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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

AN EARTHQUAKE SCENARIO FOR THE MICROZONATION
OF SOFIA AND THE VULNERABILITY OF STRUCTURES
DESIGNED ACCORDING TO THE EUROCODES

Ivanka Paskaleva
Central Laboratory Seismic Mechanics and Earthquake Engineering (CLSMEE),
Bulgarian Academy of Sciences (BAS), Acad. G. Bonchev, block 3, 1113 Sofia, Bulgaria,

Silvia Dimova
European Laboratory for Structural Assessment (ELSA),
I-21020 Ispra (VA), Italy,

Giuliano F. Panza
Dipartimento di Scienze della Terra, Università degli Studi di Trieste, Trieste, Italy
and
The Abdus Salam International Centre for Theoretical Physics, SAND Group, Trieste, Italy

and

Franco Vaccari
Dipartimento di Scienze della Terra, Università degli Studi di Trieste, Trieste, Italy.

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1 paskalev@geophys.bas.bg
Abstract

The study of site effects and the microzonation of a part of the metropolitan Sofia, based on the modelling of seismic ground motion along three cross sections are performed. Realistic synthetic strong motion waveforms are computed for scenario earthquakes (M=7) applying a hybrid modelling method, based on the modal summation technique and finite differences scheme. The synthesized ground motion time histories are source and site specific. The site amplification is determined in terms of response spectra ratio (RSR). A suite of time histories and quantities of earthquake engineering interest are provided. The results of this study constitute a “database” that describes the ground shaking of the urban area. A case study of experiment-based assessment of vulnerability of a cast-in-situ single storey, industrial, reinforced concrete frame, designed according to Eurocodes 2 and 8 is presented. The main characteristics of damage index and story drift are discussed for the purposes of microzonation.
INTRODUCTION

The city of Sofia is the main administrative centre, with the densest population in Bulgaria. The Greater Sofia Municipality includes 61 settlements, 40 of which are towns. More than 1.2 million people live in the Municipality in an area of 1310 km², so the population density is about 915 people per km². City housing consists of 475,900 units covering an area of approximately 30 km². Sofia is a main administrative centre with a dense infrastructure connected by important international railway and automobile routes from Western Europe to Istanbul via Belgrade, and from Greece and Macedonia to the Middle East. Large industrial zones are located in its vicinity. Therefore a strong earthquake that might occur in the Sofia seismogenic area can produce disastrous damages in a large region, followed by numerous heavy consequences for a much broader region as regards communications, lifelines, etc.

The recent earthquakes e.g. Kobe (17.1.1995), Gujarat (26.1.2001), Boumerdes (21.5.2003) and Bam (26.12.2003) prove once more that for the urban areas to be safe and sustainable, a long-range urban planning must be implemented, based on multidisciplinary risk assessment tools. The challenge of urban hazard mapping is to predict the ground motion effects related to various sources, path and site characteristics not just at a single site but over an extended region, and to do so with an acceptable level of reliability. Seismic zonation then consists of linking together site-by-site estimates of site response. The practice shows that such an approach may significantly underestimate the amplitudes and durations of strong ground motion, with energy getting trapped within sedimentary basins due to critical reflections at the edges of the basin. The rapid increase in the development of efficient computational methods and procedures for modeling seismic wave propagation in laterally varying geological structures enables us to model the effects of sedimentary basins on the ground motion generated by scenario earthquakes. 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 is generated applying a hybrid technique (Fäh et al. 1993; 1995a, b [11, 12, 13]). It combines the modal summation technique (Panza, 1985; Panza and Suhadolc, 1987; Panza et al., 2000 [33, 34, 35]), used to describe the seismic wave propagation in the anelastic bedrock structure with the finite difference method (Virieux, 1984; 1986 [60, 61]; Levander, 1988 [27]) used for the computation of wave propagation in the anelastic, laterally inhomogeneous sedimentary media. The hybrid approach, applied in this study, already proved, in the framework of the UNESCO-IUGS-IGCP project 414, its capabilities for several major cities in different regions: Mexico City (Fäh et al., 1995b [13]), Rome and Naples, Italy (Fäh et al., 1995a [12]; Vaccari et al., 1995 [58]; PAGEOPH 2004 [32]), Bucharest (Panza et al., 2001 [36], 2002 [37]), Thessaloniki (Triantafyllidis et al., 1998 [57]), Beijing (Sun et al., 1998 [55]), Zagreb (Lokmer et al., 2002 [28]), Ruse and Sofia (Paskaleva and Kouteva, 2001, Paskaleva, 2002, Paskaleva et al., 2004a,b [39,40,41,42]), (Kouteva et al., 2002 [25]). The hybrid approach is being increasingly used to constrain those aspects of ground motion prediction that are poorly constrained by recorded strong motion data, like in the case of Sofia City (Nenov et al., 1990 [31]). Therefore, the aim of this study is to: (1) contribute to the earthquake hazard assessment of Sofia, providing earthquake scenarios consistent with the recent geological outline and the regional earthquake hazard at Sofia; (2) supply synthetic seismic signals computed using available source and structural model; (3) provide site response estimates at Sofia due to the chosen earthquake scenarios; (4) assess the vulnerability of structures designed according to the Eurocodes.
STRUCTURE OF THE BASEMENT AND SEISMOTECTONICS

