NONLINEARITY IN SEISMIC SITE EFFECTS EVALUATION

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Received January 19, 2009

The seismic hazard of Romania has been the object of several studies based on probabilistic or deterministic methods (1). Details of the resulted hazard maps are still a controversial issue that leads to an innovative approach: a combined analysis of the available records and macroseismic information completed with numerical simulations since the strong motion records are rather scarce. The main purpose of this paper is to add new features regarding site effects evaluation and its role in seismic hazard analyses at regional and/or local scale. This study is focusing on nonlinear aspects of seismic ground motion and presents new results related to site effects induced by strong Vrancea intermediate events.

1. QUANTITATIVE EVIDENCE OF NONLINEARITY

Linear elastic modelling of the seismic response was almost universally used for description or explaining the earthquakes effects, independent of their magnitude. For the 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. Geotechnical laboratory tests on soils shows a systematically decrease of the shear modulus $G$ and simultaneous increase of the damping ratio $D$ with shear strain $\gamma$ above $10^{-4}$ %, i.e. $G = G(\gamma)$ and $D = D(\gamma)$, [2, 3]. Strong earthquakes may induce higher values of the shear strain in superficial layers , of about $\gamma \approx 10^{-3}$ [4] and in such cases the nonlinear behaviour of the soils have to be considered.

A quantitative characterization of the nonlinearity phenomena in propagation of the seismic waves induced by strong Vrancea events can be done using spectral amplification factors (SAF) defined [5, 6] like $SAF = \frac{SA_{max}}{A_{max}}$ where $A_{max}$ is the maximum recorded acceleration (horizontal component) and $SA_{max}$ represents the corresponding spectral response computed with 5% damping. In the Table below are presented the SAF computed from records of different seismic stations, considered representative as local geological conditions: BMG (5 km SE – Bucharest) – sands and gravels in quaternary sediments of about 300 m thickness; INC (NE – Bucharest) – soft soils, quaternary layers to ~ 500 m depth; nuclear
Table 1

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>$M_w$</th>
<th>BMG</th>
<th>INC</th>
<th>N.P.P.</th>
<th>BAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 March 1977</td>
<td>7.4</td>
<td>–</td>
<td>2.9807</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>30 August 1986</td>
<td>7.2</td>
<td>2.6982</td>
<td>2.6458</td>
<td>4.0781</td>
<td>4.0489</td>
</tr>
<tr>
<td>30 May 1990</td>
<td>6.9</td>
<td>3.5869</td>
<td>3.3939</td>
<td>4.7549</td>
<td>4.4629</td>
</tr>
<tr>
<td>31 May 1990</td>
<td>6.4</td>
<td>–</td>
<td>–</td>
<td>5.7851</td>
<td>5.2142</td>
</tr>
</tbody>
</table>

power plant station Cernavoda (NPP) – marls and limestone ~ 270 m and Bacău (BAC) seismic station located on metamorphic rocks with 8–10 m back-fill.

The dependence of the SAF computed for many other locations [7] with earthquake magnitude can be explained by the fact that far-field recorded accelerations tends to decrease as earthquake magnitudes increases as proved in several locations where strong motion records of Vrancea events are available [8]. In the same time, variability of the maximum recorded accelerations reflects also the seismic sources characteristics, like hypocenter depth, faulting plane, directivity, single or multiple shocks etc.

2. SITE EFFECTS EVALUATION

From the recorded seismograms is difficult to identify the nonlinear behaviors and to separate the seismograms due to local geological conditions only and the seismic effect due to source characteristics. Local effects are regularly described in terms of transfer functions, or in terms of spectral amplification ratios compared to a reference station etc. For the particular case of induced effects coming from intermediate Vrancea earthquakes we used vertical propagation of waves calibrated on local existing seismic records. Physical and numerical models used in this approach are then used for the “maximum possible” event or expected earthquake scenario. This approach allowed us to take into account properties of deep earthquake sources and even the nonlinear behavior of the soils from the superficial layers, which becomes very important in the case of strong earthquakes.

Method implies:
- a stage when possible seismic source are investigated, history and seismicity of the source zone, when it is known-like in Vrancea case-including predominant source mechanism study, election of the representative mechanism and source modeling parameters.
- a stage that involves compilation of structural models, resulted from detailed geological knowledge, geotechnical properties of the studied area and in-between path starting with Vrancea area.
local structure modeling is made, mainly, by finding geotechnical parameters and dynamic functions for soils in laboratory tests, in situ or by using published or recommended \( G = G(\gamma) \), \( D = D(\gamma) \) curves for the types of materials from the superficial layers.

another stage is computation of the seismic input, testing the influence of the chosen “base rock” and verification of the frequency completeness of the signal used in the structure; this was done by Fourier spectra of synthetic seismic excitation compared with at least one recorded seismogram from the site.

