The response of any physical system is nonlinear unless the magnitude of the input is very small. The $M_w$ magnitudes of deep Vrancea earthquakes are between 0.02 and 7.9. The leading question is: how many cities, villages, metropolitan areas etc. in seismic regions are constructed on rock sites? Most of them are located on alluvial deposits, on Quaternary layers or in river valleys. A soil is of basic type sand or gravel (termed coarse soils), silt or clay (termed fine soils) etc. Strong ground accelerations from large and deep Vrancea earthquakes can produce a non-linear response in shallow soils and the shaking from large earthquakes cannot be predicted by simple scaling of records from small earthquakes [12]. The question: is that real and how much? Laboratory tests indicate that as the strain increases above $10^{-4}$%, damping (absorption) increases and the shear modulus (rigidity) decreases. This should results in two observable effects as the level of ground motion at a soil site increases; a decrease in amplification due to the increase in damping and a lowering of the site response frequency as the shear modulus decreases. The novelty and the complexity degree comes from the fact that for first time, the final decision for NPP Cernavoda site, in 2012, was also based on local strong nonlinear spectral amplifications for strong earthquakes and used in last „STRESS TEST“ asked by IAEA Vienna in 2011. The present analysis indicates that the effects of soil nonlinearity could be very important in seismology, in seismic hazard analyses and earthquake engineering. The authors are coming with many recorded data which 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 realistic research subject in earth physics, in nonlinear seismology [1].

Key words: Nonlinear seismology, spectral amplification factors, nonlinear soil behavior, nonlinear elastic model, nonlinear viscoelastic model.

1. INTRODUCTION

The behavior of many materials under an applied load may be approximated by specifying a relationship between the applied load or stress and the resultant

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1 The paper was presented at European Geophysical Union (EGU), Natural Hazards (NH4)/SM2-Earthquake Hazards, April 07-12, 2013, Vienna.

deformation or strain. The first constitutive equation (law) was developed by Robert Hooke (≈ 1660) and it is known as Hooke’s law and it deals with the case of linear elastic materials like steel etc. As is extension, so is force... (*Ut tensio, sic vis*!), that is, \( \sigma = E \varepsilon \), where \( E \) and \( \varepsilon \) are experimentally determined. How many cities, villages, metropolitan areas etc. in seismic regions are sited on rock sites? Most of them are located on alluvial deposits, on Quaternary layers or in river valleys. A soil is of basic type sand or gravel (termed coarse soils), silt or clay (termed fine soils) etc.

Large ground accelerations from strong and deep Vrancea earthquake can produce a non-linear response in shallow soils and the shaking from large earthquakes cannot be predicted by simple scaling of records from small earthquakes [10, 12]. The question: is that real and how much? Currently, there are not constitutive laws to describe all real mechanical behaviors of deformable materials like soils. From mechanical behavior point of view there are two main groups of main importance: sands and clays. If the soil have a nonlinear behavior during of strong earthquake, then the seismology and the physics of earthquakes can’t be linear one. In all extra-Carpathian area (Fig.7) the geophysical profile composition passes from clay to sandy clays or sands, from marl to sandy marl or sand lenses etc. The sedimentary cover, relatively thick (exceeding 5,000 m), is the result of four major cycles of sedimentation: (i)-Paleozoic; (ii)-Permian-Triassic; (iii)-Jurassic-Cretaceous and (iv)-Upper Miocene-Quaternary. For example, in south of Bucharest (Fig. 1) there are layers of 400 m of dense sand and in the north the thickness of all sedimentary layers are around 1,480 m [7].

![Fig. 1 - The geological structure under Bucharest. Isobars are generally oriented East-West with slope of 8‰ down from South to North. In the same direction, the thickness of layers becomes larger [6, 8]. Boreholes 172 and 170 data for Carlton and Titulescu seismic stations, Bucharest (Table 2).](image-url)
2. NONLINEAR SOIL BEHAVIOR. LABORATORY DATA

Laboratory tests developed by National Institute for Earth Physics from Bucharest by using Hardin and Drnevich resonant columns (USA patent) consistently show the variation of dynamic torsion modulus function \((G, \text{daN/cm}^2)\) and torsion damping function \((G\%)\) of specific strain \((\gamma\%)\). There is a large reduction in shear modulus \((G)\) and increase in damping ratio \((D)\) with increasing shear strain \((\gamma)\), i.e, \(G = G(\gamma\%)\), respectively, \(D[\%] = D(\gamma\%)\), therefore linear/nonlinear viscoelastic constitutive laws are required (Fig. 3–5) and soil response is nonlinear above \(10^{-4}\%\) of specific shear strain \([5]\). This should results in two observable effects as the level of ground motion at a soil site increases; a decrease in amplification due to the increase in damping and a lowering of the site response frequency as the shear modulus decreases. The later occurs as seismic shear wave velocity decreases when the shear modulus decreases (Figures 3-6).