The input data, necessary for the ground motion simulation with the hybrid approach, consist of the regional bedrock model, the laterally heterogeneous local model, and the earthquake source model. To prepare the input data for this study, a broad range of information recently collected for the Sofia valley has been analyzed and assessed.

Sofia City is situated in the central southern part of the Sofia kettle, a continental basin in southern Bulgaria, filled with Miocene-Pliocene sediments. The bedrock is represented by heterogeneous (in composition) and different (in age) rocks, which outcrop within the depression. The Sofia kettle is filled with Neogene and Quaternary sediments and its thickness reaches 1200 m near the town of Elin Pelin. From the structural point of view, the Sofia kettle represents a complex, asymmetric block structure graben, located in the West Srednogorie region, with an average altitude of about 550m. Active tectonic movements affected the basement of the kettle and formed its block structure (Ilieva and Josifov, 1998 [21]). The most uplifted block is the one in the center of the capital, near the Sofia thermal spring, and the most subsided one is in the region of the Elin Pelin town. During the last 25-30 years large amounts of geological and geophysical data have been collected: 180 boreholes have been drilled down to the Preneogene basement, and 354 km of seismic profiles have been analyzed.

The seismotectonic conditions are most dangerous in the middle and in the southern parts of the Sofia graben, where Sofia City is situated. Following the investigations carried out on the recent geodynamic features of the Sofia complex a geological and geophysical 3D model of the Earth’s crust for that region (Shanov et al., 1998 [48]) has been derived. The analysis of the seismotectonic setting and of the structure of the basement of the Sofia depression is used to specify the reference structural model. The P-wave velocities of the 1D regional structural model are taken from Shanov et al., 1998 [48], and for the S-wave velocities we assume Vp=2Vs. The data for the quality factor for P-waves, Qp, have been taken from (Dziewonski and Anderson, 1981 [10]) and the widely applied rule Qp=2.2Qs has been used to derive the quality factor for S-waves. To determine the attenuation values $A_{P,S}$ for P and S waves the following relationship has been used: $A_{P,S} = 0.5V_{P,S}Q_{P,S}$.

The Sofia area, with the traces of the considered profiles, is shown in fig.1. The laterally heterogeneous models, corresponding to the profiles, are defined from in-situ and standard laboratory tests (table 1) (Frangov, 1995 [18], Ivanov, 1997 [22]; Ivanov et al., 1998 [23], Paskaleva et al., 2004a, b [41, 42]).
Fig. 1. Generalised tectonic scheme of Sofia region and investigated profiles.

Fig. 2. Seismic events with magnitude M=4.00-7.00 in the blocks of the Sofia graben and the adjacent horsts (Matova, 2001). 1 – faults: a – of the block boundary (the name are indicated in the fig.4), b – sector of the Vitosha fault zone activated during the 1858 Sofia earthquake (M=6.5-7.00); 2 – block of the Sofia graben, 3 – 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 hypocenters: 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 1858 Sofia earthquake.

