SEISMICITY AND SEISMIC MONITORING OF MONTENEGRO

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ABSTRACT

The coastal area encompassing the towns of Ulcinj, Bar, Budva and the entire Boka Bay is the most seismically active area in Montenegro. Going inland, the whole regions of Skadar Lake, Maganik mountain ridge, Polimlje river basin etc. are recognized as seismic sources, as well. In addition, Montenegro is influenced by neighboring seismic active zones in Croatia, eastern Bosnia and Herzegovina, northern Albania and southeast of Serbia.There are many historical evidences of destructions caused by earthquakes on the southern Adriatic coast (XVI c and XVII c). In 1667 earthquake with magnitude 7.4, devastated epicentral area in near vicinity of Dubrovnik, causing huge damages in the whole southern Adriatic - from Boka Bay to Bar and Ulcinj. The most important contemporary event is the earthquake that happened on April 15, 1979 off coast between Bar and Ulcinj. With magnitude 7.0 on Richter scale, this is the strongest earthquake instrumentally recorded in Montenegro. Given the recent earthquakes in Montenegro (Plav, 2018), Albania (Durres, 2019) and in Bosnia and Herzegovina (Nevesinje, 2019), assuming that the seismic activity in the region is on the rise is correct. Tectonics and structural setting of Montenegro is formed by intensive over-thrusting: regional thrusts such are Durmitor, Zeta-Bjelopavlici thrust, as well as the Budva-Cukali zone over-thrusting system. The present paper reviews the results of several major research projects realized in the previous decade characterizing: i)general pattern of the fault plane solutions that are indicating dominant reverse mechanism along coastline, while moving towards inland there is a transition of reverse to active strike-slip to oblique strike-slip faults, ii) recent geodetic data processing as the results ofmonitoring of active crustal deformations, iii)Seismic Hazard Map of Montenegro issued as the National Annex to new seismic design standards compliant with European norms. Sector of Seismology, Institute of Hydrometeorology and Seismology (IHMS), is the legatee of Seismological Observatory of Montenegro in charge of the national seismic monitoring. In June 2020, Sector conducted the analysis of networks' instrumental capacities, data transmission, station location and ambient noise, data processing, and current maintenance costs. Development goals and objectives were defined, tied up

by its' sustainability analysis. Goals of proposed restructuring are: i) to upgrade capacities for continuous seismic monitoring in line with the modern standards, ii) improve analysis of seismogenic sources, further improve services towards public and authorities in providing reliable earthquake information, and contribute to prevention and mitigation of adverse earthquake effects.

SEISMICITY IN MONTENEGRO

The coastal area encompassing the towns of Ulcinj, Bar, Budva and the entire Boka Bay is the most active part of Montenegro (ME). Going inland, the whole regions of Skadar Lake, Maganik mountain ridge, Polimlje River basin etc. are recognized as seismic sources. The figure 1 depicts the seismic active zones in neighboring countries like Croatia, eastern Bosnia and Herzegovina, northern Albania and south-east of Serbia potentially affecting the relatively small area of Montenegro.

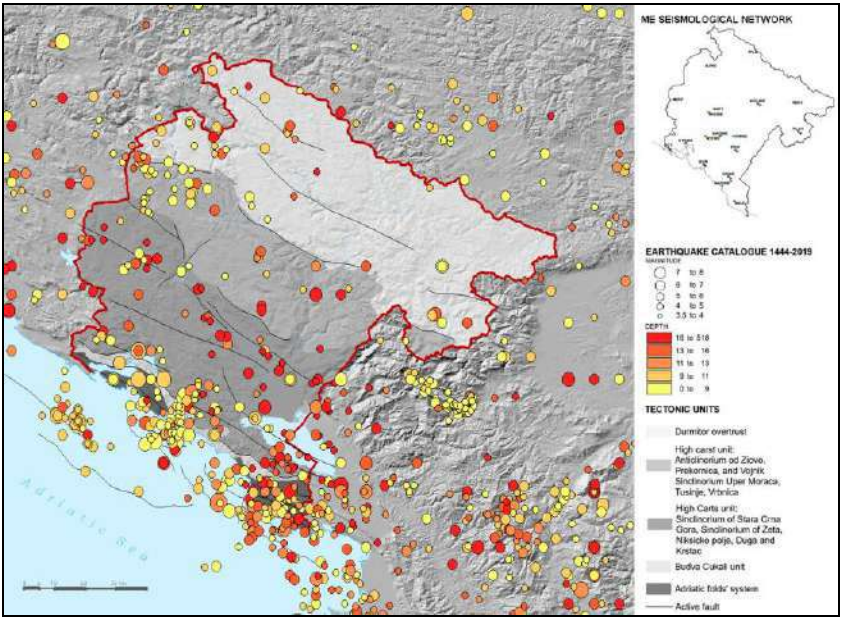

Fig. 1: Positions of tectonic units and major active faults versus national earthquake catalogue data (M>3.5, 1444-2019).

