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Seismic Zoning of Slovenia Based on Deterministic Hazard Computations

MLADEN ŽIVČIĆ,[1] PETER SUHADOLC[2] and FRANCO VACCARI[3]

Abstract—Seismic hazard of the territory of Slovenia is estimated using a deterministic approach based on the computation of complete synthetic seismograms. The input data are the catalogues of earthquakes and fault plane solutions for Slovenia and surrounding regions. Structural models are defined based on available seismological and geophysical information, but are mainly constrained by surface-wave dispersion and 3-D tomographic modelling of the upper crust. Seismogenic zones are delineated considering geotectonic characteristics, fault plane solutions and distribution of earthquake hypocentres. Outside Slovenia seismogenic zones are extended up to distances from which they can considerably influence seismic hazard estimates.

Synthetic seismograms are computed using the "receiver" structure along the entire path by normal mode summation (up to 1 Hz) for receiver sites on a 0.2 × 0.2 degrees grid and scaled to the magnitude of the earthquake allowing for spectral falloff. At each site the maximum value of horizontal velocity, horizontal displacement and design ground acceleration are considered as hazard parameter. The highest values are obtained for western Slovenia where the hazard is controlled by the strongest earthquake in the catalogue, the "Idrija" event of March 26, 1511.

Key words: Seismic hazard, seismic zoning, Slovenia.

Introduction

Studies of the seismic hazard of Slovenia were mostly performed for regulatory purposes. The first seismic map of Slovenia was proposed in 1963 (BUBNOV, 1996) and was based on maximum observed intensities. This map was further improved within the UNESCO/UNDP project on seismicity of the Balkan region (CVIJANOVIĆ, ed., 1974). RIBARIČ (1986) published a revised map of maximal observed intensities in Slovenia and it can be considered the last published seismic hazard map based on a deterministic approach. A probabilistic approach was used for the first time when compiling the 1981 Seismic Building Code, an integral part of which was also a seismic hazard map for the territory of former Yugoslavia. For

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[1] Geophysical Survey of Slovenia, Observatory, Pot na Golovec 25, SI-1000 Ljubljana, Slovenia and Slovenian Association for Geodesy and Geophysics, Kersnikova 3/II, SI-1000 Ljubljana, Slovenia.

[2] Department of Earth Sciences, University of Trieste, Via E. Weiss 1, I-34127 Trieste, Italy.

[3] Department of Earth Sciences, University of Trieste, Via E. Weiss 1, I-34127 Trieste, Italy and CNR-GNDT, Gruppo Nazionale per la Difesa dai Terremoti, via Nizza 128, I-00198 Roma, Italy.

Slovenia the Gumbel distribution of extremes was used to estimate expected intensities for return periods of 50, 100, 200, 500, 1000 and 10,000 years (ZAJEDNICA ZA SEIZMOLOGIJU SFRJ, 1987) LAPAJNE *et al.* (1995) published the first map consistent with the European prestandard Eurocode 8, using the probabilistic approach of CORNELL (1968). Later on, LAPAJNE *et al.* (1997a,b) proposed several modified versions based on recent developments of seismic hazard assessment (FRANKEL, 1995).

The seismic hazard of Slovenia was also considered in regional studies. SLEJKO and KIJKO (1991), in their study of seismic hazard of the main seismogenic zones in the Eastern Alps, included a large part of Slovenia in Ljubljana and Rijeka seismic zones.

The main objective of this study is to assess the appropriateness of the deterministic approach of COSTA *et al.* (1993), considering the size of the territory and the level of seismicity, as well as the level of detail with which seismic hazard can reasonably be mapped using this methodology.

Seismicity

Slovenia lies at the northeastern rim of the Adriatic microplate. Its seismicity is controlled by the geodynamic setting of the country within three large geotectonic units: the Alps, the Dinarides and the Pannonian basin, and is mainly constrained to the regions where these units are in direct contact.

