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Synthetic Seismogram Based Deterministic Seismic Zoning for the Hungarian Part of the Pannonian Basin

ZOLTÁN BUS,[1] GYÖZÖ SZEIDOVITZ[1] and FRANCO VACCARI[2]

Abstract—Deterministic seismic hazard computations have been done for the Hungarian part of the Pannonian basin within the framework of a cooperation of five countries. Synthetic seismograms have been computed by the modal summation method up to 1 Hz in order to determine the expected maximum displacement (D_{MAX}), velocity (V_{MAX}) and the design ground acceleration (DGA) on a $0.2° \times 0.2°$ grid. DGA values have been estimated from the seismograms by using the EUROCODE 8 (1993) standard.

This investigation justified the suspicion that a considerable part of seismic hazard of Hungary comes from the seismogenic zones of the neighbouring countries. The highest DGA reaches a value as high as 0.14 g (which corresponds approximately to the VIII intensity degree in the MSK-64 scale). Among the six largest cities of Hungary, three art particularly subject to a high seismic risk. Greater acceleration values have been found for the cities of Szeged and Debrecen than was expected before this study.

Key words: Synthetic seismograms, deterministic modelling, seismic hazard, design ground acceleration.

Introduction

In recent years it became obvious that seismic zoning can be a useful tool not only for the surveying of the areas struck by disaster, but for territories which were not affected by earthquakes in the written history.

In this study a new deterministic seismic zoning technique developed by COSTA *et al*. (1993) has been applied. This procedure has been used with success in regions with diverse geological endowments, e.g. Italy (COSTA *et al*., 1993), Algeria (AOUDIA *et al*., 1996) and Bulgaria (OROZOVA-STANISHKOVA *et al*., 1996).

The seismic hazard computations have been done for the Hungarian part of the Pannonian basin within the framework of a cooperation of five neighbouring countries (Croatia, Hungary, Italy, Romania and Slovenia).

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The territory of Hungary is seldom impacted by severe, destructive earthquakes. Nevertheless from time to time (approx. every 10–20 years) damaging earthquakes occur. One of the most active seismic zones lies in the vicinity of Budapest, the capital of Hungary. The most significant Hungarian earthquake of the XX century (Dunaharaszti, 12 January 1956, see e.g. in SZEIDOVITZ, 1986b) arose only 20 km from the centre of the city. Although in the last four centuries no earthquake with magnitude $M > 5.5$ occurred in the very area of Budapest, with this new method it is possible to see the effects of such a hypothetical event.

Many of the large cities of the country with great economical and cultural significance lie in the neighbourhood of active seismogenic zones. It is important to know the level of seismic hazard in their area.

Figure 1 shows the geographical units of Hungary and the location of its largest cities together with the epicentres of the most damaging earthquakes (after ZSIROS *et al.*, 1988).

A considerable part of the seismic risk to Hungary originates in surrounding countries. International cooperation was important during this work, since specialists of the other countries have a detailed knowledge of the properties of source zones affecting the Hungarian settlements.

