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Deterministic Earthquake Scenarios for the City of Sofia

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Abstract—The city of Sofia is exposed to a high seismic risk. Macroseismic intensities in the range of VIII – X (MSK) can be expected in the city. The earthquakes that can influence the hazard in Sofia originate either beneath the city or are caused by seismic sources located within a radius of 40 km. The city of Sofia is also prone to the remote Vrancea seismic zone in Romania, and particularly vulnerable are the long-period elements of the built environment. The high seismic risk and the lack of instrumental recordings of the regional seismicity make the use of appropriate credible earthquake scenarios and ground-motion modelling approaches for defining the seismic input for the city of Sofia necessary. Complete synthetic seismic signals, due to several earthquake scenarios, were computed along chosen geological profiles crossing the city, applying a hybrid technique, which combines the modal summation technique and finite differences. The modelling takes into account simultaneously the geotechnical properties of the site, the position and geometry of the seismic source and the mechanical properties of the propagation medium. Acceleration, velocity and displacement time histories and related quantities of earthquake engineering interest (e.g., response spectra, ground-motion amplification along the profiles) have been supplied. The approach applied in this study allows us to obtain the definition of the seismic input at low cost, exploiting large quantities of existing data (e.g. geotechnical, geological, seismological). It may be efficiently used to estimate the ground motion for the purposes of microzonation, urban planning, retrofitting or insurance of the built environment, etc.

Key words: Seismic hazard, ground-motion modelling, hybrid approach, Sofia.

Introduction

The city of Sofia is the main administrative center in Bulgaria, with the densest population. Large industrial zones are located in its vicinity. If a strong earthquake should occur in the Sofia area it could produce disastrous damage in a large region,

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followed by numerous heavy consequences for the entire country (communications, lifelines). Therefore the purpose of our study is to:

(1) contribute to the earthquake hazard assessment of Sofia, providing earthquake scenarios with respect to specific earthquakes that can affect the city, as suggested by the geological outline, the regional earthquake hazard and the seismicity records at Sofia;
(2) supply synthetic seismic signals computed using source and structural models available in the literature and to validate these theoretical results on the base of the available reports on earthquake damage;
(3) provide site response estimates at Sofia due to the chosen earthquake scenarios.

In general there are two main classes of methods used to generate synthetic ground motion: numerical and analytical methods. In this study, the synthetic ground motion was generated applying a hybrid approach (FÄH *et al.*, 1993; 1994a,b). It combines the modal summation technique (PANZA, 1985; PANZA and SUHADOLC, 1987; PANZA *et al.*, 2000), used to describe the seismic wave propagation in the anelastic bedrock structure with the finite-difference method (VIRIEUX, 1984, 1986; LEVANDER, 1988) used to model wave propagation in the anelastic, laterally inhomogeneous sedimentary media. The computations were performed separately for the SH and P-SV waves. This hybrid procedure has been proved successfully for several major cities: Mexico (FÄH *et al.*, 1994b), Rome and Naples, Italy (FÄH *et al.*, 1994a; VACCARI *et al.*, 1995), Bucharest (PANZA *et al.*, 2002), Thessaloniki (TRIANTAFYLLIDIS *et al.*, 1998), Beijing (SUN *et al.*, 1998), Naples (NUNZIATA *et al.*, 2000), Zagreb (LOKMER *et al.*, 2001).

Geological Outline

Sofia valley is situated in the northernmost part of the Central-Balkan neotectonic region. It coincides with the Sofia graben, a structure set in the downlift regions of the western part of the Sredna Gora tectonic zone. In the south the graben is limited by a fault belt which extends along the northern edge of the Vitosha and Lozen mountains and in the north by the Negushevo fault zone (CHRISTOSKOV *et al.*, 1989; JARANOFF, 1960). Recent neotectonic studies (TZANKOV and NIKOLOV, 1996) consider that the graben had been developed under the leading part of the listric faulting along the two sides of the corresponding segment of the first-rate neotectonic Maritza protofracture. This protofracture passes through the axial part of the Sofia field and marks the initial zone of the extension opening of the fault basin. The seismicity of the zone is related mainly to the marginal neotectonic faults of Sofia graben (SOLAKOV *et al.*, 2001). There are two main fault structures in the southeast-northwest direction present in the region. Other cross-faults as well as a number of disjunctive disturbances, e.g., the Lozen terrace, the central Sofia terrace, Slatina uplift, contribute to the regional seismicity.

The Sofia Kettle extends from east to west 75 km long and 26 km wide in its western part. The average altitude at Sofia Kettle is about 550 m. The Kettle is relatively flat with a relief gradually rising towards the surrounding mountains. The city of Sofia is situated in the central part of the Kettle, near the foot of the Vitosha and Ljulin mountains. The Quaternary cover, building up the uppermost part of the Sofia Kettle, is from 3 m to 100 m thick and higher. It is covered by Pliocene and Quaternary sediments from 200 m to 700 m thick, in some places reaching 1200 m. The Quaternary sediments, rather different in their composition and properties, are widespread and lie over older rock and soil. The permeability of these sediments predetermines the shallow water table in the region and the possibility for suffusion or liquefaction of the fine water-saturated sands. Neogene sediments with various grain size distributions and a high content of silt fraction (42–82 %), take part to depths of 25–30 m below the surface (FRANGOV, 1995; IVANOV, 1997; IVANOV *et al.*, 1998). The "cultural" layer is composed of old structures, technogenic soils, industrial and household waste. The first layer of old structure remnants is the thickest in the central part of the town (up to 10 m). The distribution of the technogenic soil, composed of reworked rocks and soil and industrial waste, is in proximity to the opened pits, the big city residential buildings and the power stations. Recently a detailed geological map of the surface soil conditions at Sofia (23.30 E, 42.60 N – 23.50 E, 42.80 N) has been constructed (PASKALEVA and KOUTEVA, 2001a). It covers a grid 1 x 1 km, following a four—degree scale, where soil is distinguished as rocks (soil parameter s = 3), intermediate soils (s = 1, 2) and weak soil (s = 0). Among all these soil types present at Sofia, the intermediate weak soil takes a predominant part in the area of interest.