Studies of seismicity of Slovenia (as well as that of neighbouring countries) rely mostly on macroseismic data (RIBARIČ, 1982). Until the late 1980s the number and distribution of seismological stations in Slovenia did not allow for the reliable estimate of earthquake parameters from instrumental records. It is estimated that the catalogue can be considered reasonably complete for magnitudes above 3.7 for the period after 1870 (LAPAJNE *et al.*, 1997b). As the largest magnitude since 1870 is estimated (using macroseismic data) to be 6.1 (the Ljubljana 1895 event), the range of completeness and the territory covered do not allow a reliable use of statistical methods (e.g., KRINITZSKY, 1995).

A good earthquake catalogue is required for every seismic hazard assessment. Many parts of Slovenia suffered major damage from earthquakes that originated outside its political boundaries. The strongest are the 1976 Friuli earthquake and two historical events in the Friuli-Carnia region, in 1348 and 1690. For the purpose of the seismic hazard assessment for the territory of Slovenia, we assembled a catalogue covering the region between 44.5–47.5°N and 12.5–17.5°E. The existing catalogues for the regions that surround Slovenia are rather inhomogeneous as regards their completeness as well as the methods used to derive earthquake parameters (CVIJANOVIĆ, 1981; ZSÍROS *et al.*, 1988; FIEGWEIL, 1981; OGS, 1992; and references therein). Therefore, the individual catalogues have been merged following the principle to retain the parameters determined in each catalogue only for events lying on the respective national territory. We therefore use ZSÍROS *et al.* (1988) parameters for events originating in Hungary and so on. Intensity is used as a measure of earthquake size for pre-1901 earthquakes. MCS and MSK scales used in different sources are assumed to be equivalent (WILLMORE, ed., 1979). For post-1900 earthquakes magnitude M_{LH} as defined by KARNÍK (1968) is used since the majority of earthquake magnitudes was determined uniformly when compiling the KARNÍK (1968, 1971) catalogue and the catalogue of earthquakes in Balkan Region (SHEBALIN *et al.*, 1974). Our merged catalogue contains earthquakes in the region 44.5–47.5°N and 12.5–17.5°E and we estimate it to be complete for intensities VI MSK and greater since 1890. However for deterministic hazard estimation purposes, only locations and magnitudes of the strongest earthquakes are of importance.

In estimating earthquake hazard it is of great importance to have a unified measure of the earthquake size. For historical events no instrumental data are available and magnitudes have to be estimated from macroseismic data. The relations between magnitude M_{LH} and isoseismal radii as determined from good quality isoseismal maps, have been derived from 20th century earthquake data.

For eighteen earthquakes both isoseismal maps and M_{LH} magnitudes are available. This has enabled us to derive relations for the estimation of magnitudes from macroseismic data. Isoseismals have been digitised and the relations between magnitude M_{LH} and equivalent radii R of isoseismals, as well as between M_{LH} and epicentral intensity Io and focal depth h, are derived:

$$M_{LH} = 2.72 + 1.63 \log R_{\mathrm{VI}} \quad (\text{correlation coefficient } r = 0.82),$$

$$M_{LH} = 1.08 + 2.32 \log R_{\mathrm{V}} \quad (r = 0.82),$$

$$M_{LH} = 1.14 + 1.96 \log R_{\mathrm{IV}} \quad (r = 0.84) \text{ and}$$

$$M_{LH} = 0.09 + 0.494\, Io + 1.27 * \log(h) \quad (r = 0.74).$$

The relations are derived for intensities IV, V and VI MSK because there are not enough strong earthquakes in the 20th century which would provide data for calibrating magnitude formulas for higher intensities. The strongest earthquake in the 20th century was of magnitude $M_{LH} = 5.7$ and intensity VIII MSK. Magnitudes of historical events are therefore estimated from macroseismic data. The average value obtained using the above relations is adopted as macroseismic magnitude M_M. For that purpose we considered all earthquakes for which macroseismic data as well as instrumentally determined magnitude are available. The macroseismic magnitudes, M_M, of the two strongest earthquakes are:

$$26.03.1511. \quad M_M = 6.8 \pm 0.3$$

$$14.04.1895 \quad M_M = 6.1 \pm 0.2.$$

The 1976 earthquake with epicentre in Friuli (Italy) was used for control—its macroseismically estimated magnitude is $M_M = 6.1 \pm 0.1$, whereas its instrumental magnitude estimates range from $M_b = 5.9$ to $M_s = 6.5$ (ISC, 1976).