From mechanical behavior point of view there are two main groups of main importance: sands and clays. These soils, although have many common mechanical properties require the use of different models to describe behavior difference. Soils are simple materials with memory: sands are „rate-independent” type and clays are „rate-dependent” one, names used in mechanical deformable bodies.

Sands typically have low rheological properties and can be modeled with an acceptable nonlinear elastic model and clays which frequently presents significant changes over time can be modeled by a nonlinear viscoelastic model. Viscoelastic material behavior could be characterized using Boltzmann’s formulation of the constitutive law \([2, 9]\). Theory of viscoelasticity is approaching completion… Boltzmann’s formulation of the constitutive relation between stress and strain as expressed by the convolution integrals (1) & (2) is general in the sense that all linear behavior may be characterized by such a relation. Conversely, if the response is characterized by one of the convolution integrals then the Boltzmann’s superposition principle is valid:

\[
p(t) = \int_{-\infty}^{t} r(t-\tau) \, de \, (\tau) \tag{1}
\]

where \(p(t)\) denotes stress or force per unit area as a function of time, \(e(t)\) denotes strain or displacement per unit displacement as a function of time, and \(r(\tau)\), termed a relaxation function, is causal and does not depend on spatial coordinate. The physical principle of causality imposed on the relaxation function \(r(t)\) implies the function is zero for negative time, hence the constitutive relation may be written using a Riemann-Stieltjes integral as

\[
p(t) = \int_{-\infty}^{\infty} r(t-\tau) \, dp \, (\tau) \tag{2}
\]

or more compactly in terms of a convolution operator as \(p = r*de\).
A corresponding constitutive equation relating stress to strain is one defined mathematically for which a causal spatially independent function \( c(t) \), termed a *creep function*, exists such that the corresponding strain time history may be inferred from the following convolution integral

\[
e(t) = \int_{-\infty}^{\infty} c(t-\tau) \, dp(\tau)
\]

or compactly in terms of the convolution operator as \( e = c*dp \).

If the material (soil) response is characterized by one of the convolution integrals (2 or 3) then Boltzmann’s superposition principle is valid and this could be applied to sand soils.

Clays typically have large rheological properties and frequently present significant changes over time and then can be modeled by a *nonlinear viscoelastic model*.

Displacement vector \( \mathbf{u} \), the tensors \( \mathbf{T} \) & \( \mathbf{E} \) for tension and strain, in case of nonlinear viscoelastic materials, are function of position \( \mathbf{x} \) and time \( t \), functions that define the *viscoelastic body state*. For a given time and set \( t = ct \) these functions will define a state elastic body. The reduction of viscoelastic states to elastic states is observed experimentally in samples of clay behaviour subjected to a tri-axial creep tests [4]; the isochronous \( \sigma(\epsilon) = \sigma(\epsilon, t) | t=ct \) or \( \tau(\gamma) = \tau(\gamma, t) | t=ct \) being tension-strain curves which can be modelled with a linear elastic model. The model presented here is based on reducing viscoelastic states to elastic states and the nonlinear relaxation functions \( K=K(\epsilon, t) \) and \( G=G(\gamma, t) \) functions are reduced to nonlinear elastic modulus functions, \( K = K(\epsilon) \) and \( G = G(\gamma) \) [4].

Relaxation functions of the nonlinear viscoelastic soil along the time variable \( t \) should contain as arguments the strain tensor invariants, \( K = K(\epsilon, t) \) and \( G = G(\gamma, t) \). Under these conditions the nonlinear viscoelastic constitutive equations for soils take form [2]:

\[
\tau(t) = \int_{0}^{t} G(\gamma, t-\gamma) \, \gamma'(s) \, ds \quad \text{and} \quad \sigma(t) = \int_{0}^{t} K(\epsilon, t-\epsilon) \, \epsilon'(s) \, ds
\]

in these constitutive equations: \( K(\epsilon, t) \) and \( G(\gamma, t) \) are the nonlinear relaxation functions and we can accept a strain-history of form (*harmonic & stationary*) used in resonant columns (Figure 2) (3,7,10,11):

\[
\epsilon(t) = \epsilon_0.\exp(-i\omega t); \quad \gamma(t) = \gamma_0.\exp(-i\omega t)
\]
How long time will we go with linear seismology?