Local Seismicity

Strong earthquakes with magnitude, M, up to 7 shook Sofia in the past centuries (BONCHEV *et al.*, 1982; Shebalin *et al.*, 1999; SOLAKOV *et al.*, 2001). During the last two centuries three destructive earthquakes occurred: in 1818, $M_s \sim 6.0$), in 1858, $M_s \sim 6.5$ (near the town of Sofia, macroseismic intensity I = IX–X, MSK–64) and in 1905, $M_s \sim 6.5$ (in the western marginal part of the Sofia Kettle). In the same period several weaker events with I = VI–VII (MSK–64) were also reported. In 1907 (M = 4.6), 1909 (M = 4.6) and 1910 (M = 4.8) earthquakes with I up to V–VI (MSK) were felt in Sofia. On October 18, 1917, a strong earthquake (M = 5.3) with its epicenter in the vicinity of Sofia occurred and the maximum observed macroseismic intensity was I = VII–VIII (MSK) (KIROV, 1952; PETKOV and CHRISTOSKOV, 1965; CHRISTOSKOV, 1992). In the recently compiled earthquake catalogue (SHEBALIN *et al.*, 1999), for the region of Sofia, limited by the rectangle 42.25 N, 22.75 E–43.25 N, 24.00 E, 79 events within the magnitude interval M = 4–7 have been reported for the time period 1687–1990. In fact, since 1900 four earthquakes with magnitude 5 and higher occurred in the valley: 1904, Apr. 11, $M = 5.2$, 1912, Sept. 16, $M = 5.3$, 1928, Apr. 18, $M = 5.0$, and 1934, June 7, $M = 5.3$. No strong events have been reported, nonetheless the tectonic processes generating the earthquakes are obviously still active (PASKALEVA *et al.*, 2004). During the period 1977–2000, 147 events occurred in the Sofia seismic zone, the strongest one (1980, Sept. 03) was with a magnitude of $M = 4.3$ [NEIC]. In 1983 epicentral macroseismic intensity Io $\sim$ V and I = III–V were reported for Sofia and vicinity due to the earthquake of Dec. 22, $M = 3.6$, which struck just beneath the city (GLAVCHEVA, 1993).

An epicenter map of all reported seismic events with magnitude $M = 4.0$–7.0 is shown in Figure 1 (MATOVA, 2001). The weak earthquake epicenters are located along the faults as well as in the horsts to the north, east and south of the Sofia graben. The strong and moderate earthquake epicenters are concentrated along the faults, and also in the fault crossing joints, mainly in the central and the southern parts of the Sofia graben. The earthquakes with focal depths of 11–30 km are concentrated near the Vitosha fault and in the vicinity of its crossings with the Chepintsi and the Vladaya faults (Fig. 1).

Earthquake Hazard Estimates

Several studies treating the seismic hazard in Bulgaria (BONCHEV *et al.*, 1982; OROZOVA–STANISHKOVA *et al.* 1994, 1996) and particularly for Sofia (PETKOV and CHRISTOSKOV, 1965; CHRISTOSKOV *et al.*, 1989; STANISHKOVA and SLEJKO, 1991; RANGUELOV and TOTEVA, 1996, 1998; SOLAKOV *et al.*, 2001), based on different approaches, have shown the high seismic hazard at Sofia and the surrounding area. Maximum macroseismic intensity at Sofia, I = IX (MSK), already observed in 1858 (BONCHEV *et al.*, 1982), can be expected to occur within a period of 150 years (CHRISTOSKOV *et al.*, 1989). The recently constructed seismic hazard maps of the Circum-Panonian Region (PANZA and VACCARI, 2000) reveal that Sofia could suffer macroseismic intensity reaching VIII–X (MSK—76) (MEDVEDEV, 1977). The first seismic microzonation map for Sofia was constructed in 1964 in terms of macroseismic intensity (PETKOV and CHRISTOSKOV, 1965). In this map three zones can be distinguished: zone "A", which encompasses covers the south-eastern central part of the town with maximum expected intensity (MSK) I = IX and some small "spots" out of this part; zone "B" with I = I–1 that covers mainly the northern part of the center of the town, and zone "C" with intensity I = I–1 up to I–2, that covers most of the city area, at that time. This seismic microzonation map has been extended to a larger area of the city. The macroseismic intensity at Sofia varies within 2 degrees (MSK). The intensity variation along the considered profiles is used to control the validity of the obtained theoretical results (Figs. 4, 5). If coseismic effects are considered (e.g., landsliding, liquefaction) the intensity still varies within the same interval $\Delta I = 2$. In this case its distribution within the investigated territory changes