LOCAL SEISMICITY

Strong earthquakes with magnitude, M, up to 7 hit Sofia in the past centuries. During the XIX century two destructive earthquakes, in 1818 (M$_s$ ~ 6.0) and 1858 (M$_s$ ~ 6.5) and several others with macroseismic intensity I = VI - VII (MSK - 64) have been reported. The strongest events which occurred in the region are the earthquakes of 18/30.9.1858. The hypocenters have been under the town itself and the intensity is evaluated to be IX MSK (Christoskov et al., 1989 [6]). The detailed description and summary of the local seismicity in the vicinity of Sofia can be found in Solakov et al., 2001 [53], Slavov et al., 2004 [52]. The strong and moderate earthquake epicenters are concentrated along the faults and in the fault crossing joints, mainly in the central and in the southern parts of the Sofia graben. An epicentral map of all reported seismic events with magnitude, M, in the range 4.0-7.0 is shown in fig.2 (Matova, 2001 [29]). There is a mobile sector of the Vitosha faults in the vicinity of the Boyana quarter of the Sofia City (fig.2), that can be related to the 1858 Sofia earthquake (M=6.5-7.0).
Table 1. The Generalized characteristics for the 2D models corresponding to the profiles A-B, C-D and E-F

<table>
<thead>
<tr>
<th>MODEL “SOFIA 1”</th>
<th>MODEL “SOFIA 2”</th>
<th>MODEL “SOFIA 3”</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-E</td>
<td>W-E</td>
<td>S-N</td>
</tr>
<tr>
<td>Model</td>
<td>Density g/cm³</td>
<td>Vp km/s</td>
</tr>
<tr>
<td>sed1</td>
<td>1.87</td>
<td>0.900</td>
</tr>
<tr>
<td>sed2</td>
<td>1.93</td>
<td>1.580</td>
</tr>
<tr>
<td>sed3</td>
<td>1.93</td>
<td>1.580</td>
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</tr>
<tr>
<td>sed16</td>
<td>2.52</td>
<td>3.800</td>
</tr>
<tr>
<td>sed17</td>
<td>2.6</td>
<td>4.200</td>
</tr>
</tbody>
</table>

PARAMETERIZATION OF THE EARTHQUAKE SCENARIOS

When the ground motions for evaluation and design are characterized by a scenario earthquake, the primary earthquake source parameter is the magnitude or seismic moment of the scenario earthquake. In a deterministic analysis, the scenario earthquake is typically the largest earthquake that is expected to occur on the source that controls the seismic hazard around the city. Alternatively, a possible scale of scenario earthquakes is: disastrous (average return period about 500 years), very strong (average return period 200-250 years), strong (average return period 120-140 years) and frequent (average return period 50-60 years).

The maximum macroseismic intensity at Sofia, I = IX (MSK), observed in 1858 (Bonchev et al., 1982 [3]), can be expected to occur with a return period of 150 years (Christoskov et al., 1989 [6]), i.e. it could correspond to the strong scenario earthquake. Recently seismic hazard maps of the Circum - Pannonian Region (Panza and Vaccari, 2000 [35], Gorshkov et al. 2000 [20]), show that Sofia is placed in a node having potential for the occurrence of an earthquake with M> 6.5 and that it could suffer macroseismic intensity up to X. The seismicity of the Sofia region is limited to the upper 20 - 30 km of the lithosphere. A maximum macroseismic intensity I = VIII can be expected at Sofia (Glavcheva and Dimova 2003 [19]), if an earthquake with maximum magnitude M max = 7 (Bonchev et al., 1982 [3]) occurs at a depth of about 20 km, and a maximum macroseismic intensity IX (and higher) can be provoked by an event with M max = 7 and focal depth around 10 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, earthquake scenarios have been considered to correspond to seismic sources, located at 10 km distance from the center of the city in the West and South directions (Christoskov et al., 1989 [6]; Alexiev and Georgiev, 1997 [1]; Slavov, 2000 [51]; Matova, 2001 [29]; Solakov et al., 2001 [53]). The assumed source parameters, common to all cases, are chosen to approximate the seismic event which hit Sofia in 1858. The parameters of the source mechanism adopted are:
strike angle $340^\circ$, fault dip $77^\circ$ and rake (with respect to strike) $285^\circ$. This source mechanism has been used to generate seismograms along the profiles shown in fig. 1 and named: 1A-1B “Sofia 1” (M1), 2C-2D “Sofia 2” (M2) and 3E-3F “Sofia 3” (M3).

To assess influence of the source mechanism on the so-called site effects (see next section) the source with strike angle $0^\circ$, fault dip $44^\circ$ and rake (with respect to strike) $309^\circ$ has been used, as well. With this mechanism the synthetic seismograms have been calculated only for the profile “Sofia 3A” (M3A), identified as model M3A. Both mechanisms are consistent with the available geological studies performed within the epicentral area (Christoskov et al., 1989 [6]; Solakov et al., 2001 [53]; Slavov et al., 2004 [52]).

