91	157.17	**20.9%**
05.31,1990	51.3	210cm/s^2	4.094	**1.000**	210.00	51.30	–

Table 16

Bacău-(BAC2) Seismic Station (E-W Comp.): $\Phi^0 = 46.567$; $\lambda^0 = 26.900$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	**c**	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	72.20	292cm/s^2	4.0443	1.457	425.44	105.19	**45.7%**
05.30,1990	132.43	684cm/s^2	5.1649	1.141	780.44	151.10	**24.1%**
05.31,1990	63.07	372cm/s^2	5.8942	**1.000**	372.00	63.07	-

Table 17

Cernavoda -(CVD2) Seismic Station (E-W Comp.): $\Phi^0 = 44.340$; $\lambda^0 = 28.030$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	**c**	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	62.78	256cm/s^2	4.0777	1.420	363.52	89.14	**42.0%**
05.30,1990	100.06	475cm/s^2	4.7471	1.219	579.02	121.97	**21.9%**
05.31,1990	49.73	288cm/s^2	5.7912	**1.000**	288.00	49.73	-

Table 18

Craiova-(CRV) Seismic Station (N05E Comp.): $\Phi^0 = 47.321$; $\lambda^0 = 23.798$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	**c**	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	140.7	690cm/s^2	4.9040	1.1435	789.01	160.89	**14.4%**
05.30,1990	62.41	350cm/s^2	5.6080	**1.000**	350.00	62.41	-

Table 19

Râmnicu Sărat -(RMS2) Seismic Station (N55E Comp.): $\Phi^0 = 45.380$; $\lambda^0 = 27.040$

Earthquake	a_{max}(cm/s^2) (recorded)	S_a^{max} (β=5%)	S_a^{max}/a_{max} (SAF)	*c*	$S_a^*(g)$ (β=5%)	a^*	%
08.30,1986	140.3	400cm/s^2	2.8510	1.215	486.0	170.46	**21.5%**
05.31,1990	66.4	230cm/s^2	3.4638	**1.000**	230.0	66.40	-

At the same seismic station, for example at Bucharest-Panduri Seismic Station (Table 7), horizontal components and **β**=5% damping, the values of the SAF for accelerations are: **3.29** for August 30, 1986 Vrancea earthquake (M_W= 7.1); **4.49** for May 30, 1990 (M_W= 6.9) and **4.98** for May 31, 1990 (M_W = 6.4). Vrancea earthquake on May 31, 1990 (M_W= 6.4) could be assumed that the response is still in elastic domain and then we have the possibility to compare to it.

A characteristic of the nonlinearity is a systematic decrease in the variability of peak ground acceleration with the increasing earthquake magnitude. Spectral amplification factor decrease from **4.98** for Vrancea earthquake with magnitude M_W= 6.4 to **3.29** for Vrancea strong earthquake with magnitude M_W= 7.1 (Table 7, damping **β=5%**). The amplification factors decrease as the magnitude of earthquake increase. The ground accelerations tends to decrease as Vrancea earthquake magnitude increase. For example, if we maintain the same amplification factor (SAF=**4.98**) as for relatively strong earthquake on May 31, 1990 with magnitude M_W = 6,4 then at Bucharest-Panduri Seismic Station for earthquake on May 30, 1990 (M_W = 6.9) the peak acceleration has to be a^*_{max}=**145.61** cm/s^2 **(+10.9%)** and the recorded value was only, a_{max}=**131.3** cm/s^2. Also, for Vrancea earthquake on August 30, 1986 (M_W= 7.1), the peak acceleration has to be a^*_{max}=**135.26** cm/s^2**(** that is, **+51.3%)** instead of ***real value*** of **89.4** cm/s^2 recorded at Panduri-Bucharest Seismic Station during of last strong earthquake on August 30,1986 earthquake with magnitude M_W = 7.1 (Table 7). In fact, the recorded acceleration from strong Vrancea on August 30, 1986 with magnitude M_W = 7.1 is smaller with **51.3%** that has to be if the soil would have a linear response.