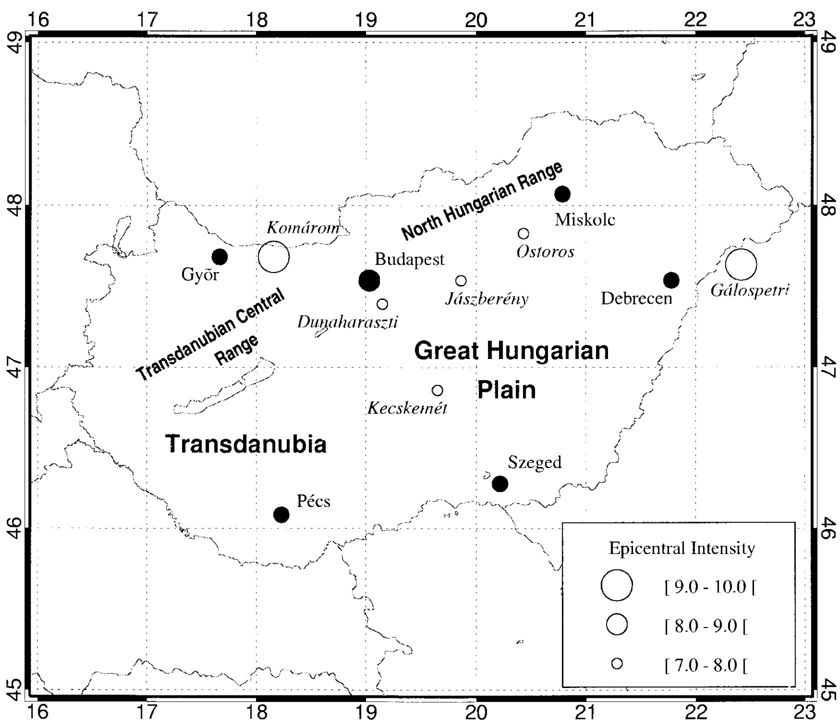

Figure 1
The geographical units of Hungary, its largest cities (filled circles) and the epicentres of the most damaging earthquakes (empty circles).

To date in Hungary mainly probabilistic seismic hazard estimations have been made. For example ZSIROS (1985) determined the maximum intensity values which will not be exceeded in 200 years with a 70% probability. Using a different approach, ZSIROS and MÓNUS (1984) computed a theoretical maximum intensity map together with acceleration, velocity and displacement data, using the intensity values of Hungarian earthquakes which occurred between 1859 and 1982. Additionally, detailed studies have been made to determine the properties of the most active seismogenic zones (compiling isoseist maps, recurrence-time analysis, seismic hazard estimation), see e.g., SZEIDOVITZ (1986a).

In the Soviet era, experts from the Soviet Union assessed qualitatively and quantitatively the level of seismic risk of the Eastern European states, see e.g., REISNER and SHOLPO (1975), although usually their estimates vary significantly from those of the given countries' scientists.

Tectonic and Seismicity of the Pannonian Basin

The Pannonian basin is a tectonically complex area which is encompassed by the Carpathian Mountains, the Dinarides and the Eastern and Southern Alps. In essence, the Pannonian basin is a set of small and rather deep subbasins, whose depth often exceeds 5 km, filled with Neogen-Quaternary sediments. Among the subbasins the ridges of the pretertiary basement can be found. Practically the whole territory of Hungary is underlain by the Pannonian basin.

The Pannonian basin and the surrounding mountains are the outcome of the collision of the European plate and the small plate fragments originating from the south which started in the Cretaceous. In the lower and middle Miocene the area within the Carpathian loop underwent an extensional period due to the subduction of the external Carpathian crust and the marginal part of the attenuated European continental crust (CSONTOS *et al.*, 1992 and HORVÁTH, 1993). After the syn-rift period two compressional events took place (the latter is ongoing) and the general thermal subsidence of the entire basins system occurred between the (HORVÁTH, 1995).

The Pannonian basin is filled with thick Neogene and rather thin Quaternary sediment layers. The total thickness of the Neogene-Quaternary sediments in the subbasins is approximately 3 km, sometimes reaching a value of 8 km (STEGENA *et al.*, 1975).

The Hungarian part of the Pannonian basin does not produce intense seismic activity. Because of the few large magnitude events and due to the lack of sufficient reliable focal solutions, it is not an easy task to make a connection between the faults determined by geologists and the observed earthquake epicentre distribution (GUTDEUTSCH and ARIC, 1988). In light of recent investigations by one of the authors (Gy. Szeidovitz), it is probable that a considerable part of the Hungarian earthquakes cannot be correlated with known faults, rather they are brought about by the effects of sedimentation in the basins.

The Most Severe Earthquakes of Hungary

The most destructive historical earthquakes of Hungary are listed in Table 1, where M is the local magnitude of the event, I_0 is the epicentral intensity and A_0 is the estimated acceleration in the epicentre. The relationship between intensity and acceleration described in BISZTRICSÁNY (1974) has been used throughout this paper. The events of unknown origin in the distant past have been omitted from the list, although they were quite strong in some cases. The epicentres of the listed events are shown in Figure 2 by empty circles.

Method

The method used for the deterministic seismic zoning of Hungary was developed at the Istituto di Geodesia e Geofisica (now Dipartimento di Scienze della Terra) of the University of Trieste, see COSTA *et al.* (1993) and PANZA *et al.* (1996).

The assessment of maximum ground acceleration, velocity and displacement is based on synthetic seismogram computation by the modal summation method (a detailed description can be found e.g., in PANZA, 1985 and FLORSCH *et al.*, 1991), which accounts for surface waves and for all those body waves which have phase velocities less than the S-wave velocity of the halfspace. In the case of our models, the most energetic S-waves are present in the seismograms. This technique makes it possible to efficiently model the wave propagation in a one-dimensional anelastic layered structure for arbitrary types of sources (e.g., explosion, double-couple, finite-length fault).