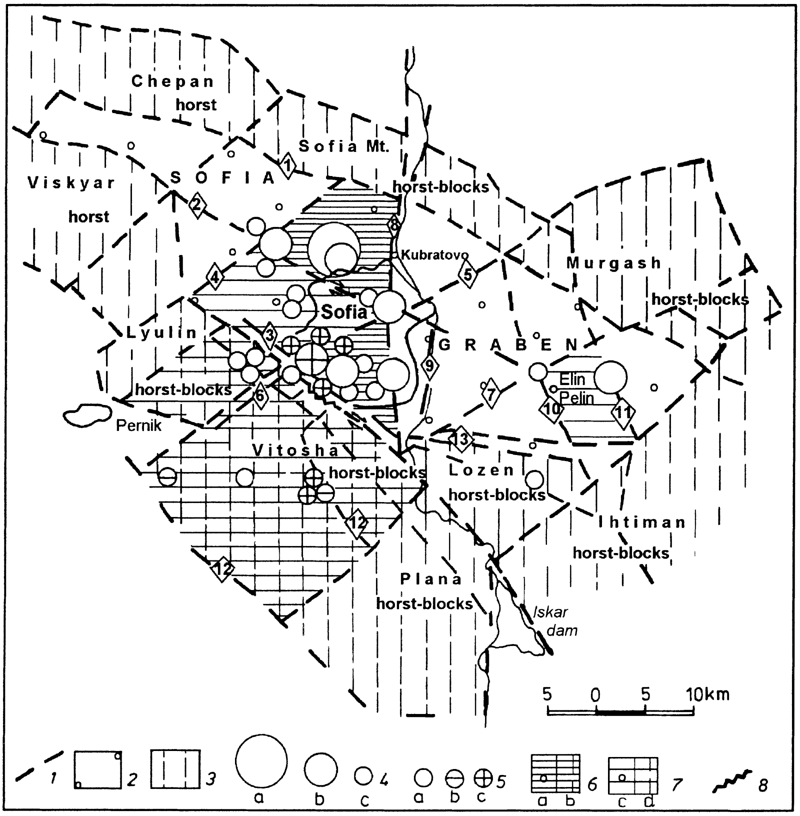

Figure 1
Seismic events with magnitude M = 4.00–7.00 in the blocks of the Sofia graben and the adjacent horsts: 1—faults: a—block boundary, b—sector of the Vitosha fault zone activated during the 1858 Sofia earthquake (M = 6.5–7.0); 2—the block of the Sofia graben, 3—the block of the adjacent horsts, 4—epicenters of earthquakes with magnitude: a—M = 6.0–7.0; b—M = 5.0–5.9, c—M = 4.0–4.9; 5—depths of earthquake hypocentres: a—up to 10 km, b—11–20 km, c—21–30 km; 6—blocks of considerable seismic mobility: a—of the graben, b—of the horsts; 7—blocks of moderate seismic mobility: a—of the graben, b—of the horsts; 8—seismic active sector of Vitosha fault during the Sofia earthquake in 1858.

visibly, particularly in the southwestern part of the region, however the maximum intensity remains at the southern part of the city center.

Several papers have been published addressing the seismic hazard in Bulgaria (e.g., Bonchev *et al.*, 1982; Orozova-Stanishkova and Slejko, 1994). Different authors consider different seismic zones that can influence the seismic hazard at Sofia (e.g., Paskaleva and Kouteva, 2001; Solakov *et al.*, 2001). Kresna, Plovdiv, Negotinska Krayna and Gorna Orjahovitza are considered to be the main seismic zones in Bulgaria capable of influencing the seismic hazard of Sofia. Sofia is also prone to the remote Vrancea seismic zone (Romania), the long-period elements of the built environment being particularly vulnerable to these events. The available data are rather limited and the statistical determination of the coefficients of the Frequency—Magnitude Relationships (FMR) for these zones is affected by major uncertainties (MOLCHAN *et al.*, 1997). Preliminary computations were carried out applying a maximum likelihood based procedure (MOLCHAN *et al.*, 1997). Two schematic tectonic models (TODOROVSKA *et al.*, 1995; PASKALEVA and KOUTEVA, 2001) were considered with respect to the Earthquake Catalogue for east and southeast Europe (SHEBALIN *et al.*, 1999) for the Bulgarian territory and the Romanian earthquake catalogue for Vrancea zone in Romania, ROMPLUS (www.infp.infp.ro). The preliminary estimates of these coefficients, which are given in Table 1, show quite large confidence intervals for the b—values.

The probabilistic seismic hazard analysis (PSHA) for the Sofia area, carried out by SOLAKOV *et al.* (2001) provides a sensitivity analysis of the PGA, keeping the same seismic source model and the same seismicity characteristics, and varying the standard deviations in the PGA attenuation mode. A difference up to 200% in the PGA value for 1000-years period was obtained and this result has been related to the fact, that regional, but not local attenuation functions were used. A doubt springs from the fact that in general the regional data sets are statistically not significant to represent the very different seismotectonic styles that are not mixable, and usually attenuation functions are derived with the assumption of the same propagation model for all events considered (DECANINI *et al.*, 2001). In this study an attempt to avoid such uncertainties, when particularly accounting for site response in the seismic hazard analyses, is performed. In our computations a deterministic procedure for ground motion modelling, capable of synthesizing the seismic ground motion from a basic understanding of fault mechanism and seismic wave propagation, has been applied (FÄH *et al.*, 1993; 1994a, b).

