EARTHQUAKE ENGINEERING RESEARCH INSTITUTE

StEER STRUCTURAL EXTREME EVENTS RECONNAISSANCE

PETRINJA, CROATIA DECEMBER 29, 2020, M_W 6.4 EARTHQUAKE

JOINT RECONNAISSANCE REPORT (JRR)

Collapsed unreinforced masonry building on Strossmayer St. in Petrinja, Photo by Damir Lazarević

January 2021

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PREFACE

The present report is a collaboration between the Learning From Earthquakes (LFE) Program of the Earthquake Engineering Research Institute (EERI) and the Structural Extreme Events Reconnaissance (StEER) Network.

The Earthquake Engineering Research Institute is the leading non-profit membership organization that connects those dedicated to reducing earthquake risk. Its multidisciplinary members include engineers, geoscientists, social scientists, architects, planners, emergency managers, academics, students, and other like-minded professionals. EERI has been bringing people and disciplines together since 1948. The objective of the Earthquake Engineering Research Institute is to reduce earthquake risk by (1) advancing the science and practice of earthquake engineering, (2) improving understanding of the impact of earthquakes on the physical, social, economic, political, and cultural environment, and (3) advocating comprehensive and realistic measures for reducing the harmful effects of earthquakes.

The National Science Foundation (NSF) awarded a 2-year EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities. StEER achieves this vision by: (1) deepening structural engineers' capacity for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) coordination leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) collaboration that broadly engages communities of research, practice and policy to accelerate learning from disasters. StEER works closely with other extreme event reconnaissance organizations and the Natural Hazards Engineering Research Infrastructure (NHERI) to foster greater potentials for truly impactful interdisciplinary reconnaissance after disasters.

Under the banner of NHERI's CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium including the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Nearshore Extreme Event Reconnaissance (NEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEEER) and Social Science Extreme Events Research (SSEER), as well as the NHERI RAPID equipment facility and the NHERI DesignSafe Cyberinfrastructure (CI), long-term home to all StEER data and reports. While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER aspires to build a network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

For more information about the Earthquake Engineering Research Institute please visit the EERI website: https://www.eeri.org/

In particular, for a full listing of over 300 different earthquakes occurring in more than 50 countries during the last 70 years for which the EERI's Learning From Earthquakes program has created products (Virtual Earthquake Reconnaissance Team (VERT) reports, datasets, and publications) please visit the EERI LFE website: http://www.learningfromearthquakes.org/

For more information about the Structural Extreme Events Reconnaissance (StEER) Network please visit the StEER website: https://www.steer.network/

In particular, for a full listing of all StEER products (briefings, reports and datasets) please visit this StEER website: https://www.steer.network/products

ACKNOWLEDGMENTS

Conducting post-earthquake reconnaissance is critically important to observe, document and analyze the seismic performance of built and natural environments. While experimental work in the laboratory and analytical modelling are extremely valuable, we will continue to rely on post-earthquake reconnaissance for many years to come to learn about and understand the effects of earthquakes on full-scale three-dimensional structures in the field which provide the ultimate test of our progress in mitigating the effects of earthquakes on structures and society. Hence, post-earthquake reconnaissance is at the very core of the missions of both the EERI's Learning From Earthquakes (LFE) program and of the Structural Extreme Events Reconnaissance (StEER) Network. This report is the result of hard swift work and contributions by a large number of individuals and organizations, both in Croatia and in many other countries that worked day and night for nine days during New Year and Epiphany holidays to put together the present report on the Petrinja December 29, 2020 earthquake.

We received valuable and continuous support from the Croatian Center for Earthquake Engineering (HCPI by its initials in Croatian). HCPI provided logistic support to our field group including safety equipment, power banks, materials for evaluation of buildings, means of transportation, as well as food. Additionally, HCPI provided information and guidance about the various affected areas as well as assisted in understanding and documenting local construction practices.

Special thanks also go to the Croatian Seismological Survey (CSS) of the Faculty of Science at the University of Zagreb who generously shared information about ground motion recorded as a result of this event. Efforts to install and maintain seismic instrumentation as well as to retrieve, process and disseminate strong motion records are key to our ability to learn about the effects of earthquakes and to mitigate the effects of earthquakes on man-made structures and on society in general. Their assistance is greatly appreciated. Prof. Matjaz Dolsek of the Faculty of Civil and Geodetic Engineering at the University of Ljubljana in Slovenia provided information on the performance of the Krsko nuclear power plant on the border of Croatia with Slovenia.