The parameters of the seismic sources and the structure in which the waves propagate are needed. The sources are confined to seismogenic areas, and the structure is simplified to a set of one-dimensional models.

Table 1

The most destructive earthquakes in Hungary (after SZEIDOVITZ*, 1986b;* SZEIDOVITZ *and* BUS*, 1995 and* ZSIROS *et al., 1988)*

Epicentre	Date	M	I_0	A_0 (g)
Érmellék (Gálospetri)	15 October 1834	6.5	9.0	0.2–0.4
Komárom	28 June 1763	6.2	9.0	0.2–0.4
Dunaharaszti	12 January 1956	5.6	7.5	0.075–0.1
Jászberény	21 June 1868	5.3	7.5	0.075–0.1
Eger (Ostoros)	31 January 1925	5.0	7.5	0.075–0.1
Kecskemét	8 July 1911	5.6	7.0	0.05–0.1

The seismogenic areas of the territory are defined on the basis of seismological and seismotectonic data. It is assumed during the computation that earthquakes occur only in these areas. For each seismogenic zone one or more representative focal plane solution is used.

The investigated area is divided into a system of flat layered structures. This subdivision is made on the grounds of the geological and geophysical attributes of the lithosphere under the investigated area.

The investigated territory is subdivided by a uniform grid (in our case the grid is $0.2° \times 0.2°$). The simulated sources and the focal mechanisms are assigned to the middle of the grid cells, while the receivers are located in the corners of the cells. For every cell a magnitude value is obtained by the use of a centered smoothing window. In this way the surrounding cells can affect the center one. The seismogenic zone's representative focal mechanism is assigned to each cell to which an event is assigned.

For the purpose of diminishing the number of synthetic seismogram computations, distance limits have been defined for specific magnitude ranges. As the hypocentre's depth is the most uncertain data among the earthquake location parameters, and the events with shallow sources are the most damaging, it is an

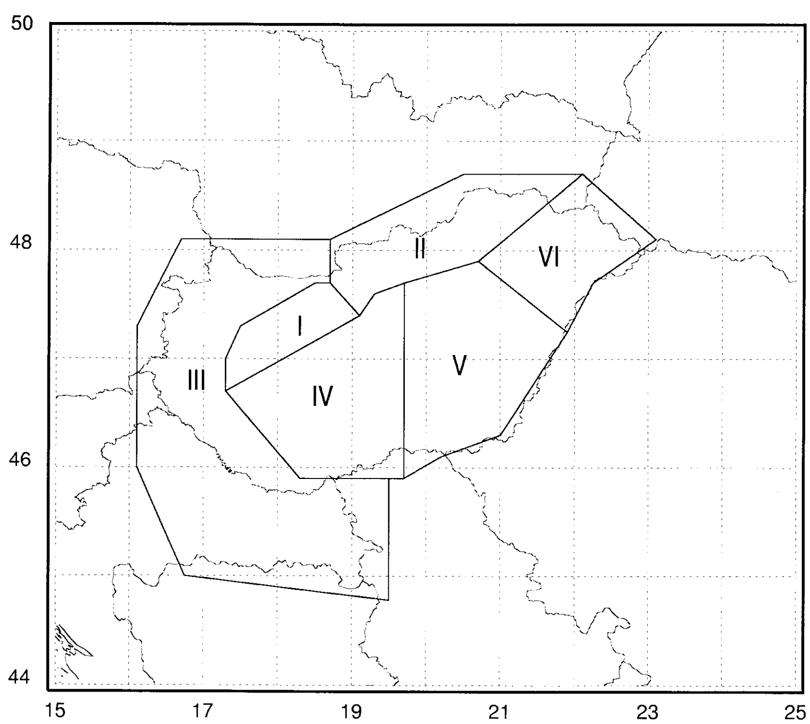

Figure 2
The boundaries of the structural units.

acceptable approximation to set all the hypocentres' depth to a fixed (in our case 10 km) value.

P–SV and *SH* seismograms are computed at each receiver for a seismic moment of 10^{-7} Nm, then the synthetic seismograms are scaled using the spectral scaling law proposed by GUSEV (1983) as reported in AKI (1987). If the propagation path crosses the structural units' boundaries, the structure at the receiver is used in the computation as the representative of the whole path. Having determined the *P–SV* and *SH* seismograms for all possible sources associated with a receiver, the peak of the signal with the largest horizontal amplitude is chosen for the representation of ground-shaking on the map.

