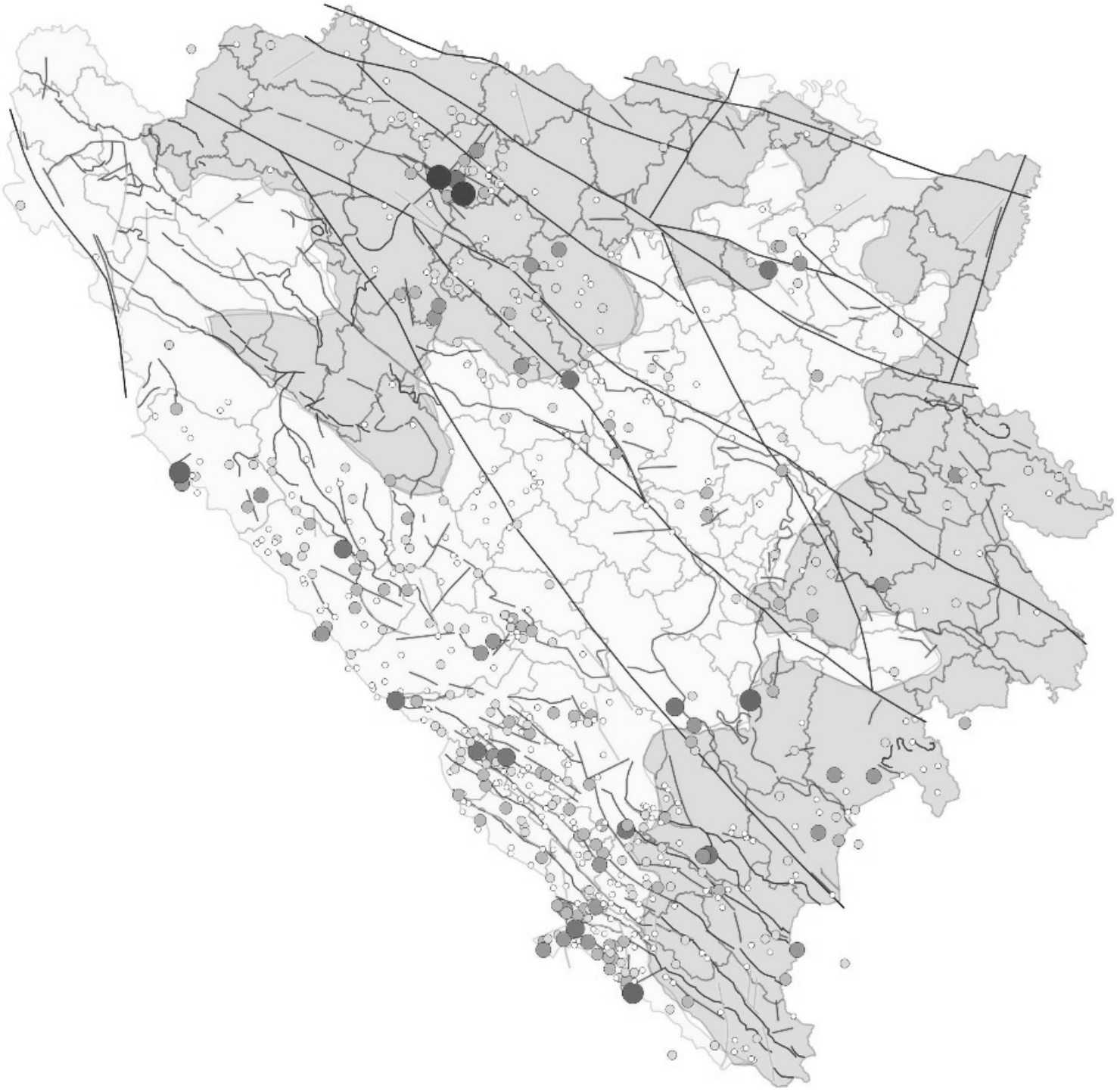
Map of earthquake magnitude in Bosnia and Herzegovina. Source:



