Brief Overview of Using Nonlinear Seismology in Analysis of the Soil Deposits Effects on Structure Location

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Abstract. The purpose of the paper is to show the great influence of nonlinear seismology in the analysis of the soil deposit response. Some elements about nonlinear seismology, the complexity of the seismic phenomenon are presented, and how we perceive seismic input for constructions at the surface of the earth. Further is presented the nonlinear behaviour of soil deposits during strong earthquakes as it results from resonant column tests (in laboratory) and from the spectral amplification factors (in situ records). The resonance phenomenon between natural period of a structure and soil deposit during strong earthquakes is analysed. All these studies have in common nonlinear behaviour of the soil deposit during strong earthquakes, in fact, the site where a new construction is built or an old one is rehabilitated and needs an optional assessment for mitigation seismic risk. All these studies stand up in supporting nonlinear seismology, the seismology of the XXI-st century.

1. Introduction
The seismic phenomena, viewed in their complex expression, involved three general aspects: source mechanism, seismic waves propagation to the surface of the earth, and their effects on surface. The concentration of the energy in the focal zone implies huge values of mechanical stress, which is released suddenly, by fractures, ruptures, violent movements across seismic faults. The seismic energy is released as elastic waves, which propagates through a rather heterogeneous geologic material. A long debated issue in seismology regards the effects of the non-linearity correlated to superficial soils response, during seismic waves propagation, and the corresponding estimation of such local effects, especially in studies of seismic hazard and risk. Here comes in the hundreds of thousands of lives and billions of Euros of losses in seismic events. The motivation for knowledge is also due to the fact that many important metropolises (with many millions of inhabitants) are located on alluvial deposits, quaternary deposits and river valleys, such as Bucharest, Mexico City etc.

Concern also exists internationally, so an important work in this sense is "Introduction to Seismology" written by Peter M. Shearer, Professor of "University of California", who develops the following concepts of non-linear seismology, which are followed also in the paper [1]:

- "Large accelerations from strong earthquakes can produce nonlinear responses in alluvial soils;"
- When we have non-linear responses at a location, then the accelerogram of a future strong seismic can’t be predicted by simply scaling down the records of low-intensity earthquakes already recorded on that site;
- Non-linear seismology is an active field of research in engineering seismology and in the analysis of strong earthquakes.”
The difficulty of seismologists to demonstrate nonlinear local effects was due to certain templates formed over time to address the seismic source and the propagation of the waves. Determining local nonlinear elements requires a complex and simultaneous understanding of how is the mechanism of earthquakes, how are propagating seismic waves through the earth, and a very good knowledge of the local geological conditions of the studied site. [2] Usually, the upper part of the lithosphere is viewed as parallel successions of soils deposits, with more or less different geophysical and mechanical parameters, above of an elastic half-space with high velocity and other characteristics. In figure 1 is presented the complex phenomenon of seismic environment presented above, the propagation of the waves from the source through the earth's crust to the surface and hence through soil-foundation-structure. Part of the waves energy of the earthquake reaches the buildings, with its consequences.

Legend: seismic waves, P- primary, S-secondary, R- Raleigh, L-Love; I – seismic source, II – base rock, III – soil layers under foundation, IV – free field.

Figure 1. Seismic waves propagation through a soil deposit

2. Seismic input
The seismic input for a site could come usually from two main sources: I) direct available recordings at site and II) an artificial accelerograms including the characteristics of the seismic source brought to the base rock and from there through the soil layers to the surface.