The synthetic seismograms are computed to an upper frequency limit of 1 Hz, so the point-source approximation can be considered valid. In the case of higher frequencies, the dimension of the fault and the rupturing process should be taken into account.

The frequencies lower than 1 Hz are important from a practical point of view as the multi-story buildings, bridges, etc. which are common in large cities have the peak response frequency in this range (CSÁK *et al.*, 1981).

Data

Structural Models

The territory of Hungary has been covered by six structural polygons (Fig. 2). Each polygon defines a part of the lithosphere which can be approximated by a series of flat, homogeneous and isotropic anelastic layers. The parameters of these layers are their thickness, density *P*-wave and *S*-wave velocity (which is, in our case, determined from the *P*-wave velocity using the Poisson ratio) and the quality factor for the *P* and *S* waves, Q_α and Q_β, respectively.

The main aspects of the separation of the structural polygons have been the depth of the sedimentary basins and the depth of the crust-mantle boundary. These parameters generally are in coincidence as follows from the properties of the evolution of the extensional style basins. Of the six structural units only one structural unit—Transdanubian Central Range unit (Structure I)—has no basin-like structure.

The crust is rather thin beneath the Pannonian basin as a consequence of the Miocene extension. The average depth of the Mohorovičić discontinuity (Moho) is around 26 km and it varies slowly between 22.5 and 27.5 km under most of Hungary, the only exception being the area of the Transdanubian Central Range where it reaches its deepest part with a value of 32.5 km, see POSGAY *et al.* (1986) and HORVÁTH (1993).

The depth of the pretertiary basement under Hungary has been taken from the map of KILÉNYI and SEFARA (1989), the thickness of the Neogene-Quaternary sediments from the paper of STEGENA *et al.* (1975).

The velocity data stems from three sources. For the velocity and density values inside the basins we have used the data of SZABÓ and PÁNCSICS (1994). The primary source for the crustal velocities has been the paper of BONDÁR *et al.* (1996), who has made single-station group velocity measurements and a genetic algorithm based inversion for the area of the Pannonian basin. His results have been checked and amended by the data of MÓNUS (personal communication, 1998), who has determined a one-dimensional, two-layered crustal model by evaluating several hundred seismograms recorded in the region. Below the crust, the velocities of the IASPEI91 model (KENNETT and ENGDAHL, 1991) have been used.

Seismogenic Zones

We have defined fourteen seismogenic zones for Hungary and for those parts of the neighbouring countries close to the Hungarian boundary (Fig. 3). As can be seen in the figure, there are gaps between the zones, in other words there is no

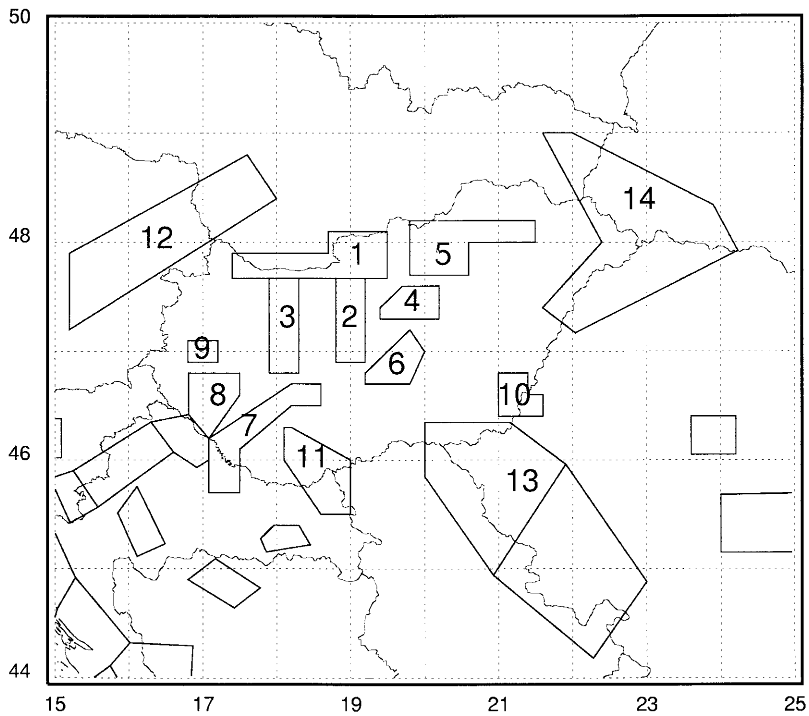

Figure 3
The boundaries of the seismogenic zones (their names are declared in Table 2).

