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Neo-deterministic seismic hazard maps of Kosovo

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ABSTRACT

Kosovo is one of the most seismically active regions in Europe, lying within the Alpine-Mediterranean tectonic belt. Historical records for the region show several catastrophic earthquakes with epicentral intensity IX (MCS). However, due to Kosovo's high population density, high prevalence of traditional construction, and insufficient enforcement of building codes, Kosovo is vulnerable to earthquake damage. In this study, we present earthquake hazard maps for bedrock conditions in Kosovo based on the well-known Neo-deterministic Seismic Hazard Assessment (NDSHA) method. NDSHA relies upon the fundamental physics of wave generation and propagation in complex geologic structures to generate realistic time series, used as input for the computation of several ground motion parameters, integrating the available knowledge of seismic history, seismogenic zones and morphostructural nodes. In accordance with continuum mechanics, the tensor nature of earthquake ground motion is preserved, producing realistic signals using structural models obtained by tomographic inversion and earthquake source information readily available in literature. Our maps are generally consistent with the observed intensity IX (MCS) and suggest that, in some instances, intensity X could be reached.

Keywords: seismic hazard; neo-deterministic; Kosovo; NDSHA; morphostructural nodes.

1. Introduction

Kosovo is a small diamond-shaped country located in the heart of the Balkan Peninsula. The country lies in between two major tectonic features, the Dinarides-Albanides orogenic belt to the west and the South Balkan extensional system (SBER, Burchfiel et al., 2008) to the south-east (Fig. 1, left). The Dinarides-Albanides domain can be further differentiated in two zones: the westernmost, coastal area that marks the boundary between the Adriatic and

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Eurasian plates and where the dominant tectonic stress is SW-NE compression; and the inner part, which is characterized by strike-slip, oblique strike-slip or normal stress, reflecting the counter-clockwise motion of Adria and its compression against Dinarides-Albanides (Gülerce et al., 2017). Here, extensional stress emerged starting in the Pliocene (Muço et al., 2002).

The latter area partially overlaps with the SBER, an extensional system of normal faults and associated sedimentary basins active since the late Cretaceous. The SBER is bounded to the south by the Northern Anatolian Fault, while its northern boundary is still poorly defined but may run through southwestern Kosovo (Burchfiel et al., 2008).

The neotectonic activity of Kosovo is mainly characterized by the uplift of the Dinarides Massif in the country's western part and of the Median (Serbo-Macedonian) Massif in the eastern part (Elezaj, 2009). Sinking depressions, like the Dukajin basin (also known as Pejë-Prizren basin) in the west and the Kosovo basin in the east, represent second-order tectonic units. Pleistocene glacial deposits are common in the western and southern parts of Kosovo, with Holocene alluvial deposits found in the youngest valleys. Kosovo's main urban areas lie within these basins or on their flanks.

The faulting pattern mainly reflects the differential vertical movements of the uplifting and subsiding blocks, with E-W-oriented shear stress superimposed on the mainly NW-SE or NE-SW normal faults that flank the basins. Thus, earthquakes mostly occur on the major basins' flanks and display normal faulting mechanisms. Historical and instrumental seismicity data collected in the SHARE European Earthquake Catalogue (SHEEC) and covering the period from A.D. 1000 to 2006 (Stucchi et al., 2013; Grünthal et al., 2013, Fig. 1) show that although only moderate events ($M_w \leq 6$) nucleated in Kosovo in the past, they caused intensities up to IX (MCS) (Elezaj, 2009). However, seismic hazard in Kosovo also comes from seismic sources in neighboring areas, such as thrust faults on the Albanian coast and normal faults at the border of North Macedonia with Bulgaria, where $M_W \geq 7$ events have been recorded (Fig. 1, right).