Parameterization of the Earthquake Scenarios and the Models Adopted

The seismicity of the Sofia region involves the upper 20–30 km of the lithosphere. Maximum macroseismic intensity I = VIII –IX can be expected at Sofia

Table 1

Estimates of the b coefficient of the FMR

Seismic zone	b Tectonic model 1	b Tectonic model 2
Sofia	0.50 ± 0.30	0.55 ± 0.33
Negotinska Krayna		1.01 ± 0.50
Kresna	0.69 ± 0.08	0.72 ± 0.08
Plovdiv	0.73 ± 0.08	0.76 ± 0.10
Gorna Orjahovitza	0.80 ± 0.20	0.76 ± 0.23
Vrancea	0.65 ± 0.15	0.70 ± 0.15

(GLAVCHEVA, 1990), if an earthquake with maximum magnitude $M_{\max}$ = 7 (BONCHEV *et al.*, 1982) occurs at a depth close to 20 km. Maximum macroseismic intensity IX (and higher) can be provoked by events with $M_{\max}$ = 6.5 and focal depth around 7 km. In the computations carried out in this study, on the basis of the earthquake history at Sofia and on the available seismic hazard assessments provided in the literature, three shallow earthquake scenarios (Table 2) were considered. They correspond to seismic sources located at different distances and azimuths (up to 30 km distant from Sofia) (SLAVOV, 2000). Preliminary computations were carried out with respect to a local seismic source that can strike just beneath the city. The earthquake epicenters correspond to real seismic event, which struck Sofia: March 9, 1980; December 22, 1983; December 14, 1995 and April 20, 1996. The complete scenarios are constructed considering the conservative combinations of information available in the literature (e.g., NEIC, SHANOV *et al.*, 1992; GLAVCHEVA *et al.*, 1996).

A generalized scheme of the model adopted for the numerical experiments is shown in Figure 2. The seismic waves propagation path consists of the travelled path between the source and the target site (the ‘‘bedrock structure’’) and the target local cross sections. The data used to build-up the local structural models, to 1000 m below the surface, are obtained from a large set of boreholes and geological cross sections (PETROV and ILIEV, 1970; KAMENOV and KOJUMDIEVA, 1983; FRANGOV, 1995; IVANOV, 1997; IVANOV *et al.*, 1998). The lower part of the local model describing the structure below this 1 km, coincides with the bedrock velocity model available in the literature and assumed to be the same for the Sofia Kettle (STANISHKOVA and SLEJKO, 1991). A summary of the geophysical properties of the geological strata beneath the city of Sofia considered in this study is shown in Table 3. The models' grids used in the computations are summarized in Table 4. This study deals with the two-dimensional problem of wave propagation and ground motion modelling.

Table 2

Earthquake scenarios studied by the numerical experiments

Profile identification as shown in Fig. 3	Earthquake date, location, latitude (La) Longitude (Lo) magnitude (M)			Seismic source moment tensor considered in the computations				
				Strike angle	Dip angle	Rake angle	Focal depth	Epicentral distance to the nearest profile considered
	La.[^{0}]	Lo.[^{0}]	M	[^{0}]	[^{0}]	[^{0}]	[km]	[km]
AB	42.95	23.36	4.4	135	43	111	10	25.0
	42.76	23.39	3.6	A Ricker impulse introduced at 2 km beneath the city				
CD	42.54	23.52	3.3	21	44	309	2	8.6
EF	42.79	23.49	6.5	340	77.6	285	8	15.0