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TECTONIC GEODESY AS A SUPPLEMENT DATA IN SEISMOLOGY

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TECTONIC GEODESY AS A SUPPLEMENT DATA IN SEISMOLOGY

ABSTRACT

Geodesy and its high precision are important instruments for the study of active tectonics and the presentation of the movement of solid parts of the earth. Deformations caused by earthquakes represent essential information for defining seismogenic zones. Precise measurements must be made on the wall of the fault itself or the system of connected active faults to measure the rate of deformation of the earth's crust between, during, and after earthquakes. In Bosnia and Herzegovina, the spatial density of GNSS stations used in modern geodynamic studies is low. The permanent GNSS station "SRJV" in Sarajevo is the only permanent GNSS station in the region. It is part of the EUREF Permanente GNSS network and, in that segment, has up-to-date available time series from GNSS coordinates.

Keywords: *GNSS station SRJV, seismogenic faults, seismogenic zones*

1. INTRODUCTION

Earthquakes that periodically threaten certain parts of the earth's surface represent seismic movements of the solid earth caused by tectonic activities. Most destructive earthquakes occur in the contact zones of large tectonic plates. These regions contain zones of the highest seismic hazard and, therefore, the risk of strong and destructive earthquakes. The most seismic active region in the world is Taiwan, where plate convergence occurs when the ground moves at a velocity greater than 83 mm/year, and it belongs to the Pacific „Ring of Fire“, where the most powerful earthquakes have ever been registered.

High seismic activity registered in these parts not only exhibits a constant potential danger to human lives and material goods but also threatens the whole of human activity and its normal development in these areas. Today, it is an indisputable fact that at certain time intervals within the same zone, earthquakes reoccur. Thus, these areas are defined as seismically active. However, earthquakes can also trigger other hazards, such as landslides, tsunamis, volcanic activity and others.

Geodetic observations in seismology are challenging and important for understanding plate boundary processes. Surface geodetic deformation data can help to find a new slip distribution capable of producing surface displacements. Tectonic geodesy is an important prong of geodesy and geophysics and has broad applications in geoscience. Tectonic geodesy is an interdisciplinary field that studies the tectonic activity of the crust and its fundamental kinematics using geodetic observation techniques, such as the Global Navigation Satellite Systems (GNSS). GNSS technology is used to compute long-term velocities, coseismic motions, and postseismic motions separate from the total motion. Real-time measurements from GNSS networks located around the world provide a characterization of ground motions that are directly related to seismic phenomena. The analysis of crustal deformations plays an important role in studies related to the whole seismic cycle. The seismic cycle refers to the notion of observing an earthquake before, during, and after its occurrence. An important part of the seismic cycle in many subduction zones is Slow Slip Events (SSE), which release some portion of accumulated strain and perhaps trigger large earthquakes by loading nearby segments of the fault.

The Mediterranean, which belongs to a group of seismically active regions, including Bosnia and Herzegovina, was exposed to catastrophic earthquakes. Bosnia and Herzegovina, in terms of geographical position, are located in south-eastern Europe on the Balkan Peninsula.

2. LOCAL TECTONICS AND URBAN PLANNING

Today, besides the usual geotechnical and seismic zonation techniques considered when developing or restoring an urban region, the local active tectonics must be taken into account [1]. Reliable estimates of the seismic hazard start with the identification and evaluation of earthquake sources by reviewing geologic evidence, tectonic evidence, historical seismicity, and instrumental seismicity [2].

The first stage of the study aims to locate active faults or fractures in the Bosnia and Herzegovina area and understand their role in spatial variability through the analysis of all existing relevant data from geology, seismology, and geodynamics. These data are very important and need to be included in the integrated analysis of space for the needs of

regional and urban planning. It is evident that urban planning, when approached in an integrated manner that considers all aspects and impacts, is potentially the most effective mechanism for mitigating the harmful consequences of many natural hazards. One of the great challenges of today is regional and urban planning resilient to the danger of potential earthquakes, which is insufficiently present in planning practice in Bosnia and Herzegovina.