3. SPECTRAL AMPLIFICATION FACTORS AS COMPARED TO REGULATORY GUIDE 1.60-USA & IAEA Safety Series No. 5-SG-S1

The recorded ground accelerations and the response spectra of past earthquakes provide a basis for the rational design for example of NPP structures to resist to large earthquakes. A calculated response spectrum is not the same as a specified standard/design spectrum (Fig. 4).

Design response spectra are a relatively smooth relation obtained by analyzing, evaluating and statistically combining a number of individual response spectra derived from the of significant past earthquakes or from a ground acceleration process generation. This standard/design response spectrum is scaled up to the value of ground acceleration, velocity and displacement specific to each site by using so called ***spectral amplification factors*** (Table 20) [9]. These idealized spectrum curves to be used as ***design spectrum*** curves (Housner, 1959, U.S., Atomic Energy Commission, 1963) are given in Fig. 8, curves accepted by IAEA Vienna (Safety Series No.5-SG-S1).

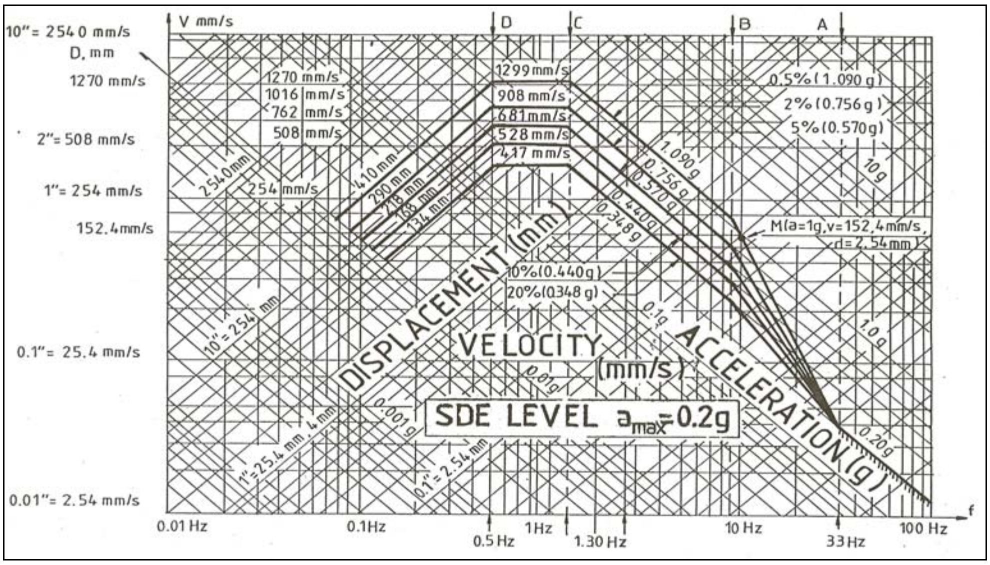

Fig. 4 – Design spectra for irradiator nuclear installation from “Horia Hulubei” National Institute of Physics and Nuclear Engineering (IFIN-HH) from Măgurele-Bucharest for SDE level with a_{max} = 0.2g [7].

Values of spectrum amplification factors for control points: A, B, C, D (Fig. 4) [9] are given in Table 20, values given by Regulatory Guide 1.69 of the U. S. Atomic Energy Commission and accepted by IAEA Vienna.

Table 20

Spectral amplification factors (SAF) given by RG 1.60 from USA and IAEA Vienna

Percent of critical damping **β**(%)	Amplification factors for control points (Fig. 20)			
	Acceleration			Displacement
	A(33 Hz)	**B**(9 Hz)	**C**(2.5 Hz)	**D**(0.25 Hz)
0.5%	1.0	4.96	5.95	3.20
2.0%	1.0	3.54	4.25	2.50
5.0%	1.0	**2.61**	**3.13**	2.05
7.0%	1.0	2.27	2.72	1.88
10.0%	1.0	1.90	2.28	1.70