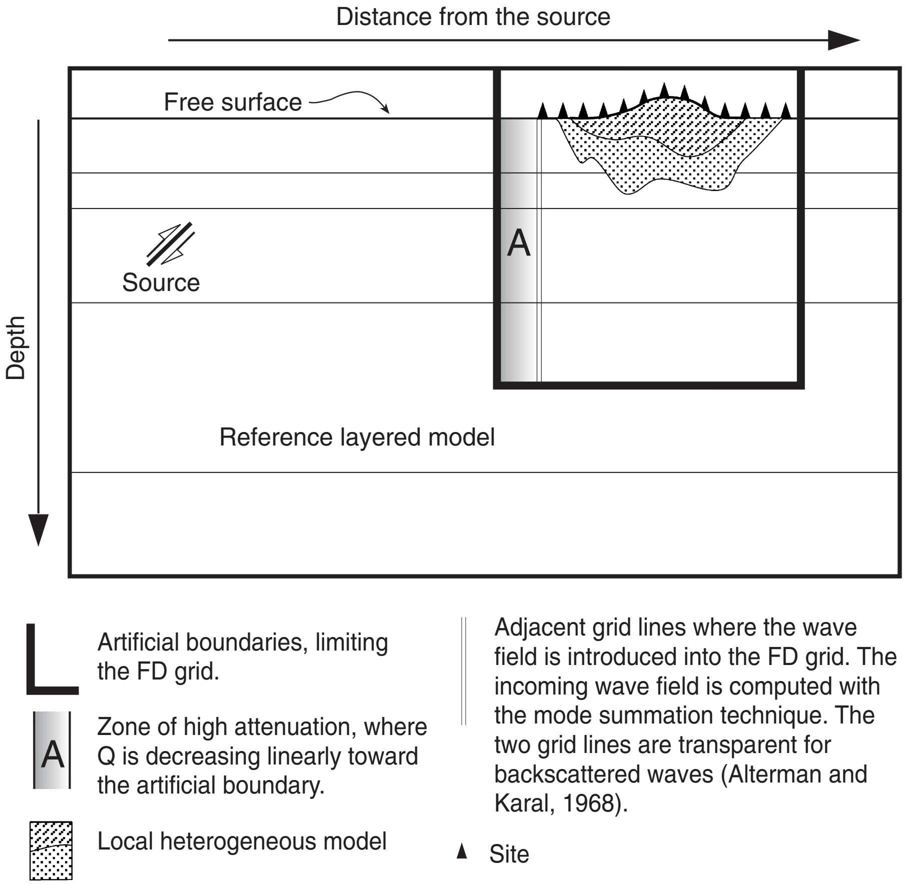

Figure 2
A generalized scheme of the model adopted for the numerical experiments.

Table 3

Geophysical properties of the geological strata used to model the Sofia kettle

Layer	Density	Seismic wave propagation velocities		Attenuation factor, Q	
	ρ [kg/m^3]	Vp [m/s]	Vs [m/s]	Qp	Qs
Soil Layer	1800	310	180	40	15
Quaternary cover	1970	950	550	50	20
Tertiary sediments	1920	1400	800	75	30
Senonian marls	2000	1900	1100	100	40
Triassic limestones	2020	2100	1200	120	50
Senonian andesites	2540	3600	2100	200	80

Table 4

Mesh and model size considered in the FD computations

Profile	Mesh size		Model size	
	X, grid points	Z, grid points	X, km	Z, km
AB	2082	577	10.41	19.80
CD	2939	310	11.76	3.95
EF	2978	474	11.91	10.00

Considering the regional topography of the studied area, it is advisable to perform investigations, implementing a three-dimensional model as well. This can be done as soon as significant records become available and that will allow the assessment of possible 3-D effects.

Numerical Experiments and Discussion of the Results

Complete synthetic seismic signals have been generated for all sites of interest along the profiles investigated, (Fig. 3 ~ 100 sites per profiles), following the earthquake scenarios given in Table 2. Two groups of experiments have been performed: (A) ground-motion modelling, applying an algorithm based on the modal summation method (PANZA, 1985; PANZA and SUHADOLC, 1987), 1-D, and (B) modelling, making use of the hybrid technique (FäH *et al.* 1993; 1994 a,b), 2-D. The distant seismic sources were considered as buried double-couple point sources. The local seismic source was modelled by introducing a single Ricker impulse at the bottom of the model.

The chosen frequency interval (up to 5 Hz) covers practically the entire range of elements of the built environment present at Sofia. Synthetic seismic signals along the profiles investigated (Fig. 3, Table 2) are computed and acceleration, velocity and displacement time histories are obtained for all ground-motion components, transverse (TRA), radial (RAD) and vertical (VER). Different quantities of earthquake engineering interest, such as peak ground accelerations (PGA), peak ground velocities (PGV), peak ground displacements (PGD), response spectra amplitudes (SA) and PGA / PGV ratios, are derived from the computed seismic signals. The site response along the investigated profiles is defined as Response Spectra Ratio (RSR). These RSR are the ratios between the amplitudes of the response spectra, for 5% damping (SA), computed taking into account the local heterogeneous media (SA2), and the corresponding values obtained considering only the bedrock structure (SA1), RSR = SA2 / SA1. The distributions of RSR versus frequency and epicentral distance for all studied scenarios have been mapped.

Comparisons between the seismic signals simulated by the modal summation method and those, obtained applying the hybrid technique for the simple bedrock