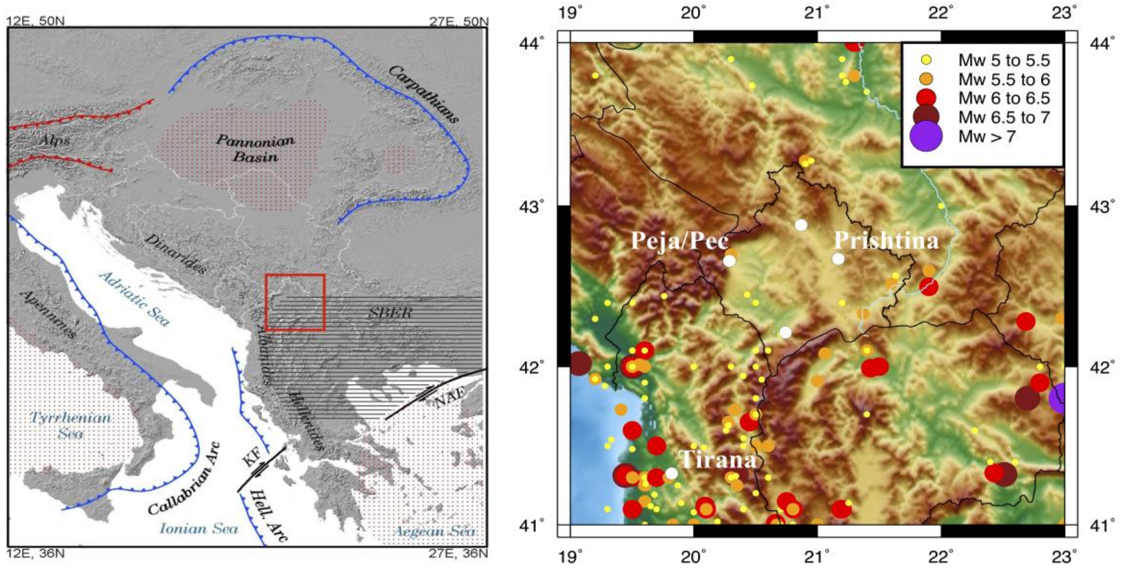

Figure 1. Left: tectonic setting of Kosovo (red square), after Burchfiel et al., (2008); right: seismicity of the study area from the SHEEC catalogue ($M_W \geq 5$). For color code, please refer to the digital version of the paper

In this study, we present seismic hazard maps generated using the well-established Neo-Deterministic Seismic Hazard Assessment (NDSHA) methodology (Panza et al., 2001; 2012; Panza and Bela, 2020; Bela and Panza, 2021; Panza et al., 2021).

In recent decades, Kosovo has experienced significant urban development, but building codes are still poorly enforced. Additionally, the country has the youngest average age population in the Old Continent and is home to several UNESCO World Heritage sites. Thus, NDSHA implementation may greatly enhance the assessment of Kosovo's seismic hazard toward the goal of sustainability and resilience.

2. Methodology and data used

NDSHA is a technique based on the physical description of the earthquake rupture process and seismic propagation paths and is aimed at obtaining realistic synthetic seismograms from which reliable ground motion parameters relevant to engineering applications can be extracted.

In assessing seismic hazard, NDSHA exploits all the known seismicity and other potential seismic sources and available knowledge of the earth structure (i.e., the propagation medium and ray-path), preserving the tensor nature of earthquake ground motion. As a rule, ground motion parameters at the regional scale are given at bedrock conditions, but more detailed studies can be performed at specific sites, taking into account the nature of local soil and complexities at the source.

NDSHA has been described in numerous previous studies (NDSHA, Panza et al., 2001; 2012; Panza and Bela, 2020; Bela and Panza, 2021; Panza et al., 2021), which detail the theoretical framework and computational workflow. Here, we summarize the main steps and describe the specific input data used in this study.

The regional structure consists of a set of 1D anelastic seismological cellular models (Fig. 2 and Table 1) with a resolution of 1°×1° (Brandmayr et al., 2010; Brandmayr, 2012) obtained from surface wave tomography. The models are extracted from a 3-dimensional model covering most of the Mediterranean and neighboring areas that contains the mechanical properties (layering of V_P, V_S, Q_P, Q_S and density) of the lithosphere-asthenosphere system down to 350 km of depth. Beneath, a standard reference structure was used (Kennett and Engdahl, 1991).