4. CONCLUSIONS

1. The significance of nonlinear-elastic soil response to strong earthquakes has long been a contentious matter. On the one hand, soil samples 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 central question of the discussion is whether soil amplification is function of earthquake amplitude dependent. The dependence of soil response on strain amplitude become a standard assumption in the geotechnical field and in earthquake and engineering seismology;

3. With a view to understand the characteristics of nonlinear soil behavior and the nonlinearity in the seismology, this study examines the ways that nonlinearity would expected to appear on strong motion records made on Romania territory during to last Vrancea earthquakes. In order to find the quantitative characteristics of the nonlinear soil behavior and nonlinear site response, authors introduced so-called „the spectral (seismic) amplification factors which are defined as the ratio between maximum spectral values of absolute acceleration (S_a), relative velocity (S_v) and displacement (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 strong motion records for the same seismic station processing;

4. From Tables 1–19 we can see that there is a strong nonlinear dependence of the spectral amplification factors (SAF) for absolute accelerations on earthquake magnitude for all records made on extra-Carpathian area from Iasi to Craiova for last strong Vrancea earthquakes;

5. The amplification factors decrease as the strength increase. This is consistent with data from Tables 1 to 19, 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 the one degree of freedom oscillator theory [7], since the peaks of the displacement seismograms in the linear and nonlinear cases are controlled by frequencies that are not amplified due to the nonlinearity;

6. The amplification factors decrease with increasing the magnitudes of deep strong Vrancea earthquakes and this values are far of that given by Regulatory Guide 1.60 of the U. S. Atomic Energy Commission;

7. The new research direction developed by NIEP and other scientists from World has and will have a large scientific impact in this XXI Century and "it will open up a new challenge for seismologists studying nonlinear site effects in 2-D and 3-D irregular geological structures, leading them to a fascinating research subject in ***nonlinear physics***" [1].

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REFERENCES

1. A. Aki, *Local Site Effects on Weak and Strong Ground Motion*, Tectonophysics, **218**, 93–111 (1993).
2. I.A.Beresnev, Kuo-Liang Wen, *Nonlinear soil response –A reality*? Bulletin of the Seismological Society of America, **86**, *6*, pp. 1964–1978.
3. I.S.Borcia, *Procesarea înregistrărilor mişcărilor seismice vrâncene puternice*, Edit. Soc. Academice "Matei-Teiu Botez", 2008.
4. C.O. Cioflan, A. Mărmureanu, Gh. Marmureanu, *The quantitative evidence of the soil nonlinear behavior during of strong Vrancea earthquakes in real/nonlinear seismology*, Romanian Reports in Physics, **63**, *3*, pp. 839–851 (2011).
5. Gh. Marmureanu, E. Cojocaru, C. Moldoveanu, *The strong Vrancea earthquakes and the dynamic (spectral) amplification factors*, in Revue Roumaine des Sciences Techniques, série Mécanique Appliquée, Romanian Academy Publishing House, **40**, *2–3*, 293–315 (1995).
6. Gh. Mărmureanu, M. Mişicu, C.O. Cioflan, F.S. Bălan, *Nonlinear Seismology - The Seismology of the XXI Century*, Lecture Notes of Earth Sciences, Perspective in Modern Seismology, Vol. 105, Springer Verlag, 2005, pp. 47–67.
7. Gh. Marmureanu, C.O. Cioflan, A. Marmureanu, *Researches on local seismic Hazard (microzonation) of Bucharest metropolitan area. Microzoning maps for accelations, fundamental periods and intensities for maximum Vrancea earthquake magnitude of 7.5 on Richter scale* (in Romanian), Tehnopress, Iasi, 2010.
8. Trendafiloski, G., Wyss, M., Rosset, Ph., Mărmureanu, Gh., *Constructing city models to estimate losses due to earthquakes worldwide: Application to Bucharest Romania*, Earthquake Spectra, **25**, *3*, 665–685 (2009).
9. *** U.S. Atomic Commission, *Regulatory Guide 1.60*: *Design Response Spectra for Seismic Design of Nuclear Power Plants*, 1973.