A WARNING ABOUT SITE EFFECTS

The experimental approach to the estimation of the site response is based on the measure of ground motion at different sites. This implies the recording, with a network of instruments, of multiple seismic sources. If a network of I sites has recorded J events, the amplitude spectrum, $O$, of the j-th event recorded at the i-th site is usually represented as (Field and Jacob, 1995):

$$O_{ij}(\omega) = E_j(\omega)P_{ij}(\omega)S_i(\omega) \quad (1)$$

where $E$ is the source term, $P$ is the path term, and $S$ is the site-effect term. In the time domain (1) becomes

$$O_{ij}(t) = E_j(t)*P_{ij}(t)*S_i(t) \quad (1b)$$

where * indicates the convolution operator.

The most traditional techniques for estimation of the S term are based on computation of the ratio between the spectrum of the signal (or a portion of it) at the sedimentary site and the spectrum of a reference signal, preferably recorded at a nearby bedrock site (convolutive methods). Similarly, Nakamura’s 1989 [30]) method is based on computation of the spectral ratio between horizontal (usually the square root of the product between the spectra of the NS and EW components is used) and vertical components (H/V) obtained from seismic noise (microtremors). Theoretical investigations (e.g., Lachet and Bard, 1994 [26]; Dravinski et al., 1996 [9]) and experimental studies (e.g., Field and Jacob, 1995 [15]; Field, 1996 [16]) have shown that Nakamura’s method can reveal the fundamental resonant frequency of a site but that it is usually not able to give the correct amplification level. Furthermore, Nakamura’s (1989 [30]) assumptions seem questionable since several studies (e.g., Lachet and Bard, 1994 [26]; Konno and Ohmachi, 1998 [24]) have demonstrated that the horizontal to vertical ratio is strictly correlated with the polarization of Rayleigh waves. For a more comprehensive comparison of the various empirical techniques the reader is referred to Bard 1997 [2]).

The most frequently used techniques for the empirical estimation of site effects, based on (1), provide reliable information about the site response to non-interfering seismic phases or to single modes of vibration; they are not adequate in most real cases when the seismic sequel is formed by several interfering waves or equivalently by several modes, generated, e.g., by a rupture on a finite dimension fault buried in a deep sedimentary basin.

Also in a mathematically very simple situation, i.e. in the far field (and point source) approximation, the l-th component of seismic ground displacement is given by:

$$u_l(t) = \sum_j M_{il}(t)*G_{ilj}(t) \quad (2)$$
where $G$ is the Green’s function that represents the medium response and $M_{ij}$ are moment tensor functions that represent the source properties (e.g. Sileny and Panza, 1991 [49]; Sileny et al., 1992 [50]). If they are considered to be independent in the description of the source, the above equation is linear (it corresponds to a mechanism generally varying with time). However, if we constrain their independence and ask for a constant mechanism (even an unconstrained one, i.e. the full moment tensor), i.e. if we impose the constraint:

$$M_{ij}(t) = M_{ij,m}(t)$$

(3)

the problem becomes non-linear because of the product $M_{ij,m}(t)$ (both $M_{ij}$ and $m(t)$ are the model parameters controlling source properties). Thus, the inverse problem, i.e. the separation of source and medium terms, in the time domain is non-linear even without the double-couple constraint usually assumed for seismic sources. An additional non-linearity derives, in fact, from the double-couple constraint that imposes a non-linear combination of the components of the moment tensor, namely zero value of its determinant. In the frequency domain the inverse problem may seem simpler because the convolution in (2) is converted to pure multiplication and the equation is solved for each frequency separately. Within linearity we get $M_{ij}(\omega)$ and this implies to obtain from (1) site effects which are dependent upon source properties. To split the source time function and the mechanism again a non-linear constraint is needed, so the advantage of the frequency domain is fictitious only.

A complementary alternative to the questionable empirical approach to site response estimation is based on computer codes, developed from the detailed knowledge of the seismic source process and the propagation of seismic waves (e.g. Field, 2000 [17] and Panza et al., 2001 [36]). This approach can simulate the ground motion associated with a given earthquake scenario. In such a way, using available geological and geotechnical information, a low-cost parametric analysis of site responses can be performed without using the convolutive methods, based on (1) whose validity is not general.