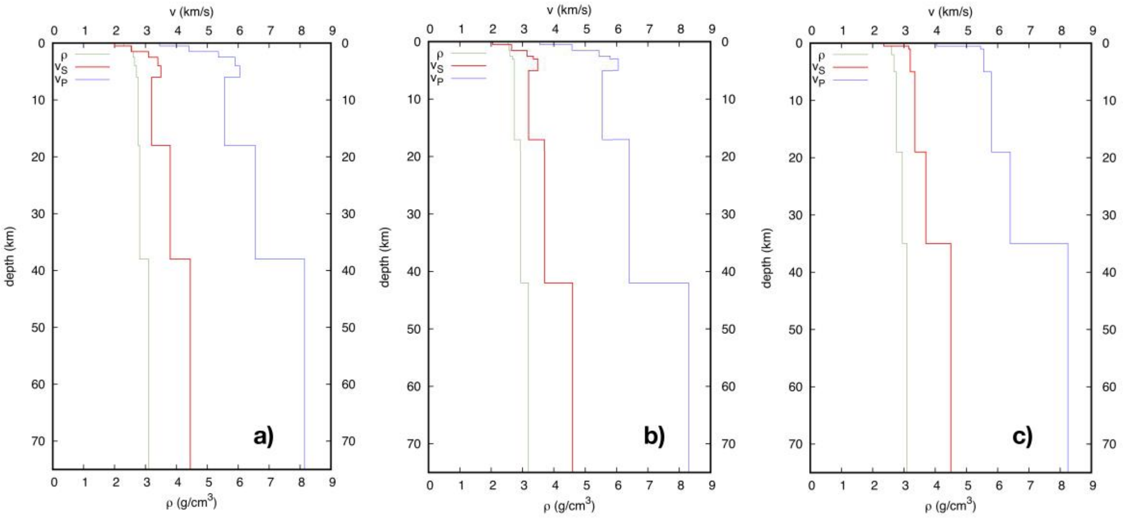

Figure 2. Structural cellular models of Kosovo: a) cell centered at 20.5°E 42.5°N; b) 20.5°E 43.5°N; c) 21.5°E 42.5°N. ρ is density. After Brandmayr (2012). For color code, please refer to the digital version of the paper. For details of structural models down to 350 km, see Table 1

Table 1. Structural models of Kosovo used in this study (after Brandmayr, 2012) down to a depth of 350 km. Coordinates refer to the center of 1°×1° cells. Q_S after Martinez et al. (2009, 2010). $Q_P=2.2*Q_S$

20.5°E 42.5°N						
Thk (km)	Density (g/cm^3)	V_P (km/s)	V_S (km/s)	Q_P	Q_S	Depth (km)
0.5	2.54	3.55	2.05	220	100	0.5
1.0	2.57	4.58	2.65	220	100	1.5
1.0	2.60	5.44	3.15	220	100	2.5
0.5	2.69	5.80	3.35	220	100	3.0
2.0	2.74	6.05	3.50	220	100	5.0
12.0	2.74	5.55	3.20	176	80	17.0
25.0	2.94	6.40	3.70	176	80	42.0
80.0	3.19	8.30	4.60	176	80	122.0
55.0	3.19	8.30	4.55	176	80	177.0
70.0	3.19	8.45	4.60	176	80	247.0
103.0	3.48	8.90	4.75	330	150	350.0
20.5°E 43.5°N						
Thk (km)	Density (g/cm^3)	V_P (km/s)	V_S (km/s)	Q_P	Q_S	Depth (km)
0.5	2.30	3.46	2.00	220	100	0.5
1.0	2.53	4.41	2.55	220	100	1.5
1.0	2.60	5.36	3.10	220	100	2.5
1.5	2.65	5.90	3.40	220	100	4.0
2.0	2.71	6.05	3.50	198	90	6.0
12.0	2.76	5.55	3.20	176	80	18.0
20.0	2.81	6.55	3.80	176	80	38.0
45.0	3.11	8.15	4.45	176	80	83.0
100.0	3.20	8.25	4.50	176	80	183.0
65.0	3.30	8.50	4.70	176	80	248.0
102.0	3.49	8.85	4.75	330	150	350.0
21.5°E 42.5°N						
Thk (km)	Density (g/cm^3)	V_P (km/s)	V_S (km/s)	Q_P	Q_S	Depth (km)
0.5	2.35	4.06	2.35	220	100	0.5
0.5	2.60	5.45	3.15	220	100	1.0
1.0	2.60	5.55	3.20	220	100	2.0
3.0	2.68	5.55	3.20	220	100	5.0
14.0	2.75	5.80	3.35	176	80	19.0
16.0	2.95	6.40	3.70	176	80	35.0
50.0	3.10	8.25	4.50	176	80	85.0
100.0	3.20	8.30	4.55	176	80	185.0
70.0	3.29	8.55	4.65	220	100	255.0
95.0	3.38	8.90	4.75	330	150	350.0