"background zone" provided. This is because we are only considering earthquakes with magnitude 5 or above and there are no such events occurring outside the seismogenic zones we defined. There are also no active faults that could generate $M > 5$ events known. Therefore we apply the procedure strictly as it has been applied in the original paper by COSTA *et al.* (1993), to produce results consistent with what has already been computed in Italy and other countries. It is in any case possible to make different hypotheses about seismicity, to perform the computations again and to compare the results. Parametric analyses are easy to perform in this deterministic approach, nonetheless they are beyond the purpose of this paper.

The definition of zones is based on the seismic lineaments determined from the distribution of the earthquake epicenters (ZSIROS *et al.*, 1988) and the properties (amount, strike, type extent) of the known faults in the area (BARVITZ *et al.*, 1990).

In some cases the delineation of seismogenic zones boundaries was quite straightforward, based on earthquake data and the knowledge of the areas' tectonical settings. In other cases it was somewhat subjective due to the sparse seismicity or complicated tectonics of the given area.

The relationship between the numbering of the seismogenic zones and their names used in the text can be found in Table 2.

All the seismogenic zones listed in Table 2 have been defined by the authors of this paper, except the zones number 13 and 14 which have been constructed by Romanian researchers (RADULIAN *et al.*, 2000).

Table 2

Focal mechanisms assigned to seismogenic zones

Seismogenic zone	Strike (°)	Dip (°)	Rake (°)
1. Hurbanovo-Diósjenö zone	**261**	**29**	**−132**
2. Dunaharaszti zone	**85**	**73**	**159**
3. Berhida zone	**227**	**77**	**−166**
4. Jászberény zone	**125**	**66**	**137**
5. Ostoros zone	60	45	270
6. Kecskemét zone	65	90	0
7. Kapos zone	65	90	0
8. Zala zone	90	90	180
9. Ukk-Türje zone	70	90	0
10. Békés zone	**266**	**70**	**42**
11. Mecsek zone	80	45	90
12. Mur-Mürz zone	**0**	**61**	**158**
13. Bánság zone	**103**	**72**	**−5**
14. Érmellék (Satu Mare) zone	329	86	−42

Fault Plane Solutions

The fault plane solutions (FPS) emanate from the paper of GERNER (1995) who collected and re-evaluated the FPSs of the Pannonian basin published in the last few decades.

However there have been seven seismogenic zones for which it was impossible to find any FPS computed from earthquake data. In these cases the strike and type of the faults have been determined with the aid of the tectonic map of Hungary by BARVITZ *et al*. (1990). The small magnitude seismicity of the country makes it difficult to get FPSs, as there are only a few events in the Pannonian basin which are large enough to ensure a sufficient number of observations for accurate FPS determination.

The strike, dip and rake angles are shown in Table 2. When more than one FPS belonged to a seismogenic zone, the one with greater magnitude was chosen, as it is considered more reliable. The rows of Table 2 are typed with bold letters if they are the results of FPS computation from earthquake data.

Earthquake Catalogue

The earthquake catalogue used for the computation (ZSIROS *et al*., 1988) covers the years between 456 and 1986. This database was completed up to the year 1989. Figure 4 shows the magnitude distribution in the seismogenic zones after the smearing. The macroseismic magnitude has been estimated from the maximum intensity (I_0) and the focal depth (h), using the Gutenberg-Richter formula:

$$M = 0.6\, I_0 + 1.8 \log h - 1.0. \qquad (1)$$

In the case of unknown focal depth a value of 10 km was assumed. The only considered events in the computations were those whose errors in the location of epicentres are smaller than 20 km (with this restriction our data come from the years ranging from 1443–1989).

Results

Figures 5–7 show the output of the computations for the design ground acceleration (DGA), the maximum values of displacement (D_{MAX}) and velocity (V_{MAX}), respectively.