There are historical evidences of destructions caused by earthquakes on the southern Adriatic coast (XVI c and XVII c). In 1667, earthquake with magnitude 7.4 devastated epicentral area in near vicinity of Dubrovnik, causing huge damages in whole southern Adriatic - from Boka Bay to Bar and

Ulcinj. In 1905, destructions in Podgorica caused by Shkoder earthquake were interpreted as the effects of VIII on MCS intensity scale.

The most important contemporary event was the earthquake that happened on April 15, 1979. This event caused disastrous consequences in Montenegro, affecting the area of app. 50.000 km^2 (including the neighboring Croatia and Albania). With magnitude 7.0 on Richter scale and epicentral intensity X, this is the strongest earthquake instrumentally recorded in Montenegro. Map of national historical and instrumental earthquake data (gathered in ME seismological network) is in the Fig.1 depicted.

On January 4, 2018, an earthquake of magnitude 5.1 struck the vicinity of Plav. Epicentral area belongs to the seismic source zone of Polimlje - characterized by complex seismotectonic settings that is generating strong earthquakes with long return period. In almost 40 years, this was the first earthquake in Montenegro that caused significant (enough) damages.

Given the recent earthquakes (Plav, 2018), Albania (Durres, 2019) and in Bosnia and Herzegovina (Nevesinje, 2019), assuming that the seismic activity in the region is on the rise would be correct.

ACTIVE TECTONICS AND GEOLOGICAL STRUCTURES

The geological structure of Balkans (and Montenegro) is strongly affected by the collision between Adria microplate and the southwestern Eurasia tectonic plate margin. Along the coast of Adriatic Sea and eastern coast of Ionian Sea, the collision between these two tectonic units has led to the build-up of Dinaro-Albanian-Hellenic folded structure. The Dinarides are a thrust and fold belt zone of elevated and deformed sediments stretching along NW-SE. The fold-thrust belt of the Dinarides is subdivided into two tectonic domains of external and internal Dinarides. The External Dinarides encompass the SW-verging thrust belt formed along the Eastern Adria margin and the NE dipping thrusts of the Central Adriatic (Mihaljevic *et al*., 2017).

Tectonics and structural setting of Montenegro is formed by intensive over-thrusting: such regional thrusts are Durmitor, Zeta - Niksicko polje - Duga - Krstac, as well as the Budva - Cukali zone over-thrusting system. The deformation of these three thrusting systems was possible over the existing flysch zones located at the very base of these thrusts. By its' high plasticity and low resistance to rock movements, flysch layers enabled the intensive sliding of masses to southwest direction (Janković *et al*., 2019). Along with the Adriatic folds system and submarine fault belt (Fig.1), these units are generating the major part of seismic activity.

As the direction of regional maximal horizontal stress is a good indicator of the dominant tectonic regime in a certain area, regional fault plane solutions (FPS) database (BSHAP, 2012-2015) was employed for the geodynamic characteristics of the region.

The general pattern of the FPS indicates that the majority of the earthquakes observed along the coastlines of Croatia, Montenegro and Albania have reverse mechanism, correlated to the thrusting in the most part of the External Dinarides and Albanides (Fig. 2a). Majority of the FPS in Montenegro, contain elements of reverse faulting of NW–SE direction, having the low dip angle in the direction towards NE. In general, there is a good agreement between FPS, stated tectonic settings and mapped faults.

Present strike-slip faults are usually perpendicular to the reverse ones, and are characterized by relatively small dimension and steeply dipping fault plane.

In the regions bordering Albania and Bosnia and Herzegovina, and in the Skadar Lake, Lim River basin, Niksic and Pluzine regions, the FPS contain elements of normal faults of NW-SE or N-S direction(Mihaljevic *et al*., 2017). Focal plane solution of the Plav earthquake 2018, shows that the dominant stress field has been extensional – coinciding with the assumption that active tectonic features of the region are represented by disjunctive and applicative forms (Fig. 2(a)) (Đokić *et al*., 1968; Živaljević *et al*., 1979).