We model three seismogenic zones (Fig. 3, top-left) within the boundaries of Kosovo, based on known seismicity and main tectonic features. Since Kosovo is also vulnerable to earthquakes generated in neighboring countries (particularly Albania, Bulgaria and Serbia), five seismogenic zones beyond Kosovo borders are also considered in the study area. Each zone is associated with a representative focal mechanism that is generally consistent with the dominant tectonic regime and with moment tensor solutions available in the RCMT catalogue (Pondrelli et al., 2007).

The seismicity of the study area (Fig. 3, top-right) is extracted from the SHEEC catalogue, covering the period from AD 1000 to 2006 (Stucchi et al., 2013; Grünthal et al., 2013). A smoothing procedure for the definition of the earthquake location and magnitude is applied to account for spatial uncertainty, catalogue incompleteness and source extension (on a 0.2°×0.2° grid; Fig. 3 bottom-left). After smoothing, only the seismic sources located within active seismogenic zones are retained.

Furthermore, we integrate the list of seismic sources using seismogenic nodes, which are specific structures formed at the intersection of morphostructural lineaments (not single faults, as a rule) that are derived by means of morphostructural zonation. The nodes are recognized to be earthquake-prone (seismogenic) through pattern recognition (Gelfand et al., 1972; Gorshkov and Panza, 2004) and thus independently from seismicity data.