In the period of former Yugoslavia, a seismological map based on maximal expected intensities was made for the area of Bosnia and Herzegovina, which defined the seismic hazard zones, according to which the calculations of structures for the planned facilities were performed and based on which the seismic risk map was later generated. Based on this map, it was necessary to make seismic micro-zoning maps for each larger urban area, which would give more detailed seismic characteristics of the area with conditions for urbanization and construction. These maps are rarely made, which speaks of the inadequate seismological basis of the territory of Bosnia and Herzegovina from that period. The city of Banja Luka, which was hit by a catastrophic earthquake in 1969, provided a map of seismic micro-regionalization in the 1970s, but today it is unreliable and needs to be updated. In the meantime, NATO seismic hazard maps of the territory of Bosnia and Herzegovina were made in 2016.

Namely, the map redefined seismic zones in such a way that some urban areas of higher seismic risk, such as Banja Luka, were defined as zones of lower hazard, which opens the possibility for initiating spatial planning mechanisms that could endanger the safety of the population from possible earthquakes. The Institute for Standardization of Bosnia and Herzegovina, together with the competent hydrometeorological institutes in Bosnia and Herzegovina, has expressed readiness to update seismic hazard maps while providing new data that are the result of relevant measurements of tectonic processes in Bosnia and Herzegovina.

Therefore, the research that is the subject of this paper is a contribution to supplementing the data on seismic characteristics of the territory, using GNSS technology that can contribute to the creation of seismic maps at the regional level, but also locally, for seismic micro regionalization. Reliable seismic hazard maps and seismic risk maps are necessary for integrated spatial planning, which, depending on the level of detail, will be able to influence land use planning and technical rules for building facilities and create a sustainable built environment.

3. SEISMOLOGY OF THE REGION OF BOSNIA AND HERZEGOVINA

According to current knowledge of its lithofacies development, the geology of Bosnia and Herzegovina is comprised of various sedimentary, igneous, and metamorphic rocks. According to some rough estimates, about 70% of this geologically rich region belongs to the Mesozoic, about 20% can be dated to the more recent Cainozoic, and about 10% to the earliest Palaeozoic eras [3]. Evidence of tectonic activity can be found throughout the region.

Bosnia and Hercegovina is a Balkan country with a high rate of seismicity. The territory of Bosnia and Herzegovina has had a history of devastating earthquakes. Based on the actual earthquakes in the past 100 years, there are several seismic zones in Bosnia and Herzegovina: the Adriatic zone, the zone of External Dinarides, the zone of the Central Dinarides and the Sava-Vardar zone [4]. The northward movement of the African plate and

its collision with Eurasia causes sliding beneath the European continent, makes complex tectonics, and involves the motions of numerous microplates and regional-scale structures.

The devastating earthquakes hit a large area of Bosnian Krajina on October 26, 27 and 31 December 1969. The magnitude of the earthquakes on 26 October and 31 December was 7-8^{o} MCS, and the earthquake that happened on Monday, 27 October, was much stronger. Its strength in an area of about 9 000 km^2 was 7^{o} MCS, on an area of 1 822 km^2 was 8^{o} MCS, and 68 km^2 was 9^{o} MCS. The earthquake hit the area of 15 Krajina municipalities. The municipalities of Banja Luka, Čelinac and Laktaši and parts of neighbouring municipalities suffered the greatest damage [5]. It is the strongest instrumentally recorded earthquake in Bosnia and Hercegovina proper over the past one hundred years. The quake area had a population of over 750,000 in 803 settlements. In the area of the Banjaluka municipality, 36,276 apartments, 131 school buildings, 61 health institutions, 26 cultural institutions, 28 social institutions, and 38 public administration buildings are registered [6]. Out of 224 commercial companies damaged by the earthquake in Krajina, 112 were in the territory of the Banja Luka municipality [7]. Another strong earthquake hit Banjaluka on 13 August 1981 [8].

The geodynamics of the Bosnia and Herzegovina region is not well understood. Geodynamical GNSS studies of friction forces and normal stresses in fault systems are essential to address this issue. These studies build on the current knowledge gained from previous 3D geodynamical GNSS research.