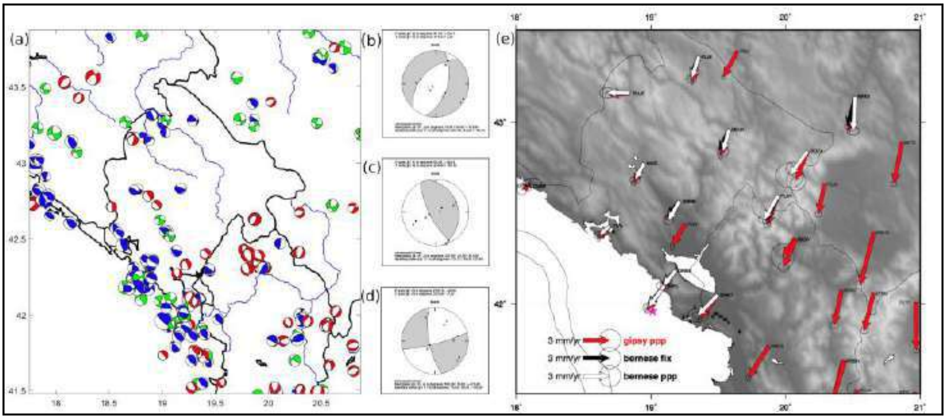

Fig. 2: (a) Integrated presentation of fault plane solutions in IHMS database. Color of beach-ball symbols denotes the FPS for different mechanisms: the blue, red and green symbols stand for the reverse, normal and strike-slip events, respectively. FPS for the mainshocks: Plav 2018 (b) on normal fault, Durrës 2019(c) on thrust fault and Nevesinje 2019 (d) on strike-slip fault; (e) Insert from the comparison between the station velocities in the Apulia reference frame obtained using Bernese GNSS and Gipsy software (Kaludjerovic and Luzzi, 2018).

The recent studies on fault slip rates show that the most active portion in this region is the south-eastern part of the External Dinarides (offshore

Montenegro and Albania), where the highest average slip rate of 2 mm/yr was calculated (Kastelic and Carafa, 2012).

During the last decade, tectonic movements in region were analyzed on a processed series of continuous GPS measurements (2008-2019) made in 42 stations in the Balkan area, via Bernese GNSS Software and its precise point positioning and double–difference network solutions. In the framework of the ongoing bilateral project with INGV, IHMS has gained experience in GNSS data processing and analyzing. Obtained results are compared to the Gipsy software analysis (N. D'Agostino), showing good coincidence (Fig. 2e) (Kaludjerovic and Luzzi 2018). A velocity profile across the Adriatic shows small internal deformation in Montenegro suggesting that 3-4 mm/yr of convergence occurs mostly offshore. These results are included in a new velocity field and strain rate analyses of the SW Balkans. Clarifying the pattern of rotation and deformation in the SW Balkans (D'Agostino *et al.*, 2020), analysis is based on homogeneously processed continuous GPS measurements from permanent sites in Albania, Bulgaria, Greece, Kosovo and North Macedonia most of which were not included in the previous geodetic studies.

SEISMIC HAZARD MAP

The new seismic hazard map for Montenegro was elaborated after a decade of intense research and a number of scientific projects (BSHAP, SHARE etc.). Map is a part of national standard MEST EN 1998-1: 2015 (*Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings - National Annex)* (Fig. 3). PSHA analysis (Glavatović and Vućić, 2014) was conducted combining two methods in logic tree:

- In one branch, method of distributed seismicity was implemented. Distributed seismicity (Stirling, 2000) is term usually associated to seismicity that cannot be assigned to the particular geologic structure or unknown nature of geologic structures. It may refer to historical earthquakes whose location is not sufficiently precise, as well. As appropriate way to model distributed seismicity, spatially smoothed procedure (Frankel 1995; Lapajne 2003) was implemented.
- The other branch implemented individual modeling of linear seismic sources and EZ Frisk software application.

Seismic hazard calculations (Janković *et al.*, 2019) were based on five different attenuation laws (Glavatović 1998; Berge-Thierry 2003; Akkar and Bommer 2007; Boore and Atkinson 2008 and Cauzzi and Faccioli 2008).

Compared to PSHA conducted in BSHAP project, max hazard values (0.38g at Vladimir, Ulcinj) are approximately the same, while - towards the inland, calculated PGA values are attenuating at slower rates. The smallest PGA value is 0.07g (Otilovići, Pljevlja).