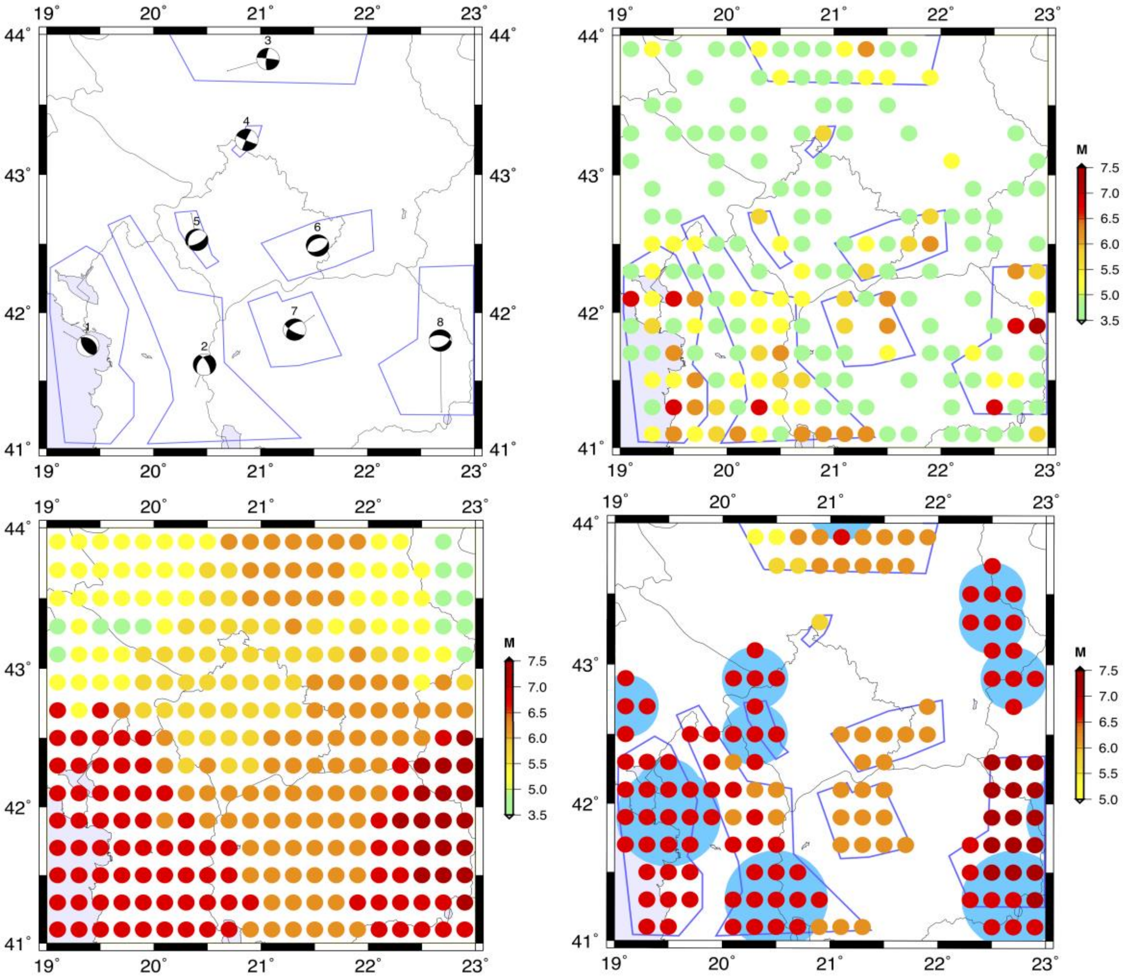

Figure 3. Input sources: seismogenic zones (polygons) and representative focal mechanisms (top-left). The SHEEC catalogue seismicity, discretized into 0.2°×0.2° cells (top-right) and smoothed on a 3 cells radius (bottom-left), is then clipped to the seismogenic zones (bottom-right) and seismogenic nodes (cyan circles) are added (bottom right). For color code, please refer to the digital version of the paper

Two seismogenic nodes (capable of M_w 6.5 events) have previously been identified by means of morphostructural zonation in western Kosovo, while the morphostructural analysis has not been completed yet in eastern Kosovo (Gorshkov, 2020 pers. comm.). Also, eleven nodes lie outside Kosovo borders but within the study area (Fig. 3, bottom-right).

Regional hazard maps with a 1 Hz cut-off frequency are computed using the Size Scaled Point Source model (SSPS, after Parvez et al., 2011) approximation. The cut-off frequency of 1 Hz used in the computations is consistent with the resolution of generally available data, and the estimates at higher frequencies are obtained by extrapolation, considering average response spectra (Panza et al., 1996) to obtain Design Ground Acceleration (DGA). In this work, we used the Eurocode 8 (CEN, 2004) response spectrum for soil type A.

3. Results and discussion

Different sets of maps have been produced using 1) only seismogenic zones, 2) only nodes, and 3) both. In the following, we present the results of using both seismogenic zones and nodes, which are the most conservative; in fact, the use of only nodes underestimates ground motion in the east (by up to three degrees of intensity), while the sole use of zones underestimates ground motion in the west (by up to two degrees of intensity).

The horizontal displacement map shows that most of Kosovo can experience displacement in the range of 3.5-7 cm, while the central part of the country experiences slightly lower values (2-3.5 cm). Locally, in the westernmost and southernmost parts of the country, horizontal displacement can exceed 7 cm (Fig. 4, top-left). Vertical displacement is generally in the range 2-3.5 cm but can exceed 7 cm in the westernmost part of the country (Fig. 4, top-right).

Horizontal velocity (Fig. 4, center-left) peaks in the range of 8-15 cm/s in the westernmost and southernmost parts of Kosovo and is lower in the NE (2-4 cm/s). Vertical velocities are relatively high in the central and SE parts of the country (8-15 cm/s), while they are again lower in the NE ($\leq$ 2 cm/s).