I) One of the main concerns of the “National Institute for Research and Development for Earth Physics”, Magurele, Romania, is the monitoring of seismic activity on the territory of Romania, with the help of seismic stations within the “National Seismic Network”. Currently, this network is made up of 156 seismometers and accelerometers located in Romania, transmitting real-time data, as well as 36 international stations. Over time, an important digital data base was made from the records obtained at the nationwide stations. The first year for which there were digital records is 1980. According to CALIXTO99 documents, until March 2000 there were 888 seismic events references in databases. Since 2004, the number of stations that contributed digitally to the network has increased considerably. For the Bucharest area, the first stations that were able to provide digital data were BUC1 (Bucuresti - Magurele) and BUC (Silver Knife) after 1997. But in order to benefit from consistent data and easy to convert from speeds / accelerations to displacements, the best period is since 2004. At present the “National Seismic Network” of “NIRDEP” is composed of six sub networks which provide the researchers with the necessary data for analysing seismic input in many regions of interest.
II) The description of the seismic input to the base rock is made by determining the characteristics of the seismic motion: maximum acceleration, natural period, actual duration of seismic motion etc.

The generation of the seismic signal on the path from source to base rock is done using the characteristics of the source (taking into account previous events): geographical coordinates, depth, strike receiver, fault dip and rake. Generating a synthetic signal in the source then transferring it to the base rock of the site, by different methods, resulting in a seismogram at that level. Turning to the method of synthetic accelerograms happens when there is a zone where there are no seismic recordings, but are known geological and geotechnical structures.

The path of seismic waves from the base rock to the surface of the earth where is the building foundation is through a soil deposit of variable thickness made of several soil layers of different physical and geotechnical characteristics. To compute the characteristics of the seismic movement at the surface of the earth is used different software, one of the most common being SHAKE 2000. [3]

3. Nonlinear soil behaviour during strong earthquakes

Nonlinear seismology is that part in earth physics which considers nonlinear behaviour in soil response during strong earthquakes. Romania is a seismic country. All disastrous earthquakes are generated within a small epicentre area - the Vrancea region - about 150 km north-east of Bucharest, see figure 2. Considering only the XXth century there have been four major earthquakes from Vrancea region: November 10, 1940, $M_w = 7.7$; March 4, 1977, $M_w = 7.4$; August 30, 1986, $M_w = 7.1$ and May 30, 1990, $M_w = 6.9$, with a lot of causalities. In the seismic event of 1940 were some several hundred victims and in 1977, about 1500 people died and major building (civil and industrial) damage on both earthquakes.

In this paper we shall focus on what happens between base rock and surface of the earth. The soil deposit is characterized by soil layers which have the following characteristics: thickness, density, shear modulus, damping, Poisson ratio etc. We know all these by direct drills (when it is possible, with depths no more than 150m, after this it will be very expensive) or by geophysical investigations. Because of the different soil layers and especially on alluvial soils we could have large amplifications and important variations in soil characteristics.

![Figure 2](image2.png)  
Figure 2. Location map of Vrancea and Romania

![Figure 3](image3.png)  
Figure 3. Nonlinear behaviour of clay

During strong earthquakes we have large strains in the soil deposit usually more than $10^{-4}\%$, which imply a viscoelastic nonlinear behaviour of geological materials of the site and one must use, for instance, a Kelvin-Voigt nonlinear model, [2]. It is observed that during strong earthquake movements
shear modulus (G) and damping (D) have important variations, G is decreasing and D is increasing, all these function of strain are considered induced by seisms (figures 3 and 4):

\[ G = G(\gamma), \quad D = D(\gamma), \]  

(1)

**Figure 4.** Nonlinear behaviour of sandy marl

**Figure 5.** Drnevich resonant column

In the National Institute of R-D for Earth Physics in the former Department of "Engineering seismology" and now the Department "Research - Development and Innovation in Earth Sciences" are carried out theoretical and experimental researches in nonlinear seismology by a group of highly qualified researchers.

These researches were made possible by theoretical studies, contracts involving the practical application of research and laboratory tests performed over time on the electro-mechanical equipment called “resonant columns” specialized in highlighting nonlinear variations of: torsional modulus (G), Young's modulus (E), torsional (D) and longitudinal damping function of the strain level (torsional or longitudinal) induced by the device. The states of deformation induced in the soil samples are equivalent to deformations produced by strong earthquakes of different magnitudes in soil deposits. [4, 5] National Institute of C-D for Earth Physics has two resonant columns: Drnevich (figure 5) and Hardin (figure 6).