NUMERICAL EXPERIMENTS AND DISCUSSION OF THE RESULTS

Realistic synthetic seismic signals have been generated for all sites of interest along the profiles shown in fig.1 (~ 100 sites per profile), adopting the parameters: $M=7, hypocentral depth 10km, epicentral distance from the beginning of each profile 10 km (Paskaleva, 2002 [40]). Two groups of experiments have been performed: (A) ground motion modelling in 1D layered anelastic media, applying an algorithm based on the modal summation method (Panza, 1985 [33]; Panza and Suhadolc, 1987 [34]), and (B) modelling in laterally heterogeneous media, making use of the hybrid technique (Fäh et al., 1993 [11]; 1995 a, b [12,13]) (see fig. 3).
Fig. 3. General scheme of the model adopted for the numerical experiments.

The chosen frequency range (up to 5 Hz) comprehends the free period of oscillation of the built environment elements present in Sofia. Along the profiles (fig.1) time histories for acceleration, velocity and displacement are computed for all ground motion components: transverse (TRA), radial (RAD) and vertical (VERT). Different quantities of earthquake engineering interest, like peak ground accelerations (PGA), peak ground velocities (PGV) and response spectra amplitudes (SA) are derived from the computed seismic signals.

The maximum PGA is obtained for model “Sofia 2” in the RAD component (PGA=932 cm/sec² and mean PGA as mean from PGA from the all receivers along the profile “Sofia 2” (PGAmean=453 cm/sec²). Such high values of PGA are in agreement with the reports (Petkov and Christoskov, 1965 [45]; Petrov and Iliiev, 1970 [46]; Christoskov et al., 1989 [6]; Matova, 2001 [29], Todorovska et al., 1995 [56]) about the damage caused by the 1858 earthquake. This event allowed for some quite reliable magnitude and intensity estimations (M=6.5-7.0 and I0~IX MSK) (Solakov et al., 2001 [53]).

The PGV for the horizontal components reaches 60.3 cm/sec for the model “Sofia 3” while for the vertical component, for model “Sofia 1”, PGV is 65 cm/sec.

The peak amplifications of the RSR increase by more than a factor of two along the profile Sofia 3 (fig.4) from South to North, following the deepening of the sedimentary basin. There are sites, at epicentral distances between 12 km and 17 km, where the amplification is relevant in both horizontal components RAD and TRA. The maximum amplifications are found in “Sofia 1” (fig.4A) for the vertical component (VERT) (RSR~1.6) and for the transverse component (TRA) (RSR~ 5.6), while the maximum value is found in Sofia 2 (fig.4B) (RSR~2.7) for the radial component (RAD). The maximum mean RSRmean= 1.7 is obtained for Sofia 3 (fig.4C) for all components along the profile. The smallest standard deviation sigma=0.25 is found for TRA component in Sofia 1.

The site amplification estimated in terms of the distribution of RSR versus frequency along the profile Sofia 1 (fig.4A) shows that the RAD amplification reaches 2.5 (1.0 - 2.75 Hz), The TRA component is amplified up to 3.3 (1.5 - 2.5 Hz), and the VERT RSR goes up to 4 within the frequency interval 0.5 - 4.0 Hz. If the scenario earthquake strikes the profile Sofia 1 then the ground motion at the site for VERT can be amplified up to more than 16 times within the frequency interval 1.25 - 2 Hz (not shown in the scale of the figures).

The influence of the source mechanism on the estimated site amplification can be seen comparing the RSR given for model “Sofia 3” in fig.4C and for model “Sofia 3A” in fig.4D.
Fig. 4 A. Model “Sofia 1”