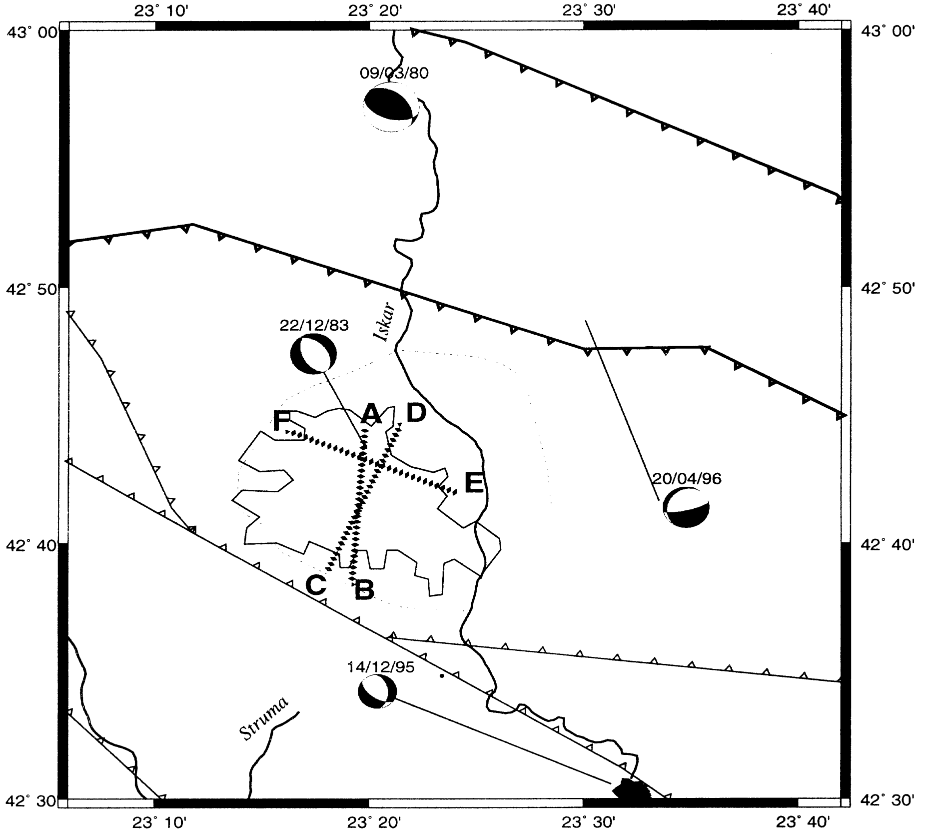

Figure 3
A generalized tectonic scheme of the Sofia region, investigated profiles (AB, CD and EF), location and focal mechanisms of the considered earthquakes.

layered structural model have been carried out. These tests are always necessary when the hybrid approach is applied in a new region. The differences between both the modal summation method and the hybrid technique are negligible (less than 3–5 %). It means that the control of the accuracy of the FD part of the computations, depending upon the efficiency of the absorbing boundaries, the correct discretization of the structural model, the presence of all phases in the seismograms and the treatment of anelasticity, has been successfully achieved.

To validate the theoretical computations, the observed macroseismic information was used. No instrumental data are available for the considered events since the digital seismological station (VTS—Sofia) began operation in May 1996. The macroseismic maps for the earthquakes in 1907, 1909, 1910, 1917, 1941, 1947 and 1952 (PETKOV and CHRISTOSKOV, 1965; GLAVCHEVA, 1990; CHRISTOSKOV *et al.*, 1989) are too general with respect to the microzonation purposes and no information is available on the fault plane solution of the mapped earthquakes. The few published maps of seismic microzonation for Sofia (PETKOV and CHRISTOSKOV, 1964; SOLAKOV, 2001) show maximum variations within two degrees of macroseismic intensity. Macroseismic intensity variation $\Delta I = 2$ is also reported for the earthquake of December 22 (GLAVCHEVA, 1990), that has been considered for the computations of the ground motion along the AB profile. The existing relation between PGA and the macroseismic intensity, I (MEDVEDEV 1977), and between PGA/PGV and I (SEED and IDRISS, 1982) have been used to provide theoretical estimates of the macroseismic intensity of each site. The theoretically estimated macroseismic intensity varies within two degrees in the investigated region, which is in agreement with the available observation. The synthetic signals obtained considering an earthquake scenario with magnitude $M = 6.5$ and focal depth $\mathrm{H} = 8$ km show $200\ \mathrm{cm/s}^2 < \mathrm{PGA} < 400\ \mathrm{cm/s}^2$, I = VIII–IX (MEDVEDEV 1977). This result is consistent with the parameterization of the isoseimals from Bulgarian earthquakes (GLAVCHEVA, 1990).

The maximum SA(2D) values, computed for 5% damping were normalized to the corresponding SA(1D) values for each site along the profiles investigated. The results for all components TRA, RAD and VER are shown in Figures 4.1–4.3. Along profile AB, Figure 4.1, the theoretical curves for TRA, RAD and VER justify the one-degree intensity increment, although they fail to explain larger intensity increments. Regarding the scenario, dealing with earthquakes beneath the city, the TRA–SA ratio variation matches the reference intensity graph within epicentral distances 25–26 km, 28–30 km and 31–33 km. Most impressive are the results we obtained along profile CD (Fig. 4.2). The peaks in the SA(2D)/SA(1D) for all components TRA, RAD and VER follow the lateral variation of the structural model. The variation of SA(2D)/SA(1D) explains well local intensity increments as large as 3, and in general are in agreement with the variation of I along the profile. For both profiles AB and CD the VER component seems uncorrelated with the intensity variation. The possible correlation of the computed amplification of the VER component to the observed damage has been reported (e.g., LOKMER *et al.*, 2001; PANZA *et al.*, 2002). Along the EF profile (Fig. 4.3) the RSR for the horizontal components varies within 2 and 4, in agreement with the reported one-degree local intensity increment. The comparison between the intensity, theoretically estimated on the base of the PGA(2D)/PGA(1D) or PGV/PGA ratios and the reported intensity, leads to similar conclusions. The observed mismatch between the synthetic signals and the reported intensity is not surprising. It may warrant refinement and renovation of the seismic microzonation intensity maps, however it can be due to inadequacies in the assumed parameters describing the source and the medium.

A successful test for the numerical modelling of the ground motions at Sofia stems from most of the PGV/PGA ratios. The computed ratios agree with the values suggested by SEED and IDRISS (1982) and DECANINI (pers. com., 1998) for intermediate soil ($V_s < 0.3$ km/s) and rocks and deep stiff soil ($0.6\ \mathrm{km} > V_s > 0.3$ km/s), Figures 5.1–5.3.