Computation of parameters which are describing best the local structure behavior: surface acceleration, relative velocities and displacements, tension and deformation history in one or more layers of interest, Fourier spectra and response spectra (with damping factors between 0 and 20%) in terms of absolute acceleration, relative velocities and displacements. All these are obtained by using any software based on linear equivalent approximation for describing the nonlinear viscoelastic behavior of soils [9–11].

Local seismic effects evaluation is made here by using transfer function analysis; its definition does not provide only the relative seismic motion parameters, but also the frequency dependence of these ratios for the used layers.

Simulation control is accomplished based on the existing records from the considered site, rotated and filtrated in the frequency domain for which the analysis is done.

3. SEISMIC INPUT

Seismic input at base rock is studied by determining the seismic characteristics of the motion at the base rock level: maximum acceleration, predominant period, effective time length of the earthquake etc. For this purpose, usually, are used accelerogram for strong earthquakes previously recorded or synthetically generated [12]. In this approach we used synthetic accelerograms obtained by modal summation [13, 14] for the structure through which the seismic waves are propagated from focus to the base rock of the studied site. The classical approach for solving the seismic input at the base rock is to use “outcrop” records [12, 15], where the base rock comes to surface of from receptors situated on the edge of sedimentary basins. In modern and very rigorously approaches of local seismic response evaluation for local geological structure [16, 17], for the seismic input definition is used an impressive number of recorded strong earthquakes from a vertical network of sensors, respectively free-field and 100 m records depth, where the base rock level was chosen for the respective sites. When there are no seismic information/recordings at the base
rock level, but the geological and geotechnical characteristics are known for the layer, synthetic accelerations are used as input; they are generated by different methods. One of the most used method is to generate an accelerogram by a superposition of harmonics or even from a “white noise” scaled on the time-domain amplitude envelope from a surface recorded seismogram; often frequency filtering is used [18, 19].

The type of computed seismic input used here has as advantage the fact that it takes into account the seismic signal attenuation through one or more traveled geological structures from focus to base rock. The modal summation method is also sensitive to earthquake mechanism, this being an important advantage compared to any other method (e.g. methods using Green function simulations).

The problem resulting from maximum soil movement values in case of strong Vrancea earthquakes will not be presented in this study, because is deeply discussed in recent papers [20, 21] together with its implications on local and regional scale seismic hazard. The seismic input dependency, computed through modal summation, is presented later for a site with a well known geological structure, where good records of strong earthquakes exists (Bucharest, Magurele). During all tests, the displacement, velocity and acceleration time series, were scaled with Gusev laws modified for intermediate events [22], for a maximum possible magnitude for Vrancea $M_w = 7.7$. The main characteristics of regional structure for seismic propagation from focus to site are represented in Fig. 1: variation in depth of the density, seismic waves velocities and quality factors (thick lines for P-waves characteristics and thin lines for secondary ones).

Fault dip angle for the intermediate depth earthquakes influences similarly all seismic motion components at surface, as in Fig. 2, where the thin line
represents the radial component (RAD), the thick line represents transversal component (TRA) and dotted line represents the vertical component (VER).

The maximum soil motion results when dip angle is between 0–10 degrees (fault plane nearly horizontal, fact never observed for Vrancea intermediate depth earthquakes) and for 70–80 degrees interval (which represents a nearly vertical faulting). This last case is possible for Vrancea, catalogue studies showing fault planes for strong Vrancea earthquakes ($M_w >5.5$) between 60 and 85 degrees.

The results in Fig. 3 are obtained from numerical simulation by using modal summation method, with rake angle taking values between 0 and 360 degrees. The hypocenter was considered at 131 km depth, similarly to 1986, August 30 event, and the scaling magnitude for synthetics is $M_w = 7.7$, according to the maximum possible magnitude evaluations for Vrancea area. The maximum values for displacements, velocities and accelerations $A_{max}$ at free surface take place in the same moment for all three components (RAD, TRA and VER) when the rake angle is between 15 and 75 degrees. The polar distribution from Fig. 3 is not symmetrical, maximum acceleration values also appear when rake angle varies within 180–255 degrees. Note that the rake angle values of the last strong earthquakes are: 97° for May 31, 1990 event, $M_w = 6.4$; 101° May 30, 1990 $M_w = 6.9$; 104° for August 30, 1986, $M_w = 7$ and 114° for the most recent one Oct. 27, 2004, $M_w = 6$.