Fig. 4 B. Model “Sofia 2”
VULNERABILITY OF STRUCTURES DESIGNED ACCORDING TO THE EUROCODES

To carry out seismic vulnerability analysis a cast-in-situ single-storey industrial reinforced concrete (RC) frame is used. It was designed and tested in the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) of the European Commission at Ispra in the framework of the research project “Seismic behaviour of reinforced concrete industrial buildings”. The frame structure shown in fig. 5 was designed according to Eurocode 2 and Eurocode 8 for ductility class H (high), as described by Ferrara (2002) [14] in the design calculations. The storey height was 5.3m, the two bays were 4m each. The columns (cross-section 300x300mm) have been reinforced with 8 φ14 bars, stirrups φ6@50mm in the critical zones and φ6@150mm in the central part. The beams (cross-section 600x300mm) have been reinforced with 8 φ14 bars, stirrups φ6@50mm in the end zones and φ6@150 mm in the middle part. Normally, the dimensioning of such kind of industrial buildings for horizontal loads is determined by non-seismic design conditions, such as the wind loading. The total horizontal force the frame was able to sustain was evaluated as \( F_d = 192.9 \text{kN} \), considering the design properties of the materials (Ferrara, 2002 [14]).
The experimental capacity curve of the structure is shown in fig. 6. Dimova and Negro (2005a) [7] estimated the yielding displacement $x_y = 0.131\text{m}$ and yielding force $F_y = 214\text{kN}$ from the experimental data as corresponding to the first yielding. The ultimate storey displacement $x_u = 0.408\text{m}$ was determined as corresponding to a 15% drop of the experimental peak base-shear force. The behaviour factor supply of 5.75 was determined as the ratio of the ‘would-be’ base-shear force obtained by linear elastic analysis as corresponding to $x_u$ and the design base-shear strength (Dimova and Negro, 2005b [8]). It matches the behaviour factor demand of 4.95 of Eurocode 8.

The experimental tests and their numerical simulation are described in details by Dimova and Negro 2005a,b [7,8]. The seismic behaviour of the structure was modelled by means of the computer code IDARC 5.5 (Valles et al., 1996 [59]), taking into account the P-delta effects. The models of the structure created to best fit the experimental behaviour for the respective test PGAs are used in the present study. The damage of the structure is qualified using the overall structural damage index (DI) (Valles et al., 1996 [59], Park and Ang, 1985 [38], Bracci et al., 1989 [4]), which has been calculated during the numerical simulations with IDARC 5.5. The damage states, in terms of the typical expected structural and non-structural damage, are described in accordance with the Homogenized Reinforced Concrete Damage Scale (HRC scale), Rossetto and Elnashai, 2003 [47]. The HRC scale damage index ($\text{DI}_{\text{hrc}}$) provides a numerical reference scale for the calibration of the damage
states. In the present study four damage states have been considered in accordance with their description by the HRC damage scale: light damage, moderate damage, extensive damage and partial collapse (Table 2). Values were assigned to DI_{hrc} according to the damage observed during the experimental tests of the structure (Dimova and Negro, 2005b [8]) and in this way the values of DI_{hrc} have been related to the inter-storey drift in percent of the storey height (ISD%). The functional relationships between DI_{hrc} and ISD%, obtained by non-linear regression for the structure have been used to estimate the ISD% at the threshold of the damage state of partial collapse. Further, these regressions were used to transform the predictive equations for DI over ISD% (obtained from the numerical simulations of the response) to DI over DI_{hrc} and in this way to relate the calculated damage indices to the index, based on observational data (table 2).

Table 2. Qualification of the structural damage

<table>
<thead>
<tr>
<th>Damage grade</th>
<th>DI_{hrc}</th>
<th>ISD%</th>
<th>DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>&lt; 50</td>
<td>&lt; 4.5</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>Moderate</td>
<td>50 - 70</td>
<td>4.5 – 6.5</td>
<td>0.3 – 0.5</td>
</tr>
<tr>
<td>Extensive</td>
<td>70 - 90</td>
<td>6.5 - 9</td>
<td>0.5 – 0.95</td>
</tr>
<tr>
<td>Partial collapse</td>
<td>&gt; 90</td>
<td>&gt; 9</td>
<td>&gt; 0.95</td>
</tr>
</tbody>
</table>

Typical damage expected in ductile moment resisting frames:
- Start of structural damage
- Hairline cracking in beams and columns near joints (< 1 mm)
- Cracking in most beams & columns
- Some yielding in a limited number
- Larger flexural cracks & start of concrete spalling
- Ultimate capacity reached in some elements – large flexural cracking, concrete spalling & rebar buckling
- Collapse of a few columns, a building wing or single upper floor

The seismic response of the RC frame was calculated for the scaled components of the accelerograms generated in Sofia. The analysis objective using IDARC 2D program as used by Paskaleva and Dimova, 2005 [43] was to provide expected response as damage index (DI), story drift and base-shear for different percent of PGA scaling and source mechanism (table 3).