Seismogenic Structures and Earthquake Mechanisms

The data from the revised earthquake catalogue, as well as both published and newly determined fault plane solutions, were combined with the available geological and geophysical information to delineate and characterise seismogenic areas of Slovenia (Poljak *et al.*, 2000). The main criteria were the geotectonic characteristics, fault plane solutions and earthquake hypocentres distribution. The studied region was divided into seven seismogenic zones (Fig. 1) having different tectonic

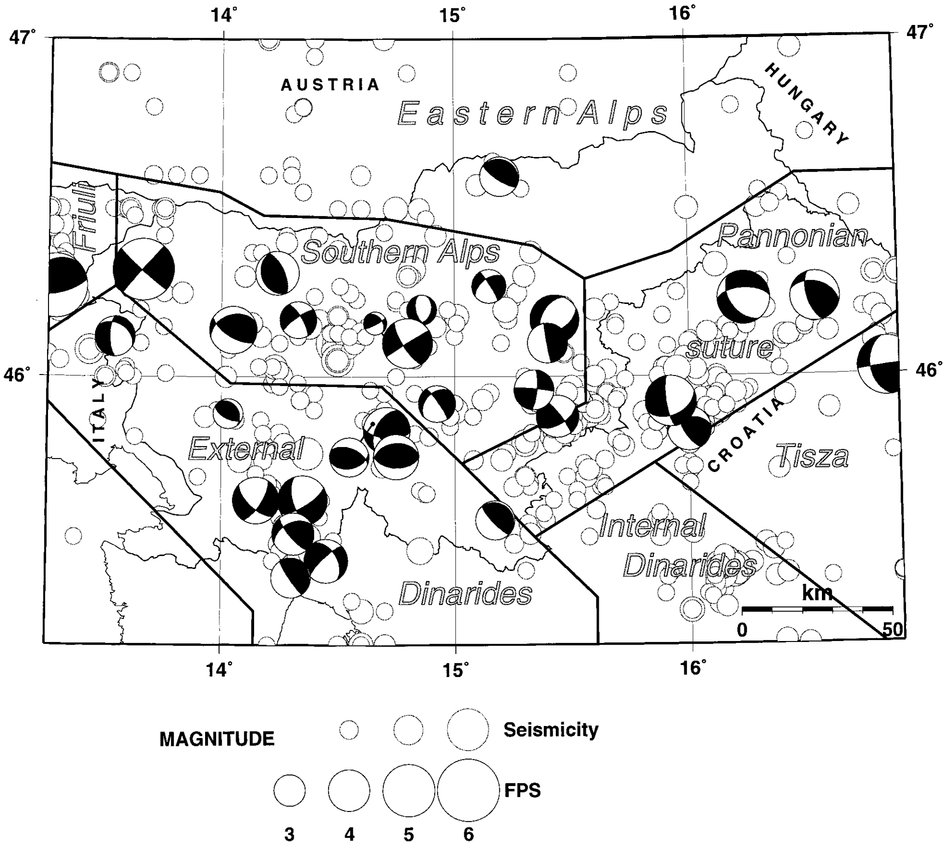

Figure 1
Seismogenic zones in Slovenia and fault plane solutions of earthquakes. Seismicity of $M > 3.7$ in the 567–1995 period is plotted as background. Note that magnitude scales are different.

evolution and seismicity characteristics. The zoning corresponds to a large extent to the structural geometry of the major geotectonic units. The entire investigated region is dominated by strike slip (NW–SE and NE–SW oriented) and thrust-type fault plane solutions, although normal type faulting is also present. For each seismogenic zone a characteristic earthquake mechanism is adopted. As a rule it corresponds to the strongest event for which the fault plane solution is available. For the Eastern Alps and the Internal Dinarides area the earthquake mechanism is assigned based on tectonic data.