"It is necessary to invest greater efforts in acquiring modern equipment and increasing the number of qualified personnel, as well as 3D monitoring of active tectonic structures and monitoring contemporary trends in seismology. New seismic sensor stations are needed. There is a need for a quick recovery of geosciences, primarily in Bosnia and Herzegovina. The available studies of geodynamic regions in Bosnia and Herzegovina are very sparse.

The low spatial density of GNSS stations used in modern geodynamical studies in Bosnia and Hercegovina does not provide quality data. The permanent GNSS station “SRJV” in Sarajevo is the region’s only permanent GNSS station. Station “SRJV” is a part of the Central European GPS Geodynamic Reference Network (CEGRN), Figure 1. The permanent station “SRJV” is situated on the roof of the Department of Geodesy at the University of Sarajevo. The station became operational on 11 June 1999.

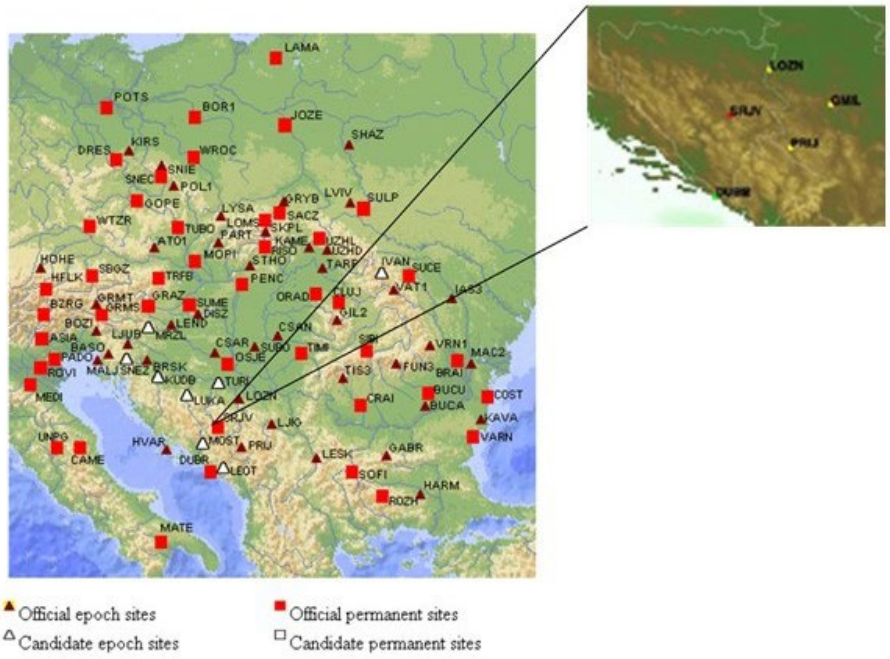

Figure 1. *CEGRN Network [9]*

4. RESULTS OF NUMERICAL RESEARCH

The estimated trend from the time series GNSS station SRJV shows positive values for the horizontal components. The trend shows the increase in the direction of northeastern 28.50 mm/year (Figure 2).

Figure 2. *Ground motion model for GNSS station SRJV (drawing by author)*

Bosnia and Herzegovina have numerous deep and active seismogenic faults. The most complete picture of the tectonic structure in BOSNIA AND HERZEGOVINA was done by Papeš [11]. He has identified deep faults passing through BOSNIA AND HERZEGOVINA, as well as 30 tectonic units. Three main deep faults in the region are distinguished: the Sarajevo Fault, the Banja Luka Fault, and the Konjic Fault. Sarajevo Fault spreads in the direction of NE-SW [11]. Along the transversal deep faults, high seismic activity is identified, while along the Sarajevo Fault (deep fault), the seismic activity is marked from low to moderate level. Sarajevo and Gradiška Faults may experience a series of earthquakes of magnitude M6 on Richter's scale or even higher [11]. Figure 3 shows deep faults, first-order thrusts, second-order thrusts, Tfaults (Thrust fault), Sfaults (Sinistral fault) and Nfaults (Normal fault), and entities the Republic of Srpska, the Federation of Bosnia and Herzegovina and the Brčko District.