We thank the Serbian Association for Earthquake Engineering (SUZI-SAEE), who provided valuable assistance throughout this post-earthquake reconnaissance and in the development of this report through the participation of several of its members.

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EXECUTIVE SUMMARY

On December 29, 2020 a magnitude 6.4 earthquake occurred in the Sisak-Moslavina county of Croatia. The earthquake occurred along the Popusko-Petrinja strike slip fault within the Eurasia plate at a depth of 10 km with an epicenter at 45.422°N 16.255°E, three kilometers (km) west-southwest of the city of Petrinja.

The maximum intensity of the earthquake was VII (severe) on the Modified Mercalli Intensity (MMI) scale and VIII (heavily damaging) to IX (destructive) on the European Macroseismic Scale (EMS). Due to the earthquake and resulting damage, there were seven fatalities, 26 people were injured, and many hundreds of people were displaced from their homes. The most affected city was Petrinja, but severe damage also occurred in Sisak, Dvor, Glina, Topusko, as well as in Croatia's capital Zagreb, located approximately 50 km northwest of the epicenter. Damage was also reported in neighboring countries, including Slovenia, located north of Croatia, and Bosnia and Herzegovina, located south of this region of Croatia.

The purpose of this post-earthquake reconnaissance report is to provide, within a few days of the earthquake, an overview of the hazard characteristics and to summarize preliminary reports of damage to buildings, bridges, roads, and other infrastructure. Moreover, key findings are also summarized with regard to geotechnical failures that include liquefaction, lateral spreading, landslides, sinkholes and damage to the extended levee system along the Kupa, Odra and Sava rivers.

1.0 Introduction

Croatia (Republika Hrvatska) is located in a highly seismically active region. In particular, the northern central portion of Croatia and Slovenia are located in a region where the collision zone between the African and Eurasian tectonic plates bends sharply. Also, the proximity of the Peripienine lineament, crossing Central Europe from Krakow in Poland over Vienna up to the Udine town in Friuli (NW Italy), contributes to the increased seismic activity in the region (Kozák & Čermák 2010).

Earthquakes and seismic activity in the wider Zagreb area are not uncommon. At the end of the 19th century, Josip Mokrović, a well-known Croatian geophysicist, calculated that Zagreb had been shaken by earthquakes as many as 661 times from 1502 to 1883 (Mokrović 1950). The strongest earthquake in recent Zagreb history occurred on November 9, 1880 and has been estimated, according to macroseismic observations, as a magnitude 6.3. This earthquake caused damage to more than 1500 buildings in the city (Figure 1.1). Another important earthquake in this region occurred on October 8, 1909 in the Kupa valley. This event, known as the Pokupsko earthquake, has many similarities to the December 29 earthquake, is well known, and occupies a special place in the history of seismology as it occurred soon after the installation of a seismographic station in Zagreb. By noticing a clear change in velocity of seismological waves Josip Mokrović determined that there was a discontinuity in the densities of rock.

Figure 1.1. Lithographic illustration and hand colored xylographic illustration of the 1880 Zagreb earthquake (source: Kozák & Čermák 2010).

More recently, on Sunday, March 22, 2020, at approximately 6:24 am local time (5:24am UTC), a moment magnitude 5.3 (M_L = 5.5 according to the Croatian Seismological Survey of the University of Zagreb) earthquake struck Zagreb, the capital of Croatia. The earthquake occured in the Medvednica Mountains and the epicenter was located 10 km north of the center of the city, with coordinates 45.907°N, 15.970°E and a hypocenter depth of 10 km (USGS, 2020b). The earthquake which had a reverse (thrust) faulting mechanism, characteristic of earthquakes in the Medvednica Mountain region, was felt across Croatia, and even in the adjacent countries of Slovenia, Bosnia and Herzegovina, Serbia, and Hungary. The earthquake was the strongest instrumentally recorded seismic event in Zagreb since Andrija Mohorovičić established his seismograph in 1908 (Markušić et al. 2020).