Design Ground Acceleration

As the frequency content of the synthetic seismograms limited to 1 Hz, the maximum values of acceleration (A_{MAX}) extracted from the synthetic seismograms

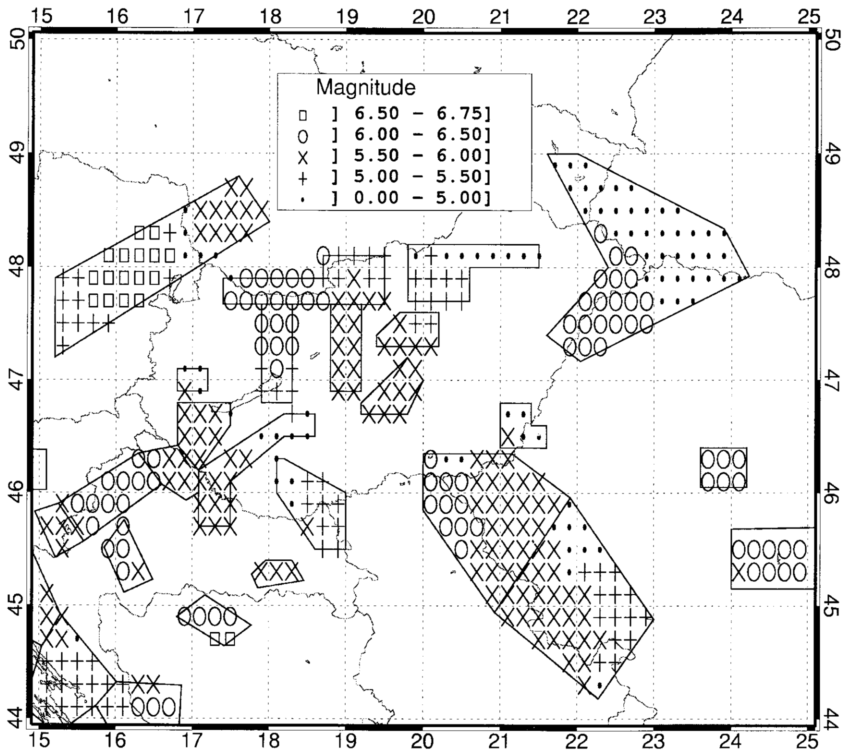

Figure 4
The seismogenic zones with the smeared magnitude distribution.

underestimate the true peak of acceleration. To overcome this limitation we may extend the deterministic results to higher frequencies by using the design response spectra (PANZA *et al.*, 1996), for instance EUROCODE 8 (1993), which define the normalized elastic acceleration response spectrum of the ground motion.

In general, this operation should be made taking into account the soil type. The structural models used in our computations are all of type A, as defined in Eurocode 8: "*stiff deposits of sand, gravel or overconsolidated clay, up to several tens of m thick, characterized by a gradual increase of the mechanical properties with depth (and by* v_s *values of at least 400 m/s at a depth of 10 m)*". The well data of SZABÓ and PÁNCSICS (1994) indicate that this assumption is reasonable for the territory of Hungary.

Therefore we can determine the Design Ground Acceleration (DGA) by fitting the response spectra computed from the synthetic seismograms (in the period range between 1 s and 5 s) with the one given by Eurocode 8.

Validation of the use of DGA instead of PGA (peak ground acceleration) can be found for accelerograms of the Italian Irpinia (1980) and Friuli (1976) earthquakes in VACCARI *et al.* (1995) and PANZA *et al.* (1996).

The distribution of DGA (Fig. 5) clearly shows that the regions with the highest seismic risk can be found near the borders of the country. The maximum values of DGA in these areas are between 0.08 and 0.15 g. In the MSK-64 scale, intensity degrees VII and VIII correspond to these acceleration values.

A significant region of the Great Hungarian Plain has no remarkable seismic risk, and this is the same for a region at the southern Hungarian part of the Danube. Due to this computation most of the sources inside Hungary do not cause accelerations higher than 0.08 g (approximately intensity VII).

The results show that we can expect epicentral intensity VI for the Kecskemét and Dunaharaszti, and an intensity value of VII for the Berhida source zone. The epicentral intensity experienced for the Kecskemét earthquake was VII (SZEIDOVITZ and BUS, 1995), for the Dunaharaszti earthquake it was between VII and VIII (SZEIDOVITZ, 1986b) and for the Berhida event it was VI (TÓTH *et al.*, 1989). We can see there is approximately a 1.0–1.5 degree difference between the experienced and theoretical epicentral intensity values. We will discuss the causes of this phenomenon later.