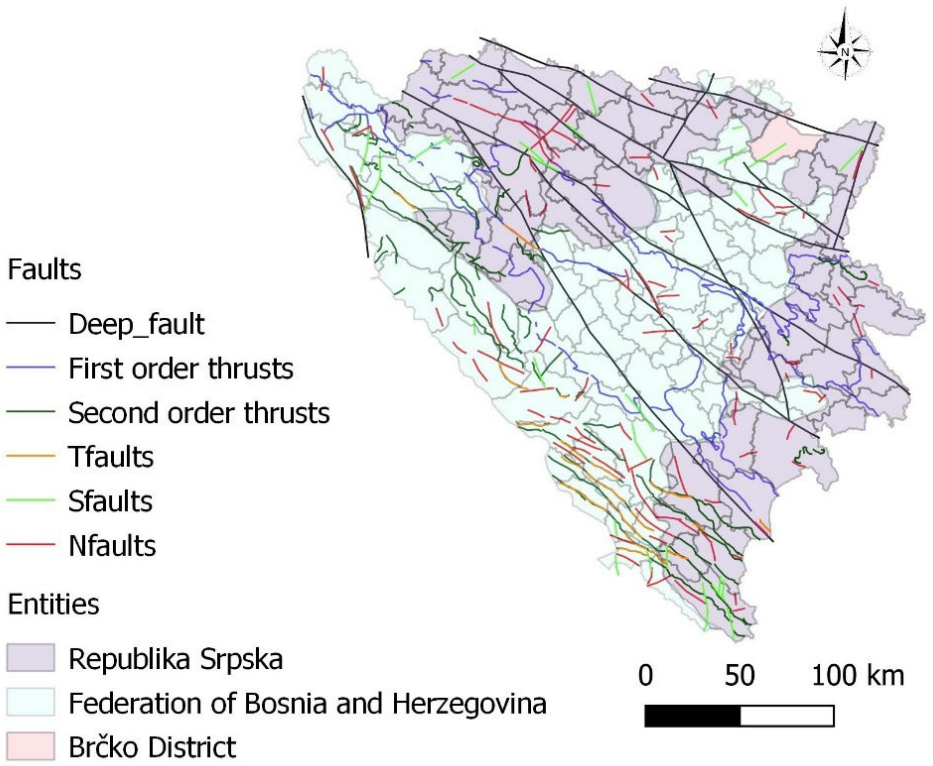

Figure 3. *Map of Bosnia and Herzegovina with deep and active seismogenic faults (drawing by author).*

After that, available historical earthquake catalogues for the region Bosnia and Herzegovina were taken over for the period from 1962 to 2019 year for magnitude 3+ and exported a total of 638 earthquakes [12]. Based on these downloaded data and assessments based on GIS analysis in Qgis, thematic maps are produced showing the area of Bosnia and Herzegovina for magnitude (Figure 4) and depth of earthquakes (Figure 5).