5 How long time will we go with linear seismology?

6 In engineering applications we are interested in the soil behavior to earthquake dangerous frequencies, that are between 0.1 and 10 Hz (Figure 6). In Figure 6 we have the dependence of dynamic torsion modulus function (G, daN/cm²) and torsion damping function (D%) with shear strains (γ%) and frequency (ω) from Hardin & Drnevich resonant columns. Both are constant for frequencies between 1.00 Hz and 10 Hz, exactly the main domain used in civil engineering and all of them are function only of shear strains (γ%) [4, 9]. Then, in this domain we can consider Gk and Dk to be constant in relation to frequency and will depend only of shear strain γ%. The dynamic functions are [7, 10, 11]:

\[
G(\gamma) = \sum_{k=0,1,2} G_k (-\gamma)^k \quad \text{and} \quad D(\gamma) = 1/ \sum_{k=0,1,2} D_k (-\gamma)^k ; k = 0,1,2
\]

where G(γ) and D(γ) are volume, respective shape modulus functions, in shape "tangent" and all of them are functions of shear strains (γ%) developed during of strong earthquake. In final, from experimental data got by using Hardin and Drnevich resonant columns from NIEP (Figures 6-6), there are the following variations of dynamic torsion modulus functions (G, daN/cm²) and torsion damping functions (D%) of specific strains (γ%) induced by strong Vrancea earthquakes [7, 8, 10, 11] for:

- **Sand with gravel**:
  \[G_n = 0.344 + 0.656 / (1 + 14.651 \cdot \gamma \exp 0.716); D_n = 1.428 - 1.212 / (1 + 2.43 \cdot \gamma \exp 0.682);\]

- **Loess**:
  \[G = 0.107 + 0.903 / (1 + 13.12 \cdot \gamma \exp 0.682); D_n = 1.556 - 1367 / (1 + 1.780 \cdot \gamma \exp 0.655);\]

- **Diluvian clay**:
  \[G_n = 0.176 + 0.824 / (1 + 27.357 \cdot \gamma \exp 0.986); D_n = 1.085 - 0.888 / (1 + 10.674 \cdot \gamma \exp 0.95);\]
-Grey marl:
\[ G_n = 0.542 + 0.468 (1 + 18.724 \gamma \exp 0.73); \]
\[ D_n = 1.711 - 1.476 (1 + 1.41 \gamma \exp 0.593); \]

-Limestone:
\[ G_n = 0.737 + 0.263 (1 + 3.974 \gamma \exp 0.456); \]
\[ D_n = 1.902 - 1.627 (1 + 0.732 \gamma \exp 0.691). \]

Fig. 3 – The variation of dynamic torsion modulus function \((G, \text{daN/cm}^2)\) and torsion damping function \((D\%)\) of specific strain \((\gamma\%)\) for marl samples obtained in Hardin & Drnevich resonant columns (USA patent) from NIEP, Laboratory of Earthquake Engineering. Absolute values [6, 10, 11].

Fig. 4 – The variation of dynamic torsion modulus function \((G, \text{daN/cm}^2)\) and torsion damping function \((D\%)\) of specific strain \((\gamma\%)\) for sand and gravel samples with normal humidity obtained in Hardin & Drnevich resonant columns (USA patent) from NIEP, Lab. of Earthquake Engineering. Normalized values [7, 9, 11].
In Figure 5, we can see, in general, the same dependence of dynamic torsional modulus function \((G, \text{daN/cm}^2)\) and torsional damping function \((D\%)\) with shear strains \((\gamma\%)\) and frequency \((\omega)\) and them are constant for frequencies between 1.00 Hz and 10 Hz, domain common used in civil engineering.

![Graph showing torsion damping function](image)

Fig. 5 – The variation of torsion damping function \((D\%)\) of specific strain \((\gamma\%)\) and frequency \((\omega, \text{Hz})\) for clay samples obtained in Hardin and Drnevich resonant columns from Hardin & Drnevich columns (USA patent) from NIEP, Laboratory of Earthquake Engineering. Absolute values \([3, 5, 9, 11]\).