Most of the seismicity in the area is constrained to be located in the upper crust, focal depths of recent events exceeding 15 km occur only in restricted areas. Due to the lack of reliable information on focal depths of historical events, the focal depth of 10 km was adopted for all events.

Structural Models

There are practically no velocity models pertinent to Slovenian territory. The research done so far, on a much larger regional scale and with low resolution, describes the structure of large regions like Europe (PANZA *et al.*, 1980; SUHADOLC and PANZA, 1989), Southeastern Europe (NESTEROV and YANOVSKAYA, 1988, 1991), Alps, Pannonian basin (BONDÁR *et al.*, 1996), Mediterranean (CALCAGNILE and PANZA, 1990) and Balkans. Only one deep seismic sounding profile crosses Slovenian territory (JOKSOVIĆ and ANDRIĆ, 1983), however its data resolve only the uppermost about 3 to 6 kilometres from the rest of the crust. Also, the total crustal thickness is determined to be between 42 km in the south under the External Dinarides and less then 30 km in the northeast.

Good structural models are essential for seismic hazard computations based on a deterministic approach using complete synthetic seismograms (PANZA *et al.*, 1996). The role of the upper crustal layers is especially important. For that purpose velocity models obtained from body wave data give rather poor results—seismological stations are as a rule situated on rock sites with high velocities and density, and seismic waves (both longitudinal and transversal) sample only faster layers. Slower structures in the upper crust are only poorly sampled or not sampled at all. As a consequence the velocity models resulting from body wave data inversions are faster than the average structure and in waveform modelling usually result in unrealistically small amplitudes.

The structural regionalization of Slovenia is based primarily on surface wave data (BONDÁR *et al.*, 1996; ŽIVČIĆ *et al.*, this issue; COSTA *et al.*, 1993) and on a tomographic inversion of longitudinal waves (MICHELINI *et al.*, 1998). Both these models describe only layers in the upper crust. The depth of the crust is taken from the maps of the depth of the Mohorovičić discontinuity (RAVNIK *et al.*, 1995 and references therein) while the upper mantle structure is assumed to be the same as in