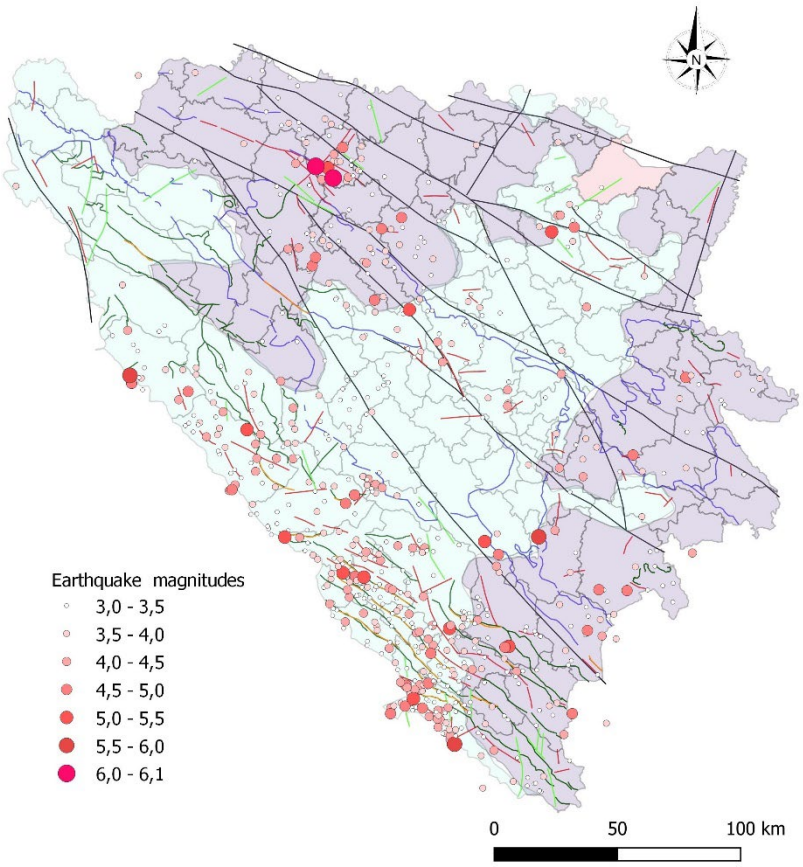

Figure 4. *Map of earthquake magnitude in Bosnia and Herzegovina (drawing by author)*

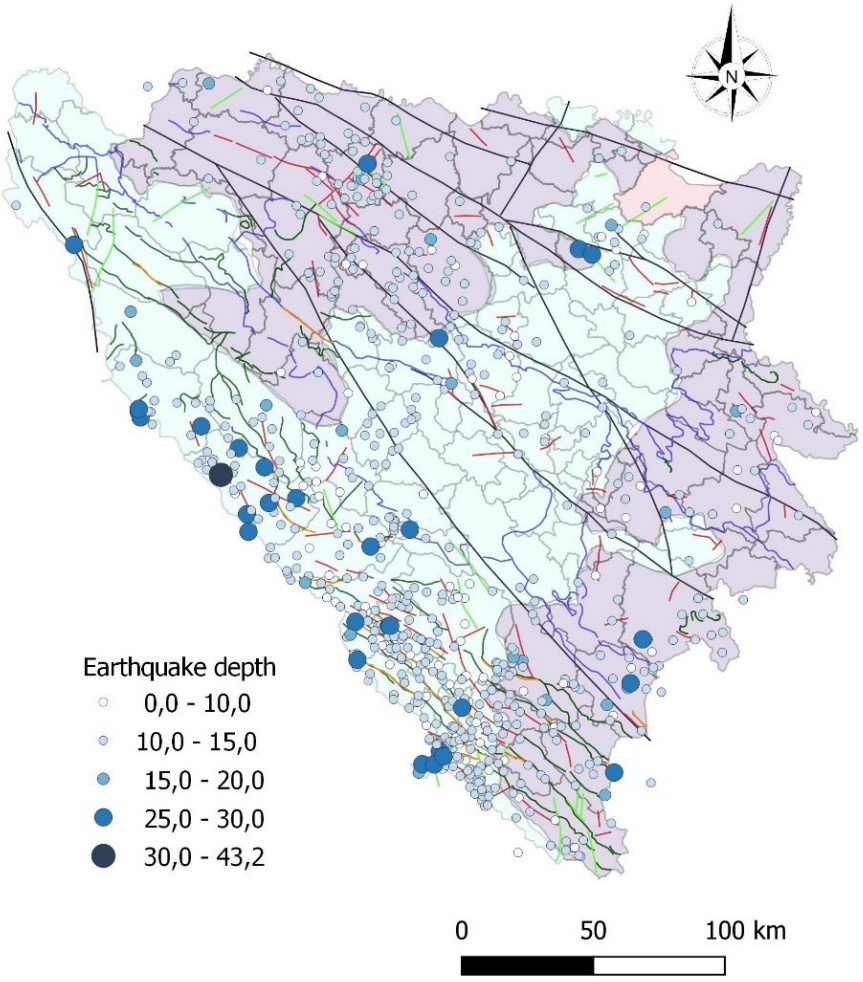

Figure 5. *Map of earthquake depth in Bosnia and Herzegovina (drawing by author)*

Research on the connection between the occurrence of earthquakes and the location of earthquake lines (faults along which earthquakes occur) has shown that they are the strongest historical earthquakes, largely concentrated along the fault zone. Based on the information on seismicity and seismotectonic of Bosnia and Herzegovina, the highest earthquake frequency is in the Herzegovina area, and Livno Canton (the Croatian border and the influence of the Adriatic microplate) and in the north of Bosnia and Herzegovina (Banja Luka).