![Graph showing dynamic torsion modulus function and torsion damping function](image)

Fig. 6 – The dynamic torsion modulus function \((G, \text{daN/cm}^2)\) and torsion damping function \((D\%)\) are constant for frequencies between 1.00 Hz and 10 Hz, domain used in civil engineering and where all of them are function only of shear strains \((\gamma\%)\) induced by strong and deep Vrancea earthquakes \([5, 9, 10]\).
3. QUANTITATIVE EVALUATION OF THE NONLINEARITY

The model of linear elastic response of the soil has been almost universally used by seismologists 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. Ground motion characteristics, particularly the duration of strong shaking, can be affected by seismic energy being trapped in large sedimentary basins. For smaller earthquakes (M$_{GR}$=6.1), the strains are smaller and we are in the left-hand side of Fig. 4; for strong earthquakes (M$_{GR}$=7.2), the strains are larger and we are in the right-hand side of Fig. 4. Consequently, the responses of a system of nonlinear viscoelastic materials (clays, marls, sands etc.) subjected, for example to vertically travelling shear waves are far away from being linear and generating large discrepancies.

Currently, there are no constitutive laws to describe all real mechanical behaviors of deformable materials like soils. In order to make quantitative evidence of large nonlinear effects, authors introduced and developed the concept of the nonlinear spectral amplification factor (SAF) as ratio between maximum spectral absolute acceleration (S$_a$), relative velocity (S$_v$), relative displacement (S$_d$) from response spectra for a fraction of critical damping ($\zeta = 5\%$) at fundamental period or any other period and peak values of acceleration (a$_{max}$), velocity (v$_{max}$) and displacement (d$_{max}$), respectively, from processed strong motion records, that are: (SAF)$_a$ = S$_a$/a$_{max}$; (SAF)$_v$ = S$_v$/v$_{max}$; (SAF)$_d$ = S$_d$/d$_{max}$. The analysis was conducted for last strong and deep Vrancea earthquakes (March 04, 1977; M$_W$ = 7.4; h = 94.5 km; August 30, 1986; M$_W$ = 7.1 and h = 134.5 km; May 30, 1990; M$_W$ = 6.9 and h = 90.9 km; May 31, 1990; M$_W$ = 6.4 and h = 86.9 km) [5, 6].

In Tables 1, 2, 3 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 Iaşi to Craiova, records obtained by NIEP [6, 7, 9–11] and INCERC [3] Bucharest. The processing of the records was made by using Kinematics methodology and in the same conditions. Also, during of our analysis, Vrancea earthquake on May 31, 1990 (M$_W$ = 6.4) is assumed that the soil response is in elastic domain (c = 1.000) in Tables 1 and 2.

An example, in detail, is given in Table 1 and for all extra-Carpathian area in Tables 2 & 3. Vrancea earthquake on May 31, 1990 (M$_W$ = 6.4) is assumed that the soil response is still in elastic domain (c = 1.000).
Fig. 7 – Extra-Carpathian area and Vrancea seismic area. Around of Vrancea corner (red area) there is a multi-layered structure with variable thicknesses and velocities. The sedimentary stuck comprised up to 6 layers and reached a maximum thickness of more 15 km within the Focşani Basin area.

Table 1

<table>
<thead>
<tr>
<th>Earthquake (Mw)</th>
<th>$\delta_{\text{max}}$(cm/s²) (recorded)</th>
<th>$S_a$ (β=5%)</th>
<th>$S_{a_{\text{max}}}$/$\delta_{\text{max}}$ (SAF)</th>
<th>c</th>
<th>$S_a$ (β=5%)</th>
<th>a*</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.30,1986 (7.1)</td>
<td>72.20</td>
<td>292 cm/s²</td>
<td>4.0443</td>
<td>1.457</td>
<td>425.44</td>
<td>105.19</td>
<td>45.7%</td>
</tr>
<tr>
<td>05.30,1990 (6.9)</td>
<td>132.43</td>
<td>684 cm/s²</td>
<td>5.1649</td>
<td>1.141</td>
<td>780.44</td>
<td>151.10</td>
<td>14.1%</td>
</tr>
<tr>
<td>05.31,1990 (6.4)</td>
<td>63.07</td>
<td>372 cm/s²</td>
<td>5.8942</td>
<td>1.000</td>
<td>372.00</td>
<td>63.07</td>
<td>-</td>
</tr>
</tbody>
</table>

Spectral amplification factors (SAF) and the quantitative evidence of large nonlinear effects in Bacău Seismic Station (E-W Comp.): $\Phi^0=46.567$; $\lambda^0=26.900$
Table 2

Spectral amplification factors (SAF) and the quantitative evidence of large nonlinear effects in all extra-Carpathian area during of last strong earthquakes (August 30, 1986; $M_W = 7.1$ and $h = 134.5$ km; May 30, 1990; $M_W = 6.9$ and $h = 90.9$ km and May 31, 1990; $M_W = 6.4$ and $h = 86.9$ km. Vrancea earthquake on May 31, 1990 ($M_W = 6.4$) is assumed that the soil response is in elastic domain ($c = 1.000$).