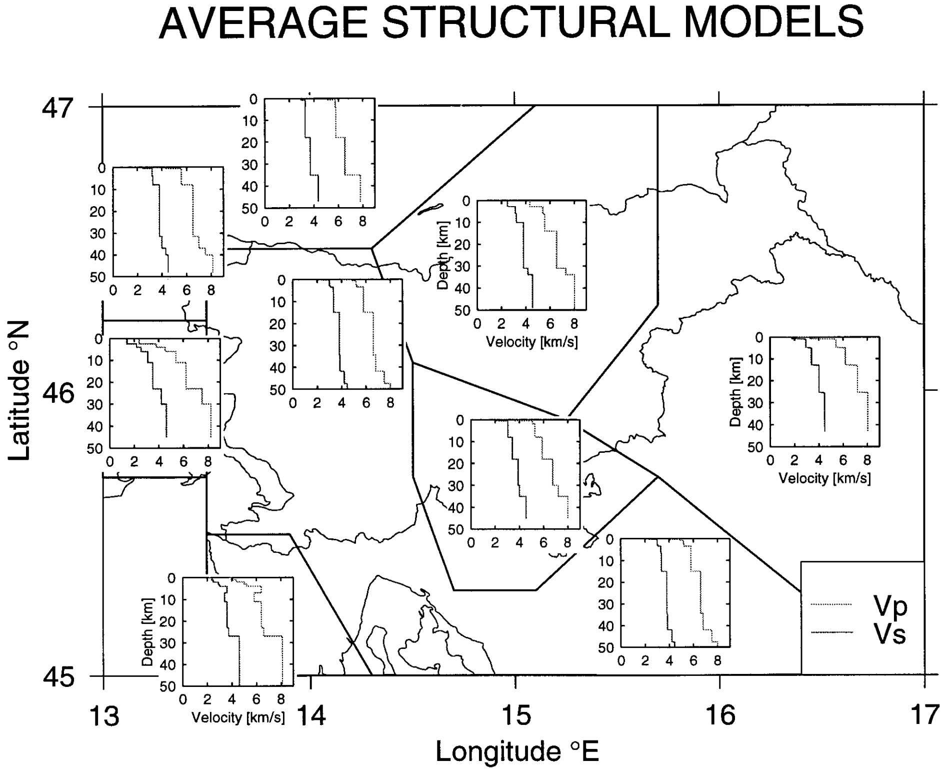

Figure 2
Structural regions used for synthetic seismogram computation with P- and S-velocity distribution in the crust.

the standard IASPEI91 model (Kennett and Engdahl, 1991). Based on these considerations, the study area is divided into eight units which have different seismic velocity structural models (Fig. 2).

Method

The deterministic seismic hazard assessment consists basically of three steps. First, pertinent structures are identified and the location and the parameters of potential earthquakes are established. Then, a relation estimating ground motion parameters from earthquake magnitude (or epicentral intensity), epicentral distance and site conditions is determined/selected. Finally, parameters representing seismic hazard are selected and their maximum value for each grid point computed. Probabilistic approach differs in the third step when the probabilities of the exceedance are computed rather than maximum values. In our deterministic procedure, fully described in COSTA *et al.* (1993), the second step is replaced by numerical calculation of complete synthetic seismograms given the source parameters, distance and earth structural model. In this paper we have selected the maximum historical earthquake observed in a seismogenic zone as the maximum possible event for that zone.

The territory under investigation is divided into eight polygons and to each of them a uniform velocity structural model is assigned. At this stage only a bedrock type of structure is considered and surface layers with S-wave velocities lower then 1 km/s are not included. The same territory is divided in terms of the seismotectonic characteristics into seven seismogenic zones, and to each of them a characteristic focal mechanism is assigned. The delineation of seismogenic zones is based on the geodynamic model proposed by POLJAK *et al.* (2000), fault plane solutions and seismicity distribution. Outside Slovenia seismogenic zones were extended only to distances from which they can considerably influence seismic hazard estimates on the territory of Slovenia.

The catalogue of earthquakes for the period 1000–1995 is discretized over a $0.2° \times 0.2°$ grid retaining the largest magnitudes within each cell. To allow for location uncertainties of historical events, as well as possible hypocentral migration along seismogenic zones and spatial extension of big-magnitude sources, these magnitudes are also assigned to the three nearest cells in each direction, as long as they fall within the seismogenic zone (always keeping the largest magnitude). This procedure defines locations and magnitudes of the seismic sources used to compute synthetic seismograms. The depth of the sources is set to 10 km. The receiver sites are situated over the area of interest on a $0.2° \times 0.2°$ grid displaced by $0.1° \times 0.1°$ from the grid of seismic sources. As a result, the shortest source to receiver distance is about 13.5 km. Synthetic seismograms are computed for all feasible source-site paths (taking the "site" structure along the whole propagation path). For thus defined source-site pairs, with a given FPS and magnitude, synthetic acceleration is computed for P-SV and SH components using the modal summation technique (PANZA, 1985; PANZA and SUHADOLC, 1987; FLORSCH *et al.*, 1991). The summation is carried out up to the frequency of 1 Hz for which we can reasonably assume the point source approximation to be valid. Seismograms are computed for a unit seismic moment and then scaled to the magnitude of the earthquake using the magnitude-moment relation of KANAMORI (1977). The finiteness of the source is accounted for by scaling the spectrum using the spectral scaling law proposed by GUSEV (1983) as reported in AKI (1987). VACCARI (1995) has demonstrated that for periods between 1 and 2 s the Gusev spectral falloff produces higher spectral values than the omega squared spectral falloff, and thus generates more conservative results in our hazard computations.