The permanent danger of catastrophic earthquakes, which occurred relatively often on the territory of Bosnia and Herzegovina and in the immediate vicinity, indicates the necessity to start preventive measures against the harmful effects of earthquakes at the stage of spatial and urban planning and design. Taking into account the specific seismic conditions of the area of the site where facilities are being built by applying the basic principles of seismology, engineering seismology and earthquake engineering in design, it is possible to directly influence the reduction of earthquake consequences to a large extent.

Given that the Banja Luka region has developed a lot urbanistically in the last 20 years and that the city of Banja Luka has a tendency to increase in population, there should not be a reduction in the seismogenic zone in this area. According to Trkulja [14], seismogenic zones in Bosnia and Herzegovina should be followed, as shown in Figure 6.

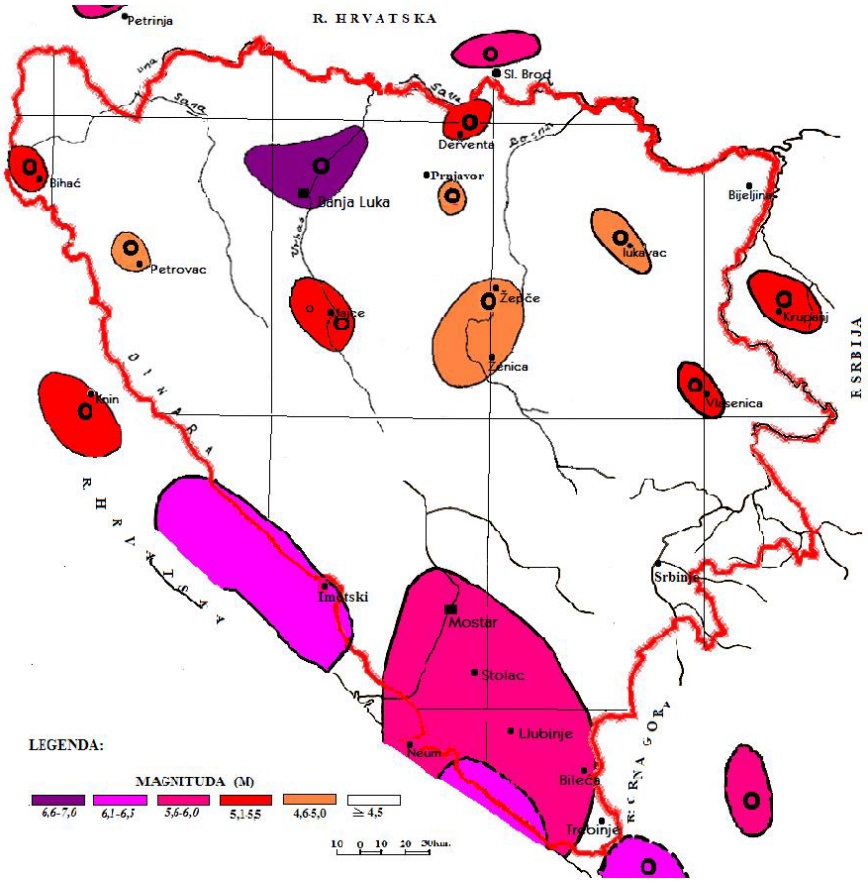

Figure 6. *Map of seismogenic zones in Bosnia and Herzegovina [13]*

5. CONCLUSION

The advanced development of modern geodetic techniques, GNSS, has made a significant contribution to estimating the temporal and spatial change of the earth's surface. Today, GNSS has reached the required accuracy and precision to track surface deformations locally and globally. Today, geodynamics is of key importance in establishing the power of detected and supposed faulting systems in the entire territory of Bosnia and Herzegovina. The Geodynamics of the Bosnia and Herzegovina region has not been sufficiently researched and understood.