Table 3. Some amplitude responses from IDARC 2D dynamic analysis

<table>
<thead>
<tr>
<th>Model “Sofia 1”</th>
<th>Model “Sofia 2”</th>
<th>Model “Sofia 3”</th>
<th>Model “Sofia 3A”</th>
</tr>
</thead>
<tbody>
<tr>
<td>scale</td>
<td>5%</td>
<td>32%</td>
<td>64%</td>
</tr>
<tr>
<td>Epicentral distance 11km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage index</td>
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<td>0.165</td>
</tr>
<tr>
<td>Storey drift [mm]</td>
<td>8</td>
<td>140</td>
<td>130</td>
</tr>
<tr>
<td>Base shear [kN]</td>
<td>40</td>
<td>191</td>
<td>223</td>
</tr>
<tr>
<td>Epicentral distance 16km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage index</td>
<td>0</td>
<td>0.09</td>
<td>0.248</td>
</tr>
<tr>
<td>Storey drift [mm]</td>
<td>7</td>
<td>62</td>
<td>198</td>
</tr>
<tr>
<td>Base shear [kN]</td>
<td>36</td>
<td>173</td>
<td>225</td>
</tr>
<tr>
<td>Epicentral distance 25km</td>
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<td></td>
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<tr>
<td>Damage index</td>
<td>0</td>
<td>0.277</td>
<td>0.32</td>
</tr>
<tr>
<td>Storey drift [mm]</td>
<td>9</td>
<td>198</td>
<td>276</td>
</tr>
<tr>
<td>Base shear [kN]</td>
<td>43</td>
<td>216</td>
<td>237</td>
</tr>
</tbody>
</table>

Note: * - partial collapse, i.e. storey drift larger than 491 mm, base shear lower than 207 kN
In fig. 7, A and D the damage index distribution along the superimposed profiles is determined from generated accelerograms scaled with a peak value of 0.32g. For the first mechanism (Sofia 3) we can expect 100% light damage. Only for the second mechanism (M3A) we can expect some moderate damages.

The influence on the damage index of the geological conditions (Models M1, M2 and M3), the scaling factor of the seismic action in %g (32%, 64%, 80%), and the epicentral distance (11km, 16km-center of the city, 22km) is shown in fig.7.A. The source mechanism influences very strongly the results (models M3 and M3A), as we could expect from the non linearity of (2) under condition (3). The results show that mechanism influenced very strongly the results (models M3 and M3A). M3A scenario mechanism is more destructive than the mechanism used in M3. In figure 7.A by shown dotted lines the damage index calculated for accelerogram with spectrum compatible with those prescribed by Eurocode 8 for subsoil class B, namely for scaling: 32%g - DI=0.161; for 64%g - DI=0.245; for 80%g - DI=0.482.

The spatial distribution of the damage index is shown in fig. 7 B, C and D. In fig. 7B for the synthetic accelerograms scaled with a peak value of 0.8g, the damage index distribution on the territory covered by the profiles shows that for the first mechanism we can expect: 67% of the region to be affected by moderate damage, 23% by extensive damage, and 11% by partial collapse.

For the synthetic accelerograms scaled with a peak of 0.64g (fig. 7C) the damage index distribution shows that light damages covered 44% and moderate damages 56% of the territory covered by the profiles.

The ad-hoc national seismic code [5] is prescribing design peak ground acceleration (DPGA) of 0.27g. So we have to expect light damages (fig. 7D) if the same value of the DPGA will be accepted in the National Standards implementing Eurocodes. The damage index distribution along the superimposed profiles for synthesized accelerograms scaled to 32%g is shown in fig.7D. The DI distribution by the level light damages e.g. DI= 0-0.3 cover 100% of the territory.

![Fig. 7 A. Influence of the geological conditions on the damage index for scaled time histories to: 1) 32%g; 2) 64%g; 3) 80%g. Dotted lines limit damage index calculated with spectrum compatible with Eurocode 8, subsoil class B, DI for: 32%g-0.161; 64%g-0.245; 80%g-0.482.](image)
Fig. 7B) Damage index distribution along the superimposed profiles: levels 0.3-0.50 moderate 67%; 0.5-0.95 extensive 23%; >0.95 partial collapse 11%. Synthetic accelerograms are scaled to 80%g.

Fig. 7 C) Damage index distribution along the superimposed profiles: levels 0-0.3 light 44%; 0.3-0.50 moderate 56%; Synthetic accelerograms are scaled to 64%g.