Results

Maps of maximum ground velocity (Fig. 3) and maximum ground displacement (Fig. 4) for frequencies up to 1 Hz are compiled. A map of design ground acceleration (Fig. 5) is compiled by fitting the long period portion of the computed spectra to the response spectrum of Eurocode-8 (CEN, 1994) soil type A (rock and stiff deposits). The maximum values are to be found in the Friuli region in NE Italy and in western Slovenia. The sensitivity study has shown that the choice of the fault plane solution can influence the hazard by a factor of about 2 (e.g., strike slip vs. thrust event in the same seismogenic zone). For the city of Ljubljana DGA values vary by only 20% due to different FPS but change fourfold depending on the alternative selection of the location of 1511 event. This so called "Idrija" earthquake of March 26, 1511, almost completely controls the seismic hazard in this region. Its magnitude is estimated from macroseismic data to be 6.8 although its epicentre is still rather uncertain (Ribarič, 1979) since it may have occurred either in Friuli, in the Southern Alps or in the western part of the External Dinarides. The values of the hazard parameters gradually diminish eastwards, their lowest values being found in the northeastern part of Slovenia. This distribution of hazard values

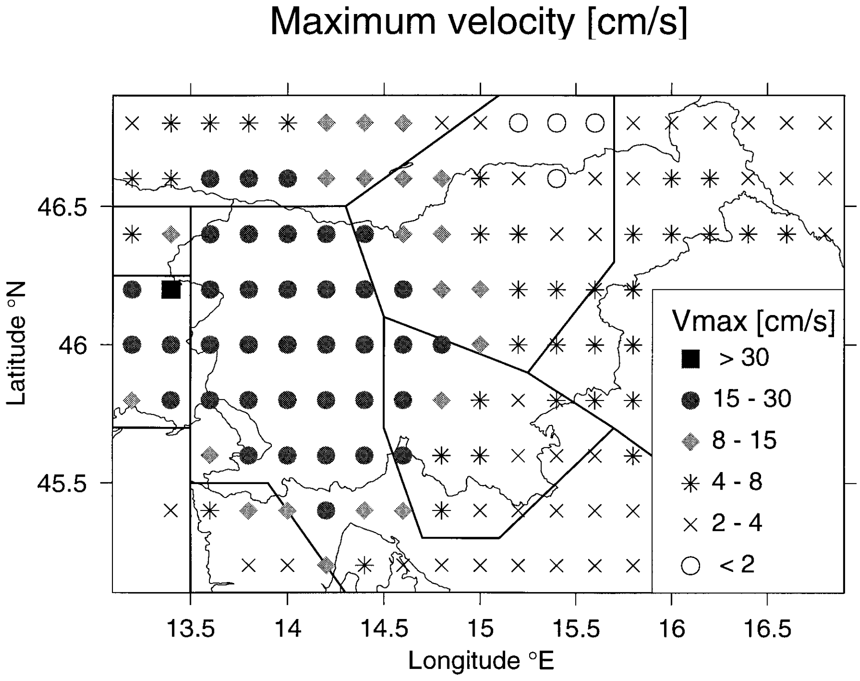

Figure 3
Map of maximum horizontal ground velocity (in cm/s) for frequencies below 1 Hz.

