Abstract

An analytical deterministic technique, based on the detailed knowledge of the seismic source process and of the propagation of seismic waves, has been applied to generate synthetic seismic signals at Russe, NE Bulgaria, associated to the strongest intermediate-depth Vrancea earthquakes, which occurred during the last century (1940, 1977, 1986 and 1990). The obtained results show that all ground motion components contribute significantly to the seismic loading and that the seismic source parameters influence the shape and the amplitude of the seismic signal. The approach we used proves that realistic seismic input (also at remote distances) can be constructed via waveform modelling, considering all the possible factors influencing the ground motion.
1 INTRODUCTION

The Bulgarian territory suffered different strong Vrancea earthquakes that caused significant damages at epicentral distances of several hundred kilometers: e.g. the Vrancea quake of March 4, 1977 (Mw = 7.5) was felt up to Central Europe at distances of about 1000 km. Even though the Vrancea 1977 event motivated some changes in the Bulgarian Code for Design and Construction in Seismic Regions, 1987, the seismic excitation from 1986 and 1990 events was stronger than the prescribed seismic loading in the BG Code 1987 [Paskaleva et al., 2001]. The seismicity records and the recent deterministic hazard assessment show that the earthquake hazard at Russe is controlled by both Shabla and Vrancea seismic sources (more significantly by the intermediate-depth Vrancea sources), even if they are located about 220 km far from the city. Macroseismic intensities I = VII - VIII (MSK-64) were reported at Russe due to the Vrancea quakes, which occurred in 1940 and in 1977 [Brankov VV. AA, 1983]. A schematic representation of the reported macroseismic intensity versus the Vrancea earthquake magnitude and its focal depth is shown in fig.1, where one can see that the reported maxima correspond to the intermediate-depth events. The recent deterministic modelling of the Vrancea earthquake hazard [Panza and Vaccari, 2000] points out that the Vrancea earthquakes can produce at Russe ground displacements up to 30 - 60 cm and effective peak accelerations over 0.5g. An analysis of the available recorded strong motion accelerograms in NE Bulgaria due to the Vrancea seismic events, performed by the moving windows technique, shows that the control periods of the response spectra, Tc, are in the range of 0.4 - 1.6 sec [Paskaleva et al., 2001]. The wavefield radiated by the Vrancea intermediate-depth earthquakes, mainly at long periods, attenuates with distance less rapidly than the wavefield of the earthquakes in other seismically active zones in Bulgaria [Todorovska et al., 1995]. Therefore the Vrancea intermediate sources should be considered as a regional hazard, since large industrial areas can be seriously affected by the strong events originating in this seismogenic area.

2 THE DATA AND THE NUMERICAL EXPERIMENTS

To define the seismic input at Russe, NE Bulgaria, exposed to the seismic hazard from Vrancea events, an analytical deterministic technique, that takes simultaneously into account the seismic source process and the travel path of the seismic waves, has been applied. It combines the modal-summation technique [Panza, 1985; Panza and Suhadolc, 1987; Florsh et al., 1991; Panza et al., 2000] for the bedrock and the mode coupling approach [Vaccari et al., 1989; Romanelli et al., 1996, 1997] for the inelastic, laterally inhomogeneous (sedimentary) media. This approach differs significantly from the widely used ground motion modelling approach that relays upon rock - site hazard maps and applies the site correction at a later stage. The computations have been performed separately for the SH and P-SV waves field, considering frequencies up to 1 Hz. The ground motion due to five recent strong Vrancea earthquakes, which occurred in 1940 (VR40), 1977 (VR77), 1986 (VR86) and 1990 (VR901 on May 30 and VR902 on May 31, respectively) have been computed. The seismic sources have been modelled adopting buried double-couple point sources, parameterised by the hypocenter location, magnitude and focal mechanism parameters, shown in Cioflan et al., [2001] (VR40, VR77 and
VR902) and Dzievonsky et al., [1991] (VR86 and VR901).

### TABLE 1

Seismic source parameters adopted in the numerical experiments

<table>
<thead>
<tr>
<th>Earthquake identification</th>
<th>Latitude [°]</th>
<th>Longitude [°]</th>
<th>Magnitude [Mw]</th>
<th>Depth [km]</th>
<th>Strike angle [°]</th>
<th>Dip angle [°]</th>
<th>Rake angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR40, 11/10/40</td>
<td>45.80</td>
<td>26.70</td>
<td>7.7</td>
<td>~150</td>
<td>225</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>VR77, 03/04/77</td>
<td>45.80</td>
<td>26.80</td>
<td>7.4</td>
<td>~90</td>
<td>225</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>VR86, 08/30/86</td>
<td>45.76</td>
<td>26.53</td>
<td>7.1</td>
<td>~133</td>
<td>240</td>
<td>72</td>
<td>97</td>
</tr>
<tr>
<td>VR901, 05/30/90</td>
<td>45.92</td>
<td>26.81</td>
<td>6.9</td>
<td>74±16</td>
<td>236</td>
<td>63</td>
<td>101</td>
</tr>
<tr>
<td>VR902, 05/31/90</td>
<td>45.83</td>
<td>26.89</td>
<td>6.4</td>
<td>87</td>
<td>308</td>
<td>71</td>
<td>97</td>
</tr>
</tbody>
</table>

*NB. Variations of +/-10° are considered for the parametric analysis of the SA and Ei variation with respect to the changes of the focal mechanism parameters.