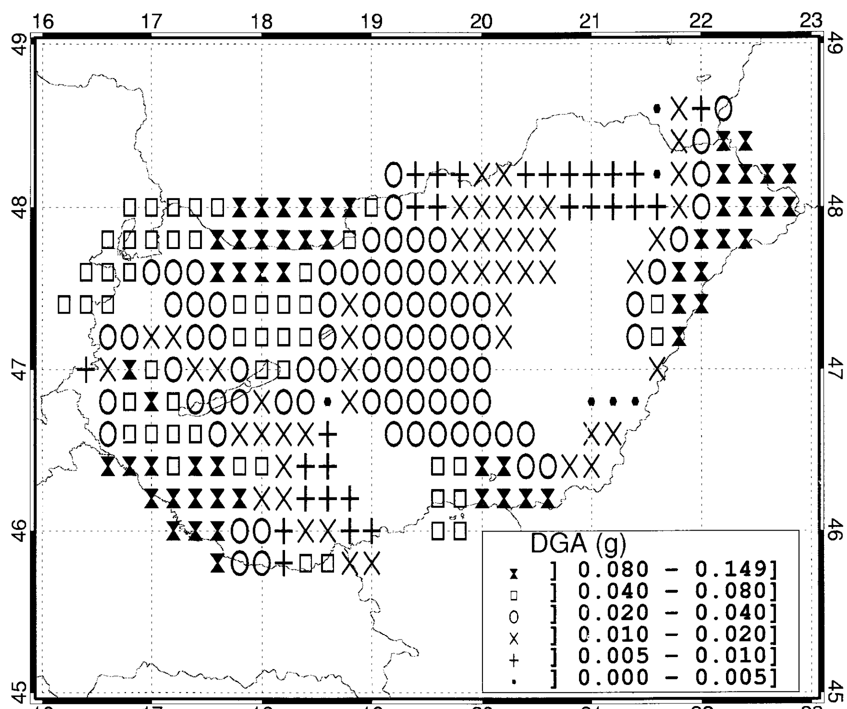

Figure 5
The DGA values for Hungary.

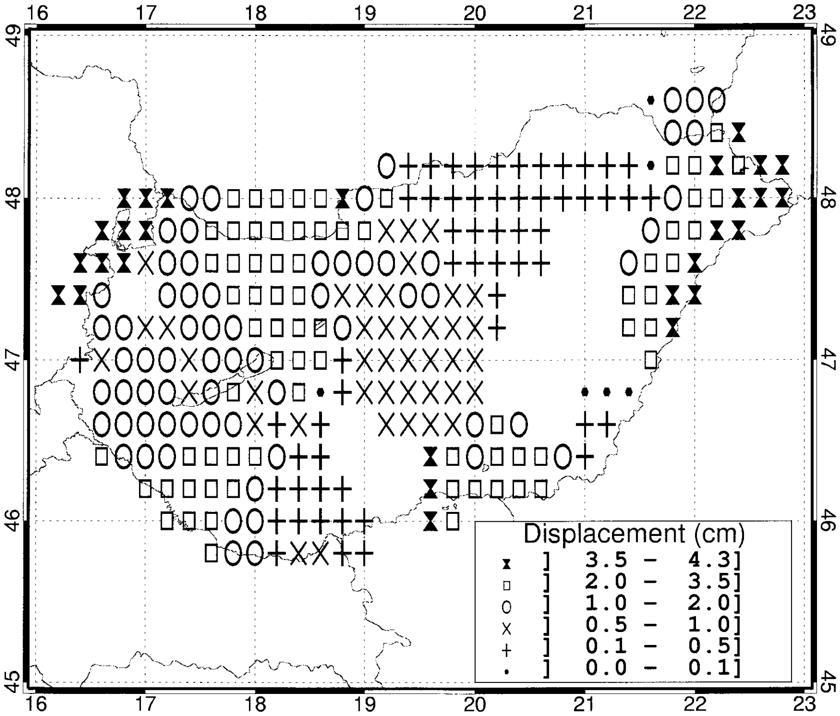

Figure 6
The D_{MAX} values for Hungary.

The six largest cities of Hungary are (in decreasing order of population): Budapest, Debrecen, Miskolc, Szeged, Pécs, Györ. Their locations and the names of the main geographical units of Hungary are shown in Figure 1. Among these cities, Szeged, Debrecen and Györ have the most significant risk with a value greater than 0.1 g (intensity VIII), and we can expect a maximum acceleration between 0.02 and 0.04 g (intensity VI) for the area of Budapest. The cities of Miskolc and Pécs have no remarkable seismic risk.