The resonant column Drnevich acts on the soil sample with a torsional/longitudinal force. The torsional modulus, G, and torsional damping D behave as a function of strain, \( \gamma \), the first decreasing as the second going up, these variations from the initial value could go to 50% and even more as strain is increasing. The stronger the earthquake more variation in soil parameters.

The scheme of a resonant column (Drnevich) is presented in figure 7. The soil and rock samples which are tested in the resonant column are cylinder type, of standard dimensions: diameter 3.57 (7.11) cm and height of 8 (14.2) cm. The lower base of the sample is fixed, and on the top of the sample is placed an electromagnetic vibration unit. This assembly sample – vibrator is installed in a plastic translucent high resistance cell, in which is made hydrostatic pressure with air. The value of this pressure is conceived to be equivalent with the sample in situ geological pressure. Shear modulus G, results from the well-known formula from elasticity (shear wave velocity in the soil sample being computed from input and output data from the column):

\[ G = \rho_a V_s^2 \]  

(2)

, where \( \rho_a \) - apparent density, \( V_s \) - shear waves velocity.
All sample parameters are computed with the data-processing system associated with the resonant column.

The resonant column Hardin acts on the soil sample with a torsional force and has the possibility to model the weight of a structure on the site.

In figure 8 can be seen the variation of G (shear modulus) and D (damping) with strain $\gamma$, and we can notice specific strain corresponding to two different earthquake magnitudes as 6.1 and 7.2, and observe the important decreasing of G and increasing of D with magnitude.

To a certain level of excitement resonant column tests can give a value of dynamic modulus G and damping value D. This value corresponds to a certain amount of strain, $\gamma$, corresponding to resonance frequency of vibrating system – soil sample. So, in this experiment, frequency and deformation are not independent variables. On the other hand from resonance column test could be obtained only a few values of G and D placed in a "section" of the surface $G = G(\gamma, \omega)$ and $D = D(\gamma, \omega)$. These sections correspond to device possibilities, specifically a band of frequency of 1-50Hz and a band width strain.
$10^{-3}\% - 5 \times 10^{1}\%$. When analysing several resonance column tests, could be seen a major influence of the strain level on shear modulus, damping and a small influence of frequency values exceeding 1Hz upon dynamic modulus $G = G(\gamma, \omega)$ and damping function $D = D(\gamma, \omega)$. Moreover, from the point of view of engineering seismology, the frequency band of 0.1-10Hz is important. So, for practical reasons can be regarded as $G$ and $D$ are constants function of $\omega$ (see figures 9, 10). [4]

Resonant column tests could be used to obtain a quantitative assessment of dynamic functions throughout their entire area of definition. Therefore, these data from these devices are very useful for evaluating the behaviour of non-linear viscoelastic model to dynamic stress.

4. **In situ nonlinearity**

A method used for making a connection between seismic hazard, local site effects and nonlinear behaviour is using spectral amplification factors (SAF). [6] This approach applied for areas with thick Quaternary sediments may offer a proof for nonlinear dependence of spectral amplification factors due to local site conditions, at strong magnitude.

Spectral amplification factors (SAF) [7] is defined as 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 ($\zeta\%$) at fundamental period and peak values of acceleration ($a_{\text{max}}$), velocity ($v_{\text{max}}$) and displacement ($d_{\text{max}}$), respectively, from processed strong motion recordings, that are: $(SAF)_a=\frac{S_a}{a_{\text{max}}}$; $(SAF)_v=\frac{S_v}{v_{\text{max}}}$; $(SAF)_d=\frac{S_d}{d_{\text{max}}}$.  