The basic two-dimensional (2D) model used for the computations is shown in fig. 2, it is formed by two different quarter-spaces in welded contact: (1) the regional structural model, called the bedrock model, that contains the seismic source and (2) the bedrock model in which the local geological structure representative for the sites of interest is embedded. The bedrock model representative of the path Vrancea - Russe passes through the Carpathians and the Moesian Platform, where Pliocene and significant Quaternary deposits are present [Brankov, VV. AA. 1983; Radulian et al., 2000]. The detailed geological and geotechnical data available for the uppermost 100 m in Russe [Evlogiev, 1993; Evlogiev et al., 2000] have been used to define the uppermost part of the local model, representative of a NE 42° SW oriented profile across the town of Russe (profile a-a in fig. 3). More details about the structures and velocity models are provided in Paskaleva et al., 2001 and Kouteva et al., 2003. The overview of the engineering geological conditions at Russe shows a rock basement covered by incoherent sediments, where complicated ground conditions are combined with a shallow water table [Evlogiev et al., 2000; Paskaleva et al., 2001]. Maps representing the zoning of the town based on the soil classifications, as provided in different seismic codes, have been constructed. The results show that for Russe site, the Eurocode 8’94 soil classification, fig. 3, is the most suitable in comparison with the Bulgarian and Romanian Codes [Paskaleva et al., 2001].

![Figure 2](image1.png)

Figure 2. Schematic representation of the model adopted for the numerical experiments. The solid horizontal lines define the geological strata, the dashed lines represent the fictitious interfaces introduced to line up the layers of the two quaterspaces.

![Figure 3](image2.png)

Figure 3. Scheme of the soil conditions at the site of Russe according to EUROCODE 8. The investigated profile is marked by the bold solid line a-a. Point P2 corresponds to the station where recorded accelerograms are available.
3 SYNTHETIC SEISMIC LOADING – DISCUSSION OF THE RESULTS

The synthetic seismic signals have been computed along a representative geological cross section at Russe (profile a-a in fig. 3) for five recent, strong and intermediate-depth, Vrancea earthquakes that occurred during the last century (1940, 1977, 1986 and 1990), and have been compared with the available observations [Nenov et al., 1990]. The validation of the theoretical results against the available data [Kouteva et al., 2000; Paskaleva et al., 2001] has been performed on the base of comparisons of different quantities used in the engineering practice (e.g. acceleration time histories, a(t), peak ground accelerations, PGA, Fourier amplitude spectra, FS, and response spectra, SA). A further validation of the obtained results [Panza et al., 2002] was drawn out comparing the synthetic and the observed SA and Absolute Energy Input, Ei, [Uang and Bertero, 1990; Decanini and Mollaioi, 1998], figs. 4.a – 4.b.

At Russe, the synthetic SA of the horizontal components (EW-86, TRA-VR901 and RAD-VR901) underestimates the recorded quantities for the VR86 and VR901 events, while for the UP component the theoretical values overestimate the observed ones (fig. 4.a). For the energetic spectra, shown in fig. 4.b, all horizontal ground motion components (TRA, RAD, EW) both for VR86 and VR901 show that the synthetic Ei values are smaller than the observed ones. For VR86 the theoretical Ei overestimates the recorded one. The best agreement between the theoretical result and the recorded signal is obtained for the VR901 - UP component.

The ground motion at a given site reflects the contribution of the seismic source and of the geophysical properties of the media through which seismic waves propagate to reach the site. There are several uncertainties which have to be considered in the analysis: e.g. the hypocentral location, the parameters of the fault plane solutions, the definition of the geological profiles and their velocity models (the latter are usually constructed either using results of geological and geophysical studies or tomography studies). To test how the recorded signals are exhaustive of the possible ground amplification in Russe, additional numerical experiments regarding SA and Ei have been carried out varying the focal mechanism parameters and the velocities of the uppermost 300 m of the local model [Kouteva et al., 2003]. Some results about the Ei variation with the change of the focal mechanism and of the local structure are shown in fig. 5.