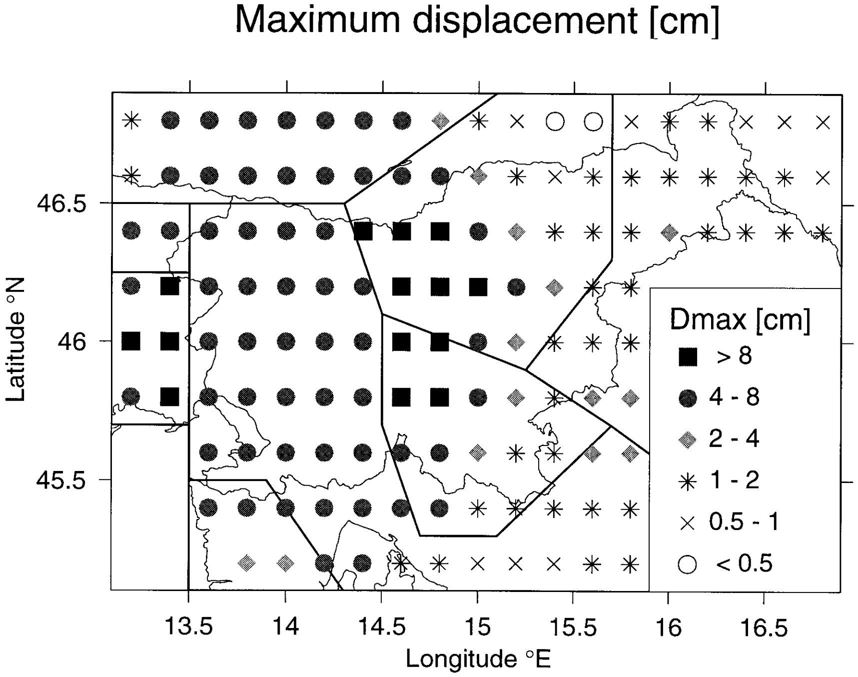

Figure 4
Map of maximum horizontal ground displacement (in cm) for frequencies below 1 Hz.

is rather similar to the one based on intensity data (RIBARIČ, 1986). However, the different levels of seismic hazard between western and eastern Slovenia are more pronounced in our study and compare well with the deterministic studies for the neighbouring regions.

To evaluate the reliability of the applied method, we have compared synthetics with the accelerograms of two earthquakes with epicentre in southern Slovenia recorded on free field strong motion instrument in Ljubljana, 50 km north of the epicentre. The synthetics were computed using published fault plane solutions (HERAK *et al.*, 1995) that are quite similar to the FPS proposed for this seismogenic zone. The values of the peak horizontal acceleration in the frequency band below 1 Hz, for which theoretical computations have been made and hazard parameters are mapped, are given in Table 1.

The peak value of acceleration is predicted within a factor of two. The acceleration response spectra for two events shown in Figure 6 match quite well the observed ones up to periods of about 4 s. For longer periods the noise dominates the records and no comparison is possible.

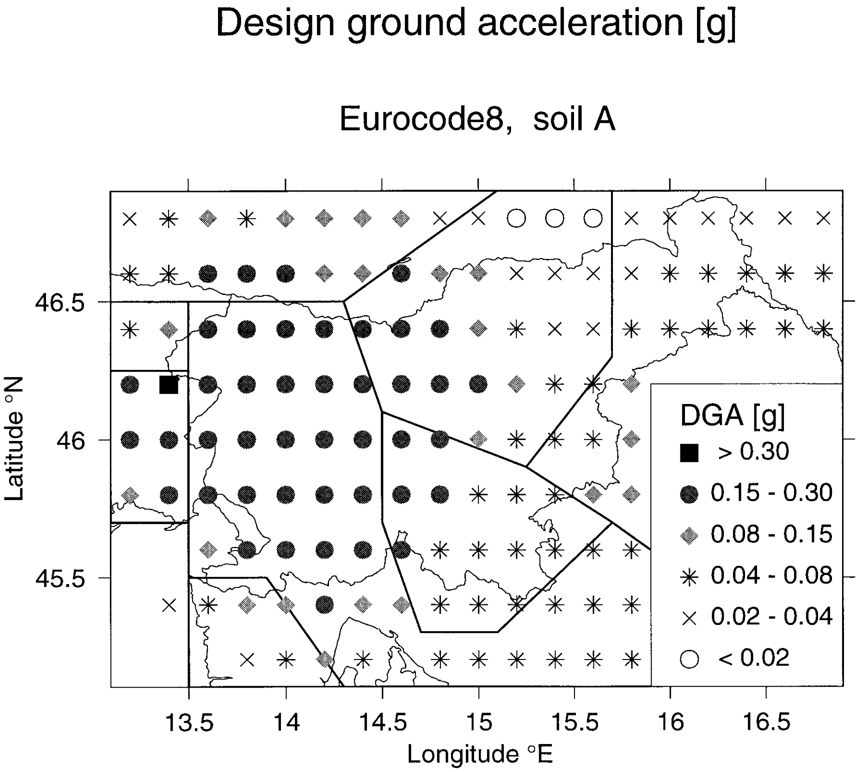

Figure 5
Map of design ground acceleration (in cm/s^2) for Eurocode-8 soil type A.