Fig. 7 D) Damage index distribution along the superimposed profiles: level 0-0.3 light 100%; Synthetic accelerograms are scaled to 32%g.
The storey drift distribution along the profiles is shown in fig. 8A for model “SOFIA 1”, fig.8B for model “SOFIA 2” and fig.8C for model “SOFIA 3 and 3A”. The synthetic accelerograms are scaled to 80%g for epicentral distance 11km, 64%g for epicentral distance 16km and 32%g for epicentral distance 22km. The influence of the geological conditions is strongest for model M3.

The storey drift shown in fig. 8D for 32%g varies in the range 6-11cm for the center of the city at the epicentral distance of 16km considering the first mechanism (M1~6cm, M2~11cm, M3~9cm). Depending on the mechanism, for 32%g it varies from 9 to 15cm (M3~9cm and M3A~15cm) in the center of the city. The story drift is more sensitive to the geological conditions than to the mechanism of the source. The same tendency can be found for the base shear (table 3). The story drift threshold of 49cm for partial collapse has not been reached for accelerograms scaled to 64%g. Model “SOFIA 2” reaches the partial collapse story drift for accelerograms scaled to 80%g.
Fig. 8B. Story drift distribution along the profile 2D MODEL “SOFIA 2” influence of the geological conditions and epicentral distance.

Fig. 8C. Influence of the earthquake mechanism on the story drift for model M3 and M3A along the profile.
**CONCLUSIONS**

The city of Sofia is exposed to a high seismic risk. Macroseismic intensities up to X (MSK -76) can be expected in the city. Sofia is a typical example of a large city that is located in a seismic area and can suffer serious damage because of soil conditions, with deep soil deposits and severe local site amplification. The risk, made evident by our review of the regional seismicity, requires the development of appropriate earthquake scenarios and the use of advanced ground motion modelling for the definition of the seismic input for the city of Sofia. This work illustrates the simulation of the ground motion along three cross-sections located in Sofia City. Realistic SH- and P-SV-wave signals are computed for two source mechanisms consistent with the regional seismotectonics. The synthetic seismic signals have been generated along three geological profiles crossing the center of Sofia. The time histories vary significantly from site to site, particularly for small epicentral distances (11-14 km). The motion contains high PGA values, and short duration pulses that can be recognized as acceleration spikes. The situation is made even more hazardous if fling and directivity effects are taken into account (e.g. PEER 2001/09 [44]; Somerville et al., 1997 [54]), but the treatment of such problems is outside the purposes of the present paper.

By taking into account parametric studies, regarding the focal mechanism of the source and the velocity model, it is shown that the hybrid method is a powerful approach that may be considered fundamental when adding information to the multidisciplinary "database" that must be defined for microzonation purposes. Given a certain earthquake scenario, and an appropriate structural model, based on detailed geological, geophysical and geotechnical data, it is possible realistically to evaluate the local amplification in the frequency range of interest for civil engineering, and to obtain valuable parameters for the realistic microzonation.

The most important result concerns the site response behaviour. The obtained records are used for engineering purposes to assess the distribution of the damage index which is useful for urban planning, retrofitting of the built environment, insurance industry, earthquake preparedness, earthquake risk reduction and earthquake risk management.

This is the first detailed study for the maximum expected scenario done for Sofia City, based on ground motion modelling, in terms of both the peak ground acceleration and the spectral amplification estimated along three profiles. The results of this study can be readily applied to site-specific design spectra based on average or maximum amplification. Such results should be accounted for in site-specific design procedures, especially for long structures and underground lifeline systems more sensitive to near surface strains than to maximum peak ground acceleration. This is a good starting point for the microzonation of
Sofia. Many more cross-sections will be required to cover the whole city, in view of a better understanding and estimation of the maximum expected risk.

The obtained results can be used to support many engineering and managing purposes like urban planning and earthquake preparedness.

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REFERENCES


47. Sileny, J. and Panza, G.F. Inversion of seismograms to determine simultaneously the moment tensor components and source time function for a point source buried in a horizontally layered medium. Studia Geophysica et Geodaetica, 35, 1991; 166-183.


49. Slavov, S., Ground Modelling in the City of Sofia (TRIL-ICTP) 2000, Visitors report.


53. Sun, R., Vacciari, F., Marrara, F., Panza, G.F. The Main features of the local geological conditions can explain the macroseismic intensity caused in Xiji-langfu (Beijing) by the MS=7.7 Tangshan 1996 earthquake, Pageoph, 1998; 152, 507-521.