In table 1, [7] are presented mean values of spectral amplification factors for three strong earthquakes, from Vrancea, Romania, in the XXth century.

It is observed that spectral amplification factors (SAF) have a nonlinear dependence of seismic magnitude, which proves the nonlinear effects due to seisms propagation from source to site.

5. **Soil – foundation – structure interaction elements**

This analysis of soil-foundation-structure with considering the nonlinear behaviour of the soil deposit during strong earthquakes is a very effective way of getting the right answers for a safe building in a seismic environment, when trying to build a special construction. This ultimate analysis considering the whole system in dynamic mood, under seismic action, yields many essential design data for the soil deposit and structure itself.
Table 1. Mean values of spectral amplification factors for three strong earthquakes

| Damping | August 30, 1986; MW=7.1 | May 30, 1990; MW=6.9 | May 31, 1990; MW=6.4 |
|---------|------------------------|---------------------|---------------------|
| β%      | (SAF)_a (SAF)_v        | (SAF)_a (SAF)_v     | (SAF)_a (SAF)_v     |
| 2%      | 4.74                   | 5.58                | 6.22                |
| 5%      | 3.04                   | 3.98                | 4.76                |
| 10%     | 2.43                   | 2.56                | 2.92                |
| 20%     | 1.78                   | 1.82                | 2.13                |

Soil structure interaction is a relatively young chapter of engineering seismology, a little more than half a century but in recent decades has developed very much with the help of powerful computers, dedicated software and mathematical techniques.

The essence of the strategy of avoiding site–structure resonance, during strong earthquakes, consists in the correct evaluation of the natural periods of both the structure $T_a$ and the site $T_g$.

However, the site natural period $T_g$ has not a unique value. The site materials have a mechanical behaviour strongly dependent on strain, stress or loading level (expressed by dynamic stiffness degradation and increasing damping). [7, 8] As a result, it becomes dependent on the earthquakes amplitude, and this dependence can be observed in the seismic records.

Therefore, an important role in the resonance occurrence belongs to seismic loading level (outlined in terms of magnitude or $PGA$) because only strong events (over $M_w=7.2$) may lead to important structural damages. Thus, for safe avoidance of resonance it is necessary to define for each site a natural period value range corresponding to strong earthquakes. In the range of magnitude $M_w=7.2$–7.8, which are considered as destructive ones, corresponding to Vrancea earthquakes, the highest value being the maximum expected magnitude, with assigned $PGA$ values of approximately $0.1g$ to $0.3g$ and dangerous natural period range between 1.22s up to $1.65s$ for INCERC site, the recommendation is to avoid building up with these resonance characteristics. [9]

In this paper there is no space for an analysis of this very fast developing chapter but authors want only to emphasize its importance in an engineering evaluation of a site for special constructions.

6. Results and discussion
All these studies (in laboratory and in situ) have in common nonlinear behaviour of the soil deposit during strong earthquakes, in fact the site where a new construction is built or an old one is rehabilitated and needs an optional assessment, because many soil parameters have an important instability during strong seismic events. Authors believe such studies could accomplish safer buildings. All these studies stand up in supporting nonlinear seismology, the seismology of the XXI-st century.

7. Conclusions
- The effect of a soil deposit is one of filtering the input (seismic) motions, increasing their amplitudes in some ranges of frequencies (periods) and decreasing it in others.
- The evaluation of the dynamic response of a soil deposit or a structure founded on soil requires knowledge of the stress-strain properties of the foundation materials.
- Spectral amplification factors (SAF) are decreasing with magnitude of strong Vrancea earthquakes. SAF has a nonlinear behaviour and is function of magnitude.
- Nonlinear damping in the soil deposit and structure during a strong earthquake plays an important role in the stability of the dynamic system. The loss of stability in the terrain-structure system occurs under certain circumstances following a dynamic process.
The necessity to define for each site a natural period value range corresponding to strong earthquakes.

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