The distribution of the seismic motion at base rock as a function of strike angle is shown in Fig. 4. Like in the previous test, the hypocentral depth of the simulated event is 131 km and $M_w = 7.7$. The variations for the maximum values of displacements, velocities and accelerations are absolutely similar to RAD (radial), VER (vertical) components, which corresponds to observed phenomena of P-SV coupling. For the TRA (transversal) component an asymmetric behavior is observed, behavior different than Rayleigh waves (P-SV coupling). The maximum values on RAD and VER components are symmetric and are taking
place on 75°-135° degrees interval. Less important maximum values correspond to strike angle interval 255°-315°. The TRA component has most important maximum values within the strike angle interval 135°-180°. For the general strong earthquake mechanism in Vrancea zone the strike of the fault varies between 208 and 308 degrees.

Another problem in the seismic input computation is the base rock and its depth. Even the 1D vertical propagation is applied for more then 30 years for local seismic response evaluation [15, 23], the method proved its correctness and efficiency in seismic engineering applications, in the specific literature there is no unanimously accepted opinion on “base rock”, this concept varies as definition depending on location and purpose of the study, but also on the theoretical background on the scientists involved in. Some general observations can be made regarding the base rock composition (24) ,which, generally was chosen at a layer of hard rocks for which the dynamic behavior can be described by simple models like linear or nonlinear elastic solid. Its depth varies depending on local structures; for its identification are used parameters like: shear velocity ($v_i$) in the layer and layer impedance variation with depth $\frac{\rho_i \cdot v_i}{\rho_{i-1} \cdot v_{i-1}} \geq 2$, where $\rho$ represents density, $v$ represents seismic waves velocity and $i$ stand for the index of the layer, starting from surface. Also, we considered necessary to introduce a frequency criteria for the computed seismic input, namely, we choose a depth for which the synthetic signal resembles best to recorded signals on the local structure, such that the seismic response to be unaffected by the absence of some frequencies from the domain.
4. APPLICATION

The most important effects are observed on transversal component (TRA) in the case of strong Vrancea earthquakes. Because there are intermediate depth earthquakes, the details regarding local effects are changing from one event to another, which makes us to conclude that the induced local effects are depending on the earthquake source parameters. In this study, these influences are taken into account by using modal summation method in the seismic input evaluation, method that includes seismic source parameters (location, depth, fault plane solutions) but also geological structures through which the seismic signal propagates from focus to site – characteristics that enables us to model any lateral discontinuities which can be found at large epicenter distances. The seismic input takes into account all these variables (as shown in parametric tests from Fig. 3–5) and gets rid of all limitations coming from using a linear elastic half space, which come from classical approaches. A self imposed condition of this approach is spectral completeness of the computed signal, a necessary condition taking into account that 1D vertical waves propagation techniques keep the accelerogram spectra content constant and change only the amplitude and duration of the signal computed at surface.

Taking into account that most of the seismic energy is carried by transversal waves (or superficial layer coupling – Love wave), in this example, the method is applied only for SH waves, which represents the transversal component of the seismic motion, but, it can be applied to other seismic components.

The local structure shown in Fig. 5 resulted from taking into consideration all the available data [21, 26] on N-E part of Bucharest. For the local soils we considered \( G = G(\gamma) \) and \( D = D(\gamma) \) curves (Fig. 6), which were experimentally determined in laboratory using Drnevich resonant column and samples from drills from Bucharest that contained the same soils.

In the seismic waves vertical propagation approach several soil models can be used; here we used nonlinear viscoelastic model, this model being the most suitable for describing the physical phenomena induced in the superficial layers by strong earthquakes. By using this method on thin or thick uniform layers of loess, clay, gravel with sand and marl, a nonlinear dependency of torsion modulus and dynamic damping values is observed. These [25] depends only on material nature or type of soil, and are inducing local seismic effects observed / evaluated here. The study of dynamic parameters dependency on earthquake magnitude [21] shows that starting from magnitudes greater than \( M_w \geq 6 \), the nonlinear behavior must be taken into account in the free surface seismic movement parameters evaluation, namely in local seismic hazard evaluation, especially for thick layers – tens of meters thick- and a nonlinear viscoelastic model must be used.
Fig. 5

Material 1 - sandy clayey silt

Material 2 - gravel with sand

Material 3 - clay

Material 4 - sandy marl

Material 5 - marl

Fig. 6
The simulated results were compared to recorded acceleration response spectra. The models for which the errors were the smallest (e.g. 7.438% for this case) were further used to predict surface motion and structure specific effects.

The strong earthquakes were recorded at INC seismic station (SMA-1, INCERC Bucharest), rotated and Gauss low-pass filtered on 0.05–1 Hz and 0.1–2 Hz.