Figure 4.a. Russe, VR86 and VR901. Validation of the theoretical results with the recorded accelerograms at Russe. SA versus frequency, computed from the synthetic (solid line) and observed signals (dashed line) for different ductility factors m=1, m=2 and m=4. Transverse (TRA), Radial (RAD) and Vertical (UP) components.
The performed numerical experiments show that all the ground motion components can give a significant contribution to the design seismic input. The ground motion is significantly influenced by the earthquake source characteristics. Among the ground motion parameters considered, SA and $E_I$, the latter is more sensitive to the changes in the source parameters. The focal mechanism parameters influence mainly the spectral amplitudes of SA and $E_I$, while the variation of the local site velocity model causes changes in the frequency content of the seismic loading. The horizontal components, transverse (TRA) and radial (RAD), give a greater contribution to the seismic loading compared to the vertical (VRTX) one. In terms of SA, the RAD component is the most sensitive to the focal mechanism, compared to the other two ground motion components. The VRT is the less influenced by the changes of the local site velocity model. In terms of $E_I$, the horizontal components contribute much more to the seismic loading than the VRT one, and the RAD and VRT components are significantly more affected by the considered variations than the TRA component. Between the two studied ground motion parameters, SA and $E_I$ [Kouteva et al., 2003], $E_I$ is more sensitive to the changes in the seismic source tensor. The seismic source parameters influence mainly the spectral amplitudes of SA and $E_I$, while the variation of the local site velocity model causes changes in the frequency content of the seismic loading, fig. 5. Some shifts of the periods, corresponding to the SA and $E_I$ maximum amplitudes, have been observed with the variations of the considered parameters. The largest period shifts of the maximum SA and $E_I$ amplitudes have been observed for the RAD component. Some additional tests were done with respect to the bedrock structure and small changes in the layered strata did not influence the seismic input at the site.

The site amplification at Russe has been defined as the ratio between the SA values obtained for the laterally varying model, normalised to the corresponding values obtained for the average bedrock model, i.e. $RSR = SA$ (bedrock) / $SA$ (site). The site response along the chosen profile has been computed and the RSR have been mapped versus epicentral distance and frequency for each ground motion component, TRA, RAD and VRT [Panza et al., 2002; Kouteva et al., 2001], and the results are shown in figs. 6.a – 6.e. Site amplification along the profile investigated was also computed as the ratio between the maximum SA amplitude, obtained considering the local heterogeneity and the corresponding value for the bedrock model. The comparison of these site amplifications, considering all earthquakes of interest is shown in fig. 6.f.
Figure 5. Absolute energy input $E_i$ computed at the recording station at Russe due to VR40, VR77, VR86, VR901 and VR902 earthquakes. Transverse (TRA), radial (RAD) and vertical (VRT) components are shown.

The comparison of the site responses, shown in figs. 6.a – 6.e and in Panza et al., 2002; Kouteva et al., 2001, shows significantly different amplification patterns for all the ground motion components. In figs. 6.a–6.e one can observe that the strongest amplification (~4) corresponds to the deepest earthquake considered in the computations, i.e. VR40 (focal depth 150 km), for the VR40-VRT component, shown in fig. 6.a. Site amplifications in the range 2 - 3 are obtained for the VR77-RAD and VR902-RAD, shown in figs. 6.b and 6.e. The TRA-SA amplification varies within 1.2 - 2.0 for all the considered earthquakes. A comparison of these results shows the significant contribution of all the ground motion components to the earthquake loading, and the very irregular amplification pattern associated to the different earthquakes and the ground motion components. This result indicates that the ground motions at the site depends not only on the elastic and non-elastic characteristics of the propagation media, but also on the seismic source parameters and its location as well.
Figure. 6. Russe site - amplification along the investigated profile, defined as the ratio between the maximum SA amplitude, obtained considering the local heterogeneity and the corresponding value for the bedrock model. a: VR40; b: VR77; c: VR86; d: VR901; e: VR902 and f: comparative plot of the amplification along the chosen profile for all the considered events. Transverse (TRA), radial (RAD) and vertical (VRT) component are shown.

4 CONCLUSIONS
The obtained results show that urban areas located at large epicentral distances with respect to the seismic source may be prone to severe earthquake hazard. The numerical experiments performed, validated by the few available records, show that all ground motion components give a significant contribution to the design seismic input. The ground motion is significantly influenced by the earthquake source characteristics. Between the ground motion parameters studied, SA and EI, the latter is more sensitive to the focal mechanism parameters, that influence mainly the spectral amplitudes of SA and EI, while the variation of the local site velocity model causes changes in the frequency content of the seismic loading.

The used approach for the ground motion modelling is capable to provide, in an efficient way large sets of seismic signals with the related quantities of earthquake engineering interest. Thus it is possible to obtain the definition of the seismic input at a low cost, exploiting large quantities of existing data (e.g. geotechnical, geological, seismological). Its main advantage is the possibility to
investigate the site response, taking into account both the seismic source and the propagation effects. In the lack of statistically significant instrumental data, the use of realistic synthetic seismograms, validated with the macroseismic and the few instrumental data available, represent the possibility for the immediate assessment of the seismic input. To define the seismic loading, different earthquake scenarios must be considered, taking into account the various factors influencing the ground motion.

The method addresses the issue of the deterministic definition of the ground motion, allowing to draw significative conclusions also for locations in which there is little seismic history. This philosophy is a result of the progress in the fields of geophysics, seismology and earthquake engineering, and has been recently independently encouraged both by seismologists and engineers. It is an innovative complementary approach for the engineering seismic hazard assessments. We strongly recommend to use this kind of analysis, together with the traditional widely used methods, for the definition of the seismic loads to be used in the engineering analysis, particularly for the purposes of seismic microzonation or for seismic risk estimates related to extended or long-span structures.

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