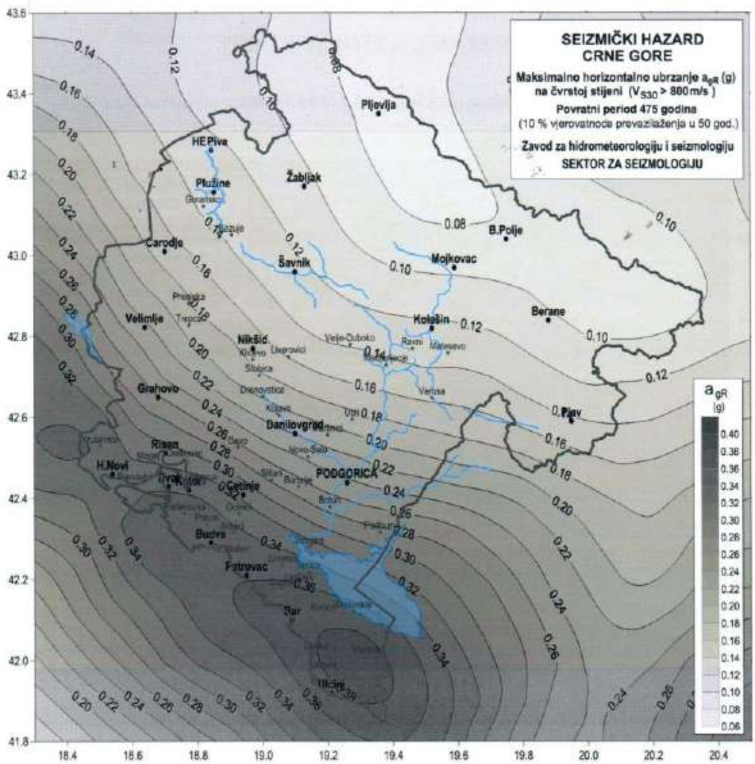

Fig. 3: Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings - National Annex (Montenegro Seismic Hazard Map - Peak horizontal ground motion a_{gR} (g) on hard rock (v_s>800m/s), Return Period 475 (10% probability exceedance in 50 years), Institute of Hydrometeorology and Seismology of Montenegro – Sector of Seismology.

SEISMIC MONITORING

Sector of Seismology, Institute of Hydrometeorology and Seismology, is the legatee of Seismological Observatory of Montenegro and in charge for the national seismic monitoring (ME seismological network is shown on Fig.1).

Seismic network of Montenegro (Fig. 1) consists of 3 BB seismometers (installed in last decade) and 10 SP one-component seismometers (installed in early 1980-es). From 2008, BB station Podgorica is part of Mediterranean Seismic Network. Steadily growing strong motion network (14 instruments) is still of insufficient coverage. Processing of geodetic data is performed on own permanent GPS stations (2), stations of Montenegrin Real Estate Agency (9) - in accordance to renewed Memorandum of Understanding (2019) and a number of regional GNSS reference stations.

Monitoring and processing have been upgraded since June 2020 with the support of CTBTO organization in Austria. - are implemented in the SeisComp3 platform was employed for all the weak and strong motion data.

Geographical coverage of seismic stations is showing good performances for earthquake detections and reliable location. Inherited (from 1980s) locations of SP seismic stations are in the buildings or in the nearby shallow volts, owned by semi-state company *Radio Broadcasting Center*. Having high reliability of transmission, quite reliable power supply and safety against vandalisms, major disadvantage of these locations is the presence of man induced seismic noise. The sources of interferences are thevibrations of antenna masts due to wind load, vibrations due to installed equipment in the building /its' surroundings (cooling systems, engine generators of multiple mobile companies etc.), internal sensor noise induced by AC current frequency (power supply or transformer house). Additional problem are the infrastructures that are newly built in the vicinity of existing stations (wind turbines, tunnel).

In June 2020, Sector conducted the analysis of network proposing its' reconstruction. Goals of proposed restructuring are: to upgrade capacities for continuous seismic monitoring in accordance to modern standards, improve analysis of seismogenic sources, improve services towards public and authorities in providing reliable earthquake information, and contribute to prevention and mitigation of adverse earthquake effects. Stated goals and objectives are tied up by sustainability analysis –supported by human resources and maintenance costs analyses. Additionally, *Law on Seismic observations* is drafted - characterizing seismic infrastructure as the critical infrastructure. Human resources are insufficient and there is need to employ young specialists with knowledge of informatics and geophysics.

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