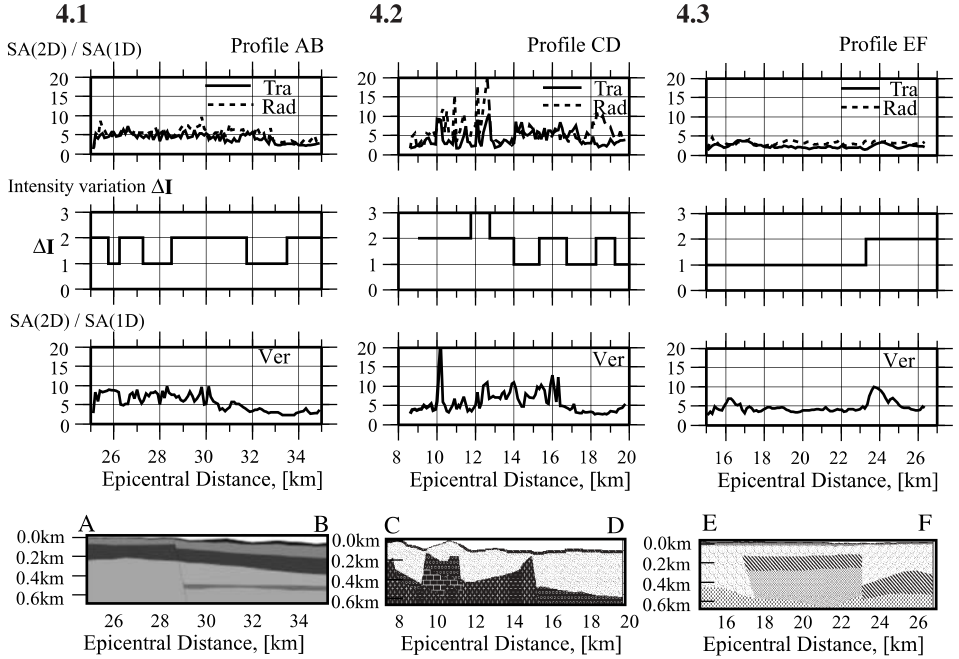

Figure 4
Spectral ratio Sa(2D)/SA(1D) for 5% damping, along the profile investigated (as shown in Fig. 3). Comparison with the macroseismic intensity I [MSK] variation graph along the same profiles (a fragment of map of seismic microzonation of Sofia). Transverse (TRA—solid line), radial (RAD—dashed line) and Vertical (Ver) components are shown). Figure 4.1: Profile AB; Figure 4.2: Profile CD; Figure 4.2: Profile EF.

Site amplification is estimated in terms of RSR distributions versus frequency and epicentral distance (Figs. 6.1–6.3). In Figure 6.1 the site amplification along the AB profile, which is exposed to a distant earthquake, is shown. One can see that the TRA component is amplified up to 4.6 (1.5–2.0 Hz), the RAD amplification reaches 3.6 (1.0–1.75 Hz) and the VER RSR increases to 7.5 within the frequency interval 1.25–3.00 Hz. If an earthquake strikes just beneath the profile AB (Table 3) then the ground motion at the site can be amplified by 10–11 times within the frequency interval 1.25–2 Hz (not shown in the figures). Along the CD profile (Fig. 6.2) the highest amplification is observed for the RAD component compared to the other two components. The maximum amplifications for all ground motion components (TRA, RAD and VER) are observed at frequencies higher than 3.5 Hz. For the RAD RSR reaches 7–8.5 (at 2.5–5 Hz), due to the VER RSR being to 3.5–5.0 (3.5–5.0 Hz) and for the TRA, the largest RSR is about 6 (3.5–4.5 Hz). The amplification along the profile EF is shown in Figure 6.3. TRA shows rather consistent amplification (less than 3) within the entire frequency

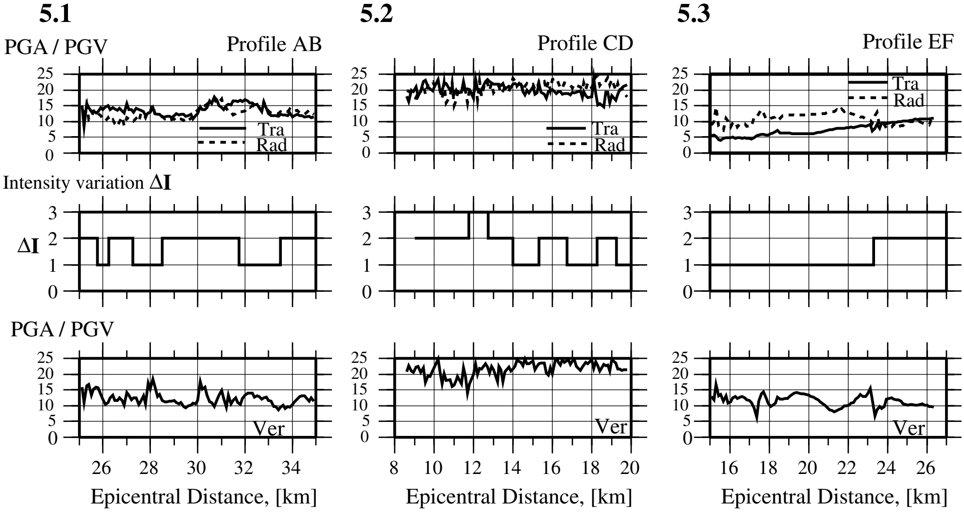

Figure 5
Scheme of the ratio of the peak ground velocity PGV to the peak ground acceleration PGA along the investigated profiles (as shown in Fig. 3), related to the macroseismic intensity *I* [MSK] variation along the same profiles (a fragment of map of seismic microzonation of Sofia). Transverse (TRA—solid line), radial (RAD—dashed line) and Vertical (Ver) components are shown). Figure 5.1: Profile AB; Figure 5.2: Profile CD; Figure 5.2: Profile EF.