In Fig. 7 are presented response spectra with 5% damping computed for the seismic station site for the strongest recorded events August 30, 1986 (VR86) and March 4, 1977 (VR77). Continuous line represents transversal recorded spectra low-pass filtered with a cut-off frequency of 1 Hz and 2 Hz respectively. Local structure period for the synthetic signal is exactly correlated with VR86 event up to 1 Hz and for the 2 Hz signal for the same event, the synthetic has only one peak exactly on the same place with the average maximum recorded values. The maximum spectral peak for the synthetic signal appears for stronger event VR77; its rotated and 2 Hz filtered recording has only one peak. Also for the 1977 event we observe that the maximum of the synthetic signals are over evaluated: 16% for 2 Hz and 4.45% for 1 Hz which leads us to the conclusion that the soil behavior from the local geological structure is even more nonlinear than in our modeling (using curves determined from other drills, but not from INC site), the nonlinearity (practically the energy absorption) acting strongly proportional with magnitude. For the VR86 event, the 5% damped synthetic acceleration spectra in 0.1–2 Hz (dotted line – left side of Fig. 7) fits very well the recorded one (continuous line): synthetic $S_A_{\text{max}} = 260 \text{ cm/s}^2$ and $S_A_{\text{max}} = 242 \text{ cm/s}^2$ real, over evaluation of 7.438%. The bedrock and local structure models including the same seismic method response were used for 5 real earthquakes with magnitude from 6 (2004, October 27) to 7.4 (1977, March 4) and one hypothetic event, “the maximum possible Vrancea earthquake”, with magnitude $M_w = 7.7$.
The local effects described in terms of amplification spectra are represented in Figs. 8 and 9. From Fig. 8 it can be observed that seismic excitation produces strong amplifications in the considered local structure, especially for “small” magnitude earthquakes: $M_w = 6.0$ (2004, Oct. 27), respectively $M_w = 6.4$ (1990, May 31-denoted 1990-2); for strong earthquakes (denoted 1997, 1986, maxim), the transfer functions representing the seismic movement amplifications decrease as magnitude increase. For example in Fig. 9, the maximum expected amplification for the maximum possible event is 4.5 and it takes place at 1.4 sec. The maximum amplification of the same structure is 16.5 at 0.35 seconds in the case of the earthquake magnitude $M_w = 6.0$. 

![Fig. 8](image1.png)

![Fig. 9](image2.png)
5. CONCLUDING REMARKS

The deterministic hazard approach involves simulation of seismic motion for a site using a variety of expected or possible events for each seismic region; when the study is made a large area with increased seismic risk due to high populated areas or industrial facilities etc., is taken into account the combination of all seismic sources and local geological conditions. The deterministic seismic hazard evaluation methodology is based on synthetic seismograms computation at surface for large area of interest; by taking into account all the known sources characteristics and environment mechanical properties where the propagation of the seismic signal takes place.

In our country the seismic hazard studies are based on a small number of strong recorded events (practically starting from 1977), out of these records, only a few of them having the necessary qualities for motion evaluation during an earthquake; this is due to the fact that the majority of records are describing the behavior of the buildings (soil-building interaction) instead of free field motion. Station service and configuration factors can lead to incomplete seismic records or to incorrect frequency content. In this way, after unitary processing of seismic records at a site, we can have very few useful signals for the microzonation process. The alternative to the lack of recorded signals comes from complex numerical simulations, which take into account, as much as possible, the existing knowledge in seismology, geology and geotechnics.

Choice of deterministic method for seismic hazard assessment is a direct consequence of the database recorded until now with intermediate depth strong earthquakes ($M_w > 6$), this database being very small for probabilistic estimations. The seismic deterministic hazard assessment [20, 21] combined with local effects evaluation – as shown in this paper – ensures the local seismic hazard coherency and important steps in the destructive effects reduction.

The method used in this paper represents an alternative way for estimating the seismic response and local seismic effects, developed especially for sedimentary structures exposed to a significant hazard generated by intermediate depth seismic sources. This method benefits from modal summation technique advantages for computing excitation movements for layers from the local structure combined with simplicity in the determination of the local seismic response by vertical propagation of seismic waves, taking into account the nonlinear effect induced by seismic excitation of local geological materials, part of the structure. Its application and verification was succeeded at a satisfactory level, from the point of view of engineering seismology, for intermediate depth earthquakes (60–150 km) in a frequency domain up to 2 Hz. This fact is of crucial importance for highly populated areas microzonation, due to the fact that a 0.05–4 Hz domain would include all seismic excitations, capable to induce damages to small buildings (e.g. 3 or more floors buildings). Simulations calibrated
on at least one station allow us to evaluate the seismic response in places where no record for the respective event is present, very important fact in local seismic hazard studies for the capital city and other densely populated towns from extracarpathic area of Romania.

Acknowledgements. This work has been done within the frame of CEEX Project HHRO contract 144/2006. Prof. G. F. Panza and DST of Trieste University are kindly acknowledged for modal summation codes and computer facilities.

REFERENCES