Horizontal DGA falls in the 0.08-0.15 g range in a wide area in the eastern part of Kosovo, including the Peja/Peć, Gjakova, Gjilani and Kaçaniku areas in the SE part of the country. Elsewhere, it is in the 0.04-0.08 g range (Fig. 4, bottom-left). Vertical DGA ranges between 0.15 and 0.30 g in the Dukajin basin and between 0.08 and 0.15 g in the SE, while it falls below 0.04 g in the NE (Fig. 4, bottom-right). In terms of intensity, 0.08-0.15 g corresponds to an intensity of ≈ IX (MCS) and 0.15-0.30 g ≈ X (Panza et al., 2001).

Significant ground motion can also be caused in Kosovo by deep Vrancea (a seismic region located in Romania, several hundreds of kilometers away) earthquakes. Our computation performed for the 1940, M_w 7.7 earthquake scenario (source parameters after Radulian et al., 2000) with hypocentral depth at 133 km shows that horizontal DGA can be in the 0.04-0.08 g range (≈I-VIII) in the northern part of Kosovo and between 0.02 and 0.04 g (≈I-VII) in the western part of the country (Fig. 5, left).

Kronrod et al. (2013) presented a transnational map of macroseismic intensities from the strongest Vrancea earthquakes and determined that ≈I-V was the maximum known intensity felt in Kosovo; in contrast, our scenario shows that the effect of a Vrancea could be far more damaging in the study area.