Banja Luka and the Livno faults, both in the midsection of the Sarajevo Fault system, should be examined and further researched to be understood. Including regions in Bosnia and Herzegovina in projects, the EUREF (European Reference Frame), and the CERGOP (Central Europe Regional Geodynamics) creates an opportunity for advancement in the field of seismology and earthquake monitoring. Surely, the next steps should follow modern trends in equipment and methodology. One of the steps involves placing new GNSS stations in the

areas of the Banja Luka faults, Livno faults, and the Herzegovina region. New regional and local seismic hazard maps would build on the current knowledge gained from 3D geodynamical GPS studies.

Today, many tectonically active regions are covered by a global real-time GNSS network. In some seismically active regions, the number of GNSS receivers exceeds the seismometers disposed of for earthquake and tsunami monitoring. Recent Developments in High-Rate Geodetic Techniques are invaluable to the rapid evaluation of earthquake hazards. High-rate geodetic data and associated models can help improve ground motion characterization and prediction. Three-dimensional seismic velocity models play an important role in many aspects of seismological research, including strong ground motion modelling, earthquake location, and application of inversion techniques to determine the earth's structure.

It is important to point out that man cannot prevent or eliminate earthquakes because they are natural phenomena related to specific parts of the earth's crust and specific to certain areas. However, by organized and preventive measures, their negative effects can be reduced to a reasonable level.

We can say with certainty that we can fight against the harmful effects of earthquakes only through prevention. This implies that it should be started at the stage of spatial and urban planning by applying mandatory legal regulations in the area of aseismic design and construction so that the effects of earthquakes are mitigated as much as possible. Legal regulation exists. It just needs to be fully respected.

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Tanja Đukanović was born on 22 February 1994 in Nevesinje. She completed her basic academic studies in 2017 at the Faculty of Architecture, Civil Engineering and Geodesy, study program Geodesy, University of Banja Luka, where she also obtained her master's degree in 2021. She is a PhD student at the Faculty of Civil Engineering, University of Belgrade. She has been employed at AGGF since 2019. She is a teaching assistant on a group of course units in the scientific field of geodetic surveying.

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She was born in Banja Luka on 13 May 1981. She graduated in 2008 from the Faculty of Civil Engineering, University of Belgrade. She obtained her PhD from the Faculty of Civil Engineering of the University of Belgrade in 2020. In her scientific research, she deals with the analysis and modelling of tectonic movements and deformations of the earth's crust using GNSS technology, as well as with calibration and quality control of geodetic instruments and laboratory testing of scales in geodesy, civil engineering and other related areas, as well as volumetric scales. She is employed at the Faculty of Architecture, Civil Engineering and Geodesy as an assistant professor.

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ТЕКТОНСКА ГЕОДЕЗИЈА КАО ДОПУНА ПОДАЦИМА У СЕИЗМОЛОГИЈИ

Сажетак: Геодезија и њена висока прецизност је важан инструмент за проучавање активне тектонике и презентацију модела кретања чврстих дијелова Земље. Деформације изазване земљотресом представљају битне информације за дефинисање сеизмогених зона. Да би се измјерила брзина деформисања Земљине коре између, током и после земљотреса, морају се извршити прецизна мјерења на зиду самог расједа или на систему повезаних активних расједа. У Босни и Херцеговини је ниска просторна густина ГНСС станица које се користе у савременим геодинамичким студијама. Перманентна ГНСС станица "CPJB", у Сарајеву, једина је стална ГНСС станица у региону. Она је дио ЕУРЕФ Перманенте ГНСС мреже и у том сегменту има ажурне доступне временске серије из ГНСС координата.

Кључне ријечи: *ГНСС станица CPJB, сеизмогени расједи, сеизмогене зоне.*