<table>
<thead>
<tr>
<th>Seismic station</th>
<th>Vrancea earthquake on May 31, 1990, $M_W = 6.4$; $h = 86.9$ km</th>
<th>Vrancea earthquake on May 30, 1990, $M_W = 6.9$; $h = 90.9$ km</th>
<th>Vrancea earthquake on August 30, 1986, $M_W = 7.1$; $h = 131.4$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_{max} (cm/s^2)$</td>
<td>$S_{max} (cm/s^2)$</td>
<td>$a_{50} (cm/s^2)$</td>
</tr>
<tr>
<td>1. Diaa-Tulea</td>
<td>38.7  250  6.459  1.00</td>
<td>77.70  330  4.504  1.43</td>
<td>1.43  45%</td>
</tr>
<tr>
<td>2. Bolinяет Vale</td>
<td>35.6  155  4.354  1.00</td>
<td>215.0  800  3.721  1.17</td>
<td>1.17  17%</td>
</tr>
<tr>
<td>3. Braila</td>
<td>46.8  195  4.166  1.00</td>
<td>239.0  900  3.924  1.05</td>
<td>1.05  23%</td>
</tr>
<tr>
<td>4. Bacau (1)</td>
<td>63.0  390  6.032  1.00</td>
<td>132.0  600  5.227  1.04</td>
<td>1.04  14%</td>
</tr>
<tr>
<td>5. Bacau (2)</td>
<td>63.07  372  5.894  1.00</td>
<td>132.4  684  5.165  1.14</td>
<td>1.14  14%</td>
</tr>
<tr>
<td>6. Balta Alba</td>
<td>15.9  75  4.716  1.00</td>
<td>63.13  270  4.276  1.10</td>
<td>1.10  14%</td>
</tr>
<tr>
<td>Bucharest</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Braneşti, Ilfov</td>
<td>24.4  85  4.832  1.00</td>
<td>126.0  450  3.571  1.35</td>
<td>1.35  35%</td>
</tr>
<tr>
<td>8. CarAS, Bucharest</td>
<td>19.5  70  3.599  1.00</td>
<td>90.45  300  3.317  1.08</td>
<td>1.08  30%</td>
</tr>
<tr>
<td>9. Campulung Muscel</td>
<td>N-S  -  -  -  -</td>
<td>46.8  185  3.987  1.00</td>
<td>1.00  -  -</td>
</tr>
<tr>
<td>10. Campulung Muscel</td>
<td>E-W  -  -  -  -</td>
<td>41.2  170  4.526  1.00</td>
<td>1.00  -  -</td>
</tr>
<tr>
<td>11. Cernavoda</td>
<td>37.0  200  5.405  1.00</td>
<td>100.4  485  4.831  1.12</td>
<td>1.12  12%</td>
</tr>
<tr>
<td>12. Cernavoda (center)</td>
<td>31.7  180  5.678  1.00</td>
<td>92.6  400  4.319  1.31</td>
<td>1.31  31%</td>
</tr>
<tr>
<td>13. Cernavoda</td>
<td>48.7  288  5.791  1.00</td>
<td>100.1  475  4.747  1.22</td>
<td>1.22  22%</td>
</tr>
<tr>
<td>14. Chisinau</td>
<td>61.2  285  4.657  1.00</td>
<td>172.6  700  4.051  1.15</td>
<td>1.15  15%</td>
</tr>
<tr>
<td>15. Romanicu Sarat</td>
<td>-  -  -  -  -</td>
<td>66.4  230  3.464  1.00</td>
<td>1.00  -  -</td>
</tr>
<tr>
<td>16. Craiova</td>
<td>-  -  -  -  -</td>
<td>62.4  230  3.508  1.00</td>
<td>1.00  -  -</td>
</tr>
<tr>
<td>17. Peştera</td>
<td>46.8  190  4.059  1.00</td>
<td>117.9  405  3.435  1.18</td>
<td>1.18  18%</td>
</tr>
<tr>
<td>18. Galaţi (IPJ)</td>
<td>47.11  205  4.352  1.00</td>
<td>74.2  250  3.369  1.29</td>
<td>1.29  29%</td>
</tr>
<tr>
<td>19. Iaşi–Capu (NIIeF)</td>
<td>49.44  211  4.267  1.00</td>
<td>97.22  365  3.754  1.14</td>
<td>1.14  14%</td>
</tr>
<tr>
<td>20. Iaşi (Center)</td>
<td>45.76  180  3.934  1.00</td>
<td>109.5  355  3.242  1.21</td>
<td>1.21  21%</td>
</tr>
<tr>
<td>21. Iaşi (Bălău) (N–S)</td>
<td>76.0  300  3.847  1.00</td>
<td>135.6  450  3.318  1.19</td>
<td>1.19  19%</td>
</tr>
<tr>
<td>22. Iaşi (Bălău) (E–W)</td>
<td>31.2  170  5.448  1.00</td>
<td>90.4  400  4.444  1.23</td>
<td>1.23  23%</td>
</tr>
</tbody>
</table>
Spectral amplification factors (SAF) and the quantitative evidence of large nonlinear effects in INCERC Seismic Station (E-W and N-S Components) from Bucharest: $f^0 = 44.442$, $f^1 = 26.105$ during last strong earthquakes (March 04, 1977, $M_w = 7.4$; $h = h = 94.5$ km; August 30, 1986; $M_w = 7.1$ and $h = 134.5$ km; May 30, 1990; $M_w = 6.9$ and $h = 90.9$ km. Vrancea earthquake on May 30, 1990 ($M_w = 6.9$) is assumed that the soil response is still in elastic domain ($e = 1000$).