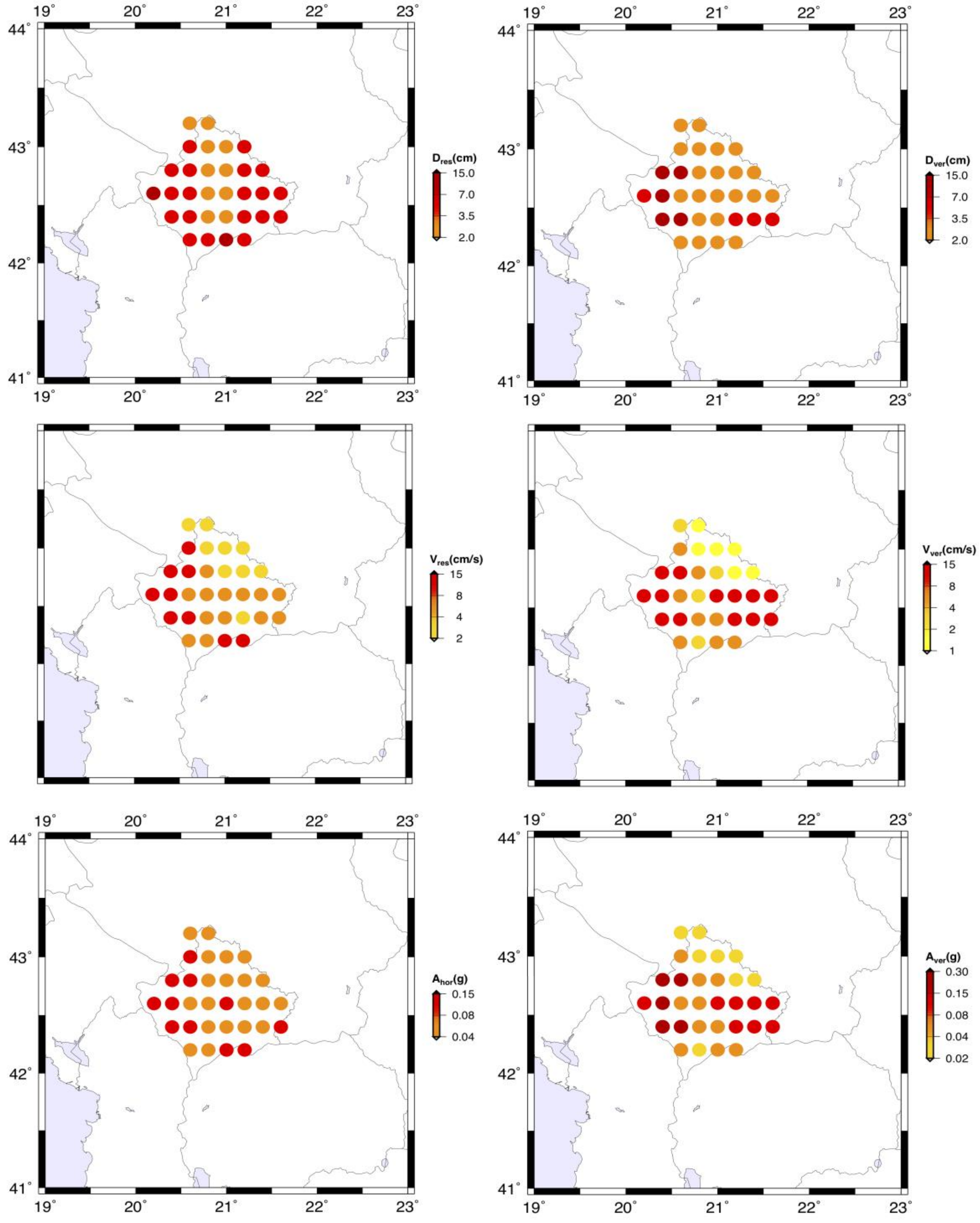

Figure 4. National hazard maps for Kosovo at 1 Hz cut-off frequency. Left column: horizontal component; right column: vertical component. The values for displacement and velocity are taken from the resultant of the horizontal components (NS and EW). The values shown in the acceleration maps are obtained using Eurocode 8 (Soil A) to extrapolate the DGA at T=0 s. For the evaluation of the horizontal DGA, either the NS or the EW accelerogram is considered, whichever leads to the highest DGA. For color code, please refer to the digital version of the paper

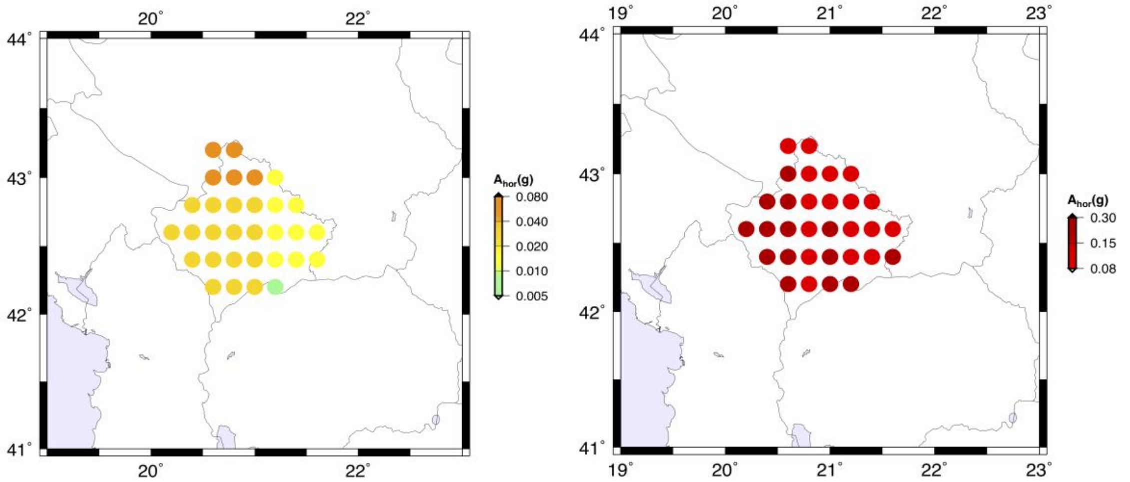

Figure 5. Left: horizontal DGA caused by a M_W 7.7 earthquake in Vrancea (133 km of depth); right: horizontal DGA when M_{design} is applied to the maximum magnitude in both seismogenic nodes and zones. For color code, please refer to the digital version of the paper

Furthermore, following Rugarli et al. (2019), we perform hazard computation considering M_{design} for all sources (nodes and zones). Namely, we added a safety increment $\Delta M = \boldsymbol{\gamma}_{EM}\boldsymbol{\sigma}_M$ to the maximum magnitude observed or estimated for the nodes (with pattern recognition of morphostructural zonation), where $\boldsymbol{\gamma}_{EM}$ (here set to 2.0) is a tunable safety factor and $\boldsymbol{\sigma}_M$ (here set to 0.25) is a value representative of the global uncertainty on magnitude determination (Båth, 1973).