Conclusions

The outlined deterministic method based on the computation of complete synthetic seismograms is able to delineate the main features of seismic hazard even for regions as small as Slovenia. Seismic hazard is controlled mainly by the

Table 1
Observed and synthetic peak ground accelerations for frequencies below 1 Hz for two earthquakes at 50 km distance

Event	ML	N–S observed PGA [g]	N–S synthetic PGA [g]	E–W observed PGA [g]	E–W synthetic PGA [g]
22.05.1995. 11:16	4.4	$1.2*10^{-5}$	$2.8*10^{-5}$	$0.9*10^{-5}$	$2.1*10^{-5}$
22.05.1995. 12:50	4.7	$1.5*10^{-5}$	$3.5*10^{-5}$	$1.2*10^{-5}$	$1.1*10^{-5}$

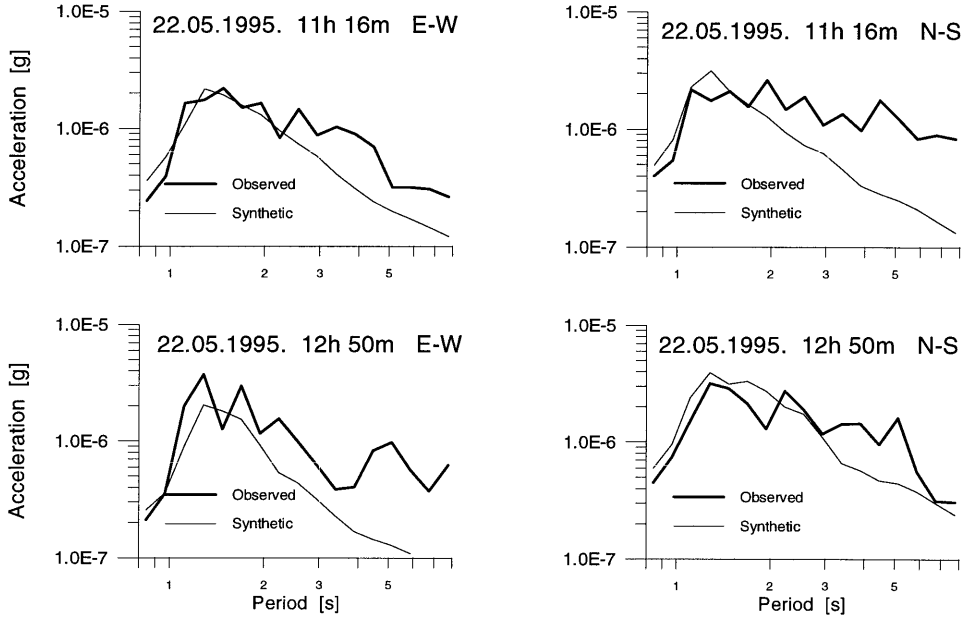

Figure 6
Comparison of observed and synthetic horizontal acceleration response spectra for frequencies below 1 Hz for two earthquakes at 50 km distance.

strongest event in the area and is found to be highest in western Slovenia, where the design ground acceleration reaches values exceeding 0.25 g.

Since its effects on seismic hazard determination are enormous, the main efforts in the future should be concentrated to precisely determine the size and location of the biggest event in the Slovenian catalogue, the Idrija event of March 26, 1511.

Peak values of acceleration in the case of Mt. Snežnik events are well modelled even with this rather rough approach, but the duration of the strong shaking is underestimated, partly because of the used point source approximation, partly because soft shallow sediments are not included in the modelling. However, if estimates of site effects for a given location are available, one can easily superimpose their effect to the "bedrock" motion estimated in this paper. Finally, we have shown that comparisons of the computed and recorded acceleration response spectra in the case of 1995 Mt. Snežnik exhibit considerable similarity, illustrating the appropriateness of the methodology applied in the paper.

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