<table>
<thead>
<tr>
<th>Seismic station</th>
<th>Vrancea earthquake on May 30, 1990, $M_w = 6.9$; $h = 90.9$ km</th>
<th>Vrancea earthquake on August 30, 1986, $M_w = 7.1$; $h = 131.4$ km</th>
<th>Vrancea earthquake on March 4, 1977, $M_w = 7.4$; $h = 94.5$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{max}$</td>
<td>$S_{max}/S_0$</td>
<td>$a_{max}$</td>
</tr>
<tr>
<td>1. INCERC, Buch. (E-W)</td>
<td>98.9</td>
<td>280</td>
<td>2.83</td>
</tr>
<tr>
<td>2. INCERC, Buch. (N-S)</td>
<td>66.2</td>
<td>275</td>
<td>4.15</td>
</tr>
</tbody>
</table>
4. CONCLUDING REMARKS

The authors developed in last time the concept of “Nonlinear Seismology – The Seismology of the XXI Century” [6]. The leading question is: how many cities, villages, metropolitan areas etc. in seismic regions are constructed on rock sites? Most of them are located on alluvial deposits, on Quaternary layers or in river valleys. A soil is of basic type sand or gravel (termed coarse soils), silt or clay (termed fine soils) etc.

Laboratory tests consistently show the reduction in dynamic torsion modulus function (\(G, \text{daN/cm}^2\)), and increase in torsion damping function (\(D\%\)) with increasing shear strain (\(\gamma\%\)) induced by strong Vrancea earthquakes, i.e., \(G = G(\gamma)\), respectively, \(D = D(\gamma)\); therefore nonlinear viscoelastic constitutive laws are required.

There is a strong dependence of the spectral amplification factors (SAF) with earthquake magnitude. At the same seismic station, for example at Bacau NIEP Seismic Station, horizontal components and 5% damping, the values of the SAF for accelerations are: 4.0443 for August 30, 1986 Vrancea earthquake (\(M_w = 7.1\)); 5.1649 for May 30, 1990 (\(M_w = 7.9\)) and 5.8942 for May 31, 1990 (\(M_w = 6.4\)).

Tables 1, 2 and 3 confirm all data about nonlinear behavior of soils to strong Vrancea earthquakes.

The amplification factors decrease as the earthquake magnitude increases. This is consistent with recorded data from Tables 1 to 3, which confirm that the ground accelerations decrease as earthquake magnitude increases. When a nonlinear site response is present, then the shaking from large and deep Vrancea earthquakes cannot be predicted by simple scaling of records from small earthquakes [8].

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.

Over time in seismic hazard evaluation and risk mitigation there were many random and epistemic uncertainties. It is essential for seismologists and engineers to understand seismic hazard and risk, as well as the science behind them.

This is an active area of research in strong motion and engineering seismology and this strong nonlinear behavior of soils to strong earthquakes is the weakest point in any hazard and seismic risk analysis.

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How long will we go with linear seismology?

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