Rugarli et al. (2019b) demonstrated that the application of this increment to the lower bound magnitude of seismogenic nodes in Italy returns hazard levels that envelope or match the 1000-years long Italian earthquake catalogue almost everywhere. They showed that the application of this ΔM increment is equivalent to applying a partial safety factor $\boldsymbol{\gamma}_q$ to the seismic moment at the fault M_0, as normally asked by Eurocodes and other international standards for typical structural design.

The application of M_{design} to Kosovo gives a more conservative estimate of the seismic hazard, with horizontal DGA ranging from 0.08-0.15 g to 0.15-0.30 g (Fig. 5, right). Incidentally, these values are much closer to those resulting from the 10 Hz computation that is the subject of a forthcoming paper. This highlights the fact that, although a 10 Hz computation can provide spectral details of ground motion that are of engineering significance, the application of M_{design} to a 1 Hz computation can provide appropriately protective estimates of hazard in areas where 10 Hz computations may be not feasible due to insufficient data about ray-path mechanical properties and earthquake source kinematics.

DGAs produced in this study agree well with or slightly exceed peak accelerations estimated by probabilistic studies (10% probability in 50 years) for the area (Gülerce et al., 2017; Lee and Trifunac, 2018). However, vertical DGA is, in some cases, significantly higher than previously estimated, especially in the Dukajin basin, and the M_{design} application shows that probabilistic estimates largely underestimate hazard in most of the country.

Overall, our results support the maximum observed intensity of IX (MCS) for Kosovo (Kárnik et al., 1983 and Elezaj, 2009). In terms of displacement and vertical DGA, locally, ≈I-X can be felt. Furthermore, if M_{design} is applied, wide areas of the country can experience ≈I-X accelerations.

4. Conclusions

NDSHA relies upon the fundamental physics of wave generation and propagation in complex geologic structures to generate realistic synthetic seismograms, used as input for the computation of several ground motion parameters, integrating available knowledge about seismic sources (seismogenic zones and seismogenic nodes) and medium structure.

National-scale hazard maps in Kosovo show DGA values up to 0.15 g in the southern and western part of the country, generally in agreement with observed I≈IX (MCS). Vast areas of Kosovo are vulnerable to deep earthquakes nucleated in Vrancea (Romania) that could possibly cause intensities up to VIII. Ground accelerations estimated through probabilistic method by previous studies are matched or enveloped by our results. In some instances, DGA up to 0.30 g (I≈X) can be reached, especially if M_{design} is applied.

Considering seismogenic nodes in Italy, Rugarli et al. (2019b), showed that adding a safety increment ΔM is equivalent to applying a partial safety factor $\boldsymbol{\gamma}_q$ to the seismic moment at the fault M_0, as normally asked by Eurocodes and other international standards for typical structural design. Ground motion estimates so obtained envelope the ones obtained using the seismic catalogue. Similarly, we find that application of seismogenic nodes and M_{design} to Kosovo (where seismic catalogue completeness is lower than Italy) safely envelopes the results obtained using only seismogenic zones or probabilistic methods. Therefore, we suggest that the application of M_{design} to 1 Hz computations can be a low cost, effective way to provide appropriately protective estimates of hazard in areas where 10 Hz cut-off computations may be not possible due to insufficient data about seismic sources and medium structure. Given Kosovo's ongoing urban development, the young average age of its population, and the country's numerous UNESCO World Heritage sites, these estimates show the benefits of NDSHA implementation toward achieving sustainability and resilience.

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