interval considered, RAD has its maximum amplification (2.5–3.0) at 3.5–4.5 Hz and VER amplifies to 3.5–4.0 at frequencies 0.5 Hz and 1.3–1.8 Hz. For all scenarios the maximum amplifications along the profiles correspond to the weak or intermediate soil conditions as shown in the map of engineering geological conditions at Sofia (Paskaleva and Kouteva, 2001).

In all scenarios the presence of thick sediments leads to an increase of the ground-motion amplitudes and of the amplification, due to multiple reflections. The maximum PGA values correspond to both the thickest sediments and the thickest parts of the surface low velocity layer. A comparative study of the spectral amplification of the different ground-motion components reveals that TRA, RAD and VER significantly contribute to the seismic input, where as the RAD component exerts the prime influence on the site amplification, reaching values up to 7–8 whereas for TRA and VER components, the maximum amplification is 5–6. This result differs from the widely accepted idea that the transverse component predominantly contributes to the seismic input definition.

Four earthquake scenarios were chosen and complete synthetic seismic signals were generated along three geological profiles crossing the city of Sofia. A hybrid procedure that accounts simultaneously, into the ground-motion estimate, the seismic source moment tensor and the mechanical characteristics of the propagating media was used. The results obtained through the theoretical modelling

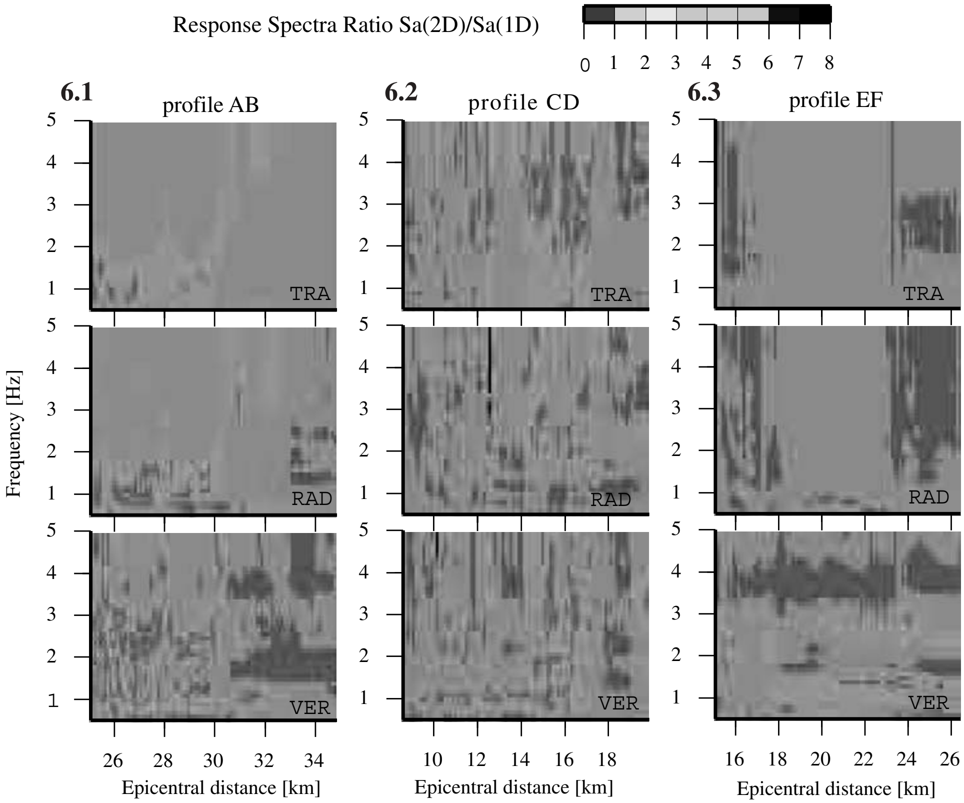

Figure 6
Site amplification defined as Response Spectra Ratio, (RSR), mapped versus frequency and epicentral distance along the profiles investigated (as shown in Fig. 3). Transverse (TRA), radial (RAD) and vertical (VER) components are shown.

have been successfully compared with the macroseismic field information available.

The approach used to model the ground motion at Sofia capably provides realistic acceleration, velocity, displacement time histories and related quantities of earthquake engineering interest. The most important result concerns the site response behavior. The comparative study of the spectral amplification of the different ground-motion components shows that TRA, RAD and VER significantly contribute to the seismic input. RAD exerts the major influence on the site amplification—this fact differs from the widely accepted idea that the transverse component predominantly affects the seismic input definition. The obtained results can be used for different engineering purposes, urban planning, retrofitting of the built environment, insurance industry, earthquake preparedness, earthquake risk reduction and earthquake risk management.

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