Displacement and Velocity

The highest displacement values (Fig. 6) appear near the Mur–Mürz zone, the Érmellék (Satu Mare) zone and the Bánság zone with a value between 3.5 and 7 cm.

The highest velocity values (Fig. 7) on an extended territory are produced by the Hurbanovo-Diósjenö and the Érmellék (Satu Mare) source zone. The velocity in these regions is between 8 and 15 cm/s.

Conclusions

Synthetic seismogram based deterministic seismic hazard computations have been performed for the territory of Hungary within the framework of international cooperation. The results show that we can expect considerable seismic hazard in three of the six largest cities of Hungary, namely the design ground acceleration reaches and passes the value of 0.1 g which corresponds roughly to VIII degree intensity on the MSK-64 scale. For a significant part of the Great Hungarian Plain the seismic hazard can practically be neglected.

As a matter of fact, the seismic hazard of Hungary originates mainly from abroad. Its main sources are the Mur–Mürz zone (Austria), Medvednica–Kalnik zone (Croatia), Bánság zone (Romania–Yugoslavia) and the Érmellék (Satu Mare) zone (Romania).

As we have seen, some of the results obtained in this paper—chiefly in the case of intra-Hungarian earthquakes—contradict the macroseismic observations. A possible source of the discrepancy is that the investigated territory can be characterized with laterally highly heterogeneous thin sediments with very low wave veloc-

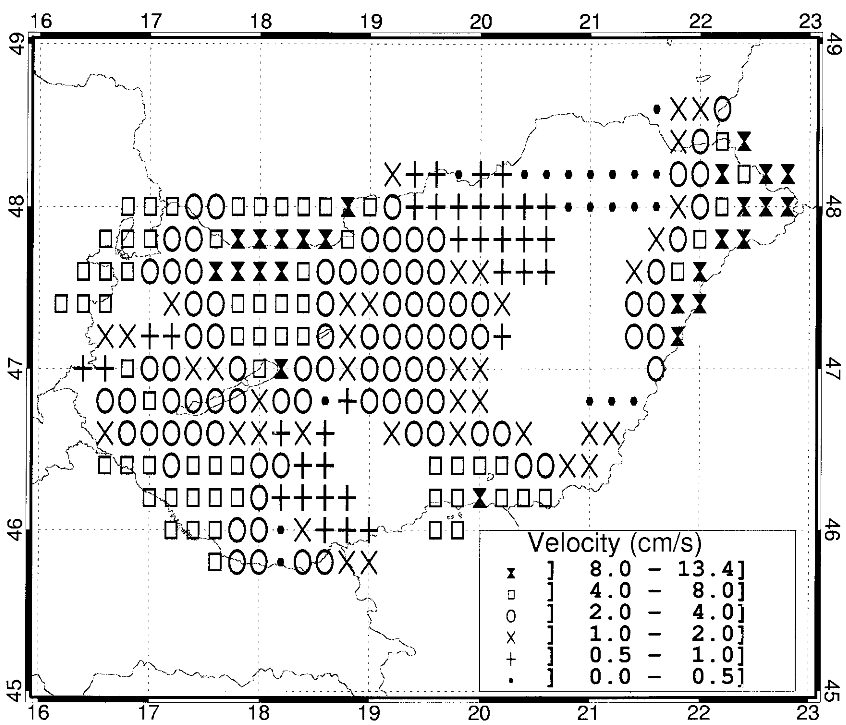

Figure 7
The V_{MAX} values for Hungary.

ities due to the before-mentioned flavours of the Pannonian basin. These heterogeneities can be handled efficiently only by two-dimensional methods. Experience demonstrates that these site effects can change the intensity values in some cases by two degrees on the MSK-64 scale. As the aim of this paper was the first-order seismic zoning of Hungary, the investigation of local site effects is beyond the scope of this work.

We have compared our results for the largest cities with those of ZSIROS (1985), who determined the intensities which will not be exceeded in 200 years with a 70% probability. We have found that our estimates are the same for Budapest and Miskolc, Zsiros gained higher intensity for Pécs (VI vs. V), we have higher intensity for Györ (VIII vs. VII), Debrecen (VIII vs. V) and Szeged (VIII vs. V).

Our research has provided important new results for the seismic risk of Szeged and Debrecen, which show that it is necessary to heed the seismic safety in these cities.

Acknowledgements

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