Although the magnitude of the March 22, 2020 event was not very large, damage was spread throughout the city of Zagreb, ranging across all damage levels. According to the Croatia Earthquake Rapid Damage and Needs Assessments (Government of the Republic of Croatia 2020), this earthquake caused extensive damage to structures in the region near to the epicenter. The seismic event also caused one fatality, 26 injuries, and the displacement of thousands of people. Furthermore, over 26,000 buildings suffered some level of damage, with approximately 1,900 of them being uninhabitable after the event (Markušić et al. 2020, Novak et al. 2020). Figure 1.2 shows photos of damage in Zagreb caused by the March 22, 2020 earthquake and Figure 1.3 shows the prime minister of Croatia, assessing the damage of the city center of Zagreb.

The estimated economic losses due to the March 22, 2020 earthquake are €11.301 billion EUR, separated in two categories: €10.6 billion in destroyed assets and €0.64 billion in losses due to disruption in the economy (Government of the Republic of Croatia 2020). The losses are significantly high because of the historic nature of many of Zagreb's buildings that were affected during this event. Table 1.1 shows the breakdown of the damages and losses by building occupancy.

Table 1.1. Damage and losses caused by the March 22, 2020 earthquake by sector (in millions of EUR) (Adapted from Government of the Republic of Croatia 2020).

	Damage	Losses	Total
Housing	6,881	364	7,245
Health	826	61	887
Education	1,071	9	1,080
Culture and Cultural Heritage	1,378	21	1,399
Business	505	184	689
TOTAL	**10,661**	**640**	**11,301**

The March 22, 2020 earthquake occurred a day after Croatia had implemented a nationwide lockdown due to the COVID-19 pandemic, which made the response to the emergency even more challenging than usual.

Figure 1.2. Photos of damage in Zagreb caused by the March 22, 2020 earthquake. (source: (1CroCEE 2021).

Figure 1.3. Croatian Prime Minister Andrej Plenković assesses the damage caused by the March 22, 2020 earthquake: (source: BBC News 2020e).

On December 29, 2020, at approximately 12:20 pm local time (11:20 am UTC), a moment magnitude 6.4 (M_L = 6.2 according to the Croatian Seismological Survey of the University of Zagreb) earthquake struck in the Vukomeric Hills (Vukomeričke gorice in Croatian) and Kupa valley in the Sisak-Moslavina County of Croatia, located approximately 50 km south of Zagreb, the capital of Croatia. U.S. Geological Survey (USGS) located the hypocenter at 45.422°N 16.255°E, with a depth of 10 km (USGS 2020), whereas the Croatian Seismological Survey located the hypocenter at 45.400°N 16.219°E, 3 km southwest of Petrinja and 12 km southwest of Sisak, with a depth of 11 km (CSS 2020a). The location and depth of the hypocenter suggests that the rupture occurred within the central portion of the shallow strike-slip Pokupsko-Petrinja Fault which is oriented in the NW-SE direction within the Eurasian plate. This is the strongest earthquake to occur in the country since the November 9, 1880 Great Zagreb earthquake which had an estimated magnitude of 6.3.

The purpose of this report is to provide a preliminary assessment of the December 29, 2020, Petrinja earthquake and its effects. The report is based on information gathered by a field team of Croatian engineers who conducted post-earthquake reconnaissance between December 29, 2020 and January 7, 2021, as well as information which is publicly available on the internet and other sources gathered by an international group of engineers whose names are listed as authors of this report.

1.1 Social Impacts

1.1.1 Casualties (Fatalities and Injuries)

The 2020 Petrinja earthquake resulted in seven deaths. Included in these deaths were a 13-year-old girl from the town of Petrinja, five people from the Majske Poljane village (municipality of Glina), and an organist of the church in the Zazina village (municipality of Lekenik) who was found in the ruins of the collapsed building (BBC 2020a, ABC News 2020, HINA 2020, Vecernji List 2020). Most of the news agencies covering the earthquake have reported that at least twenty people were injured in the earthquake (Večernji list 2020, Reuters 2020, US News, World Report). The Croatian State News Agency, HINA, reported about twenty people with slight injuries and at least six people with severe injuries. Many people were transferred to the hospitals in Zagreb and Sisak (Reuters 2020, BBC 2020b). The head of Emergency Medical Services in Sisak reported that the injuries of the people from Petrinja and the surrounding areas included fractures and concussions (Reuters 2020). Figure 1.4 depicts one such individual with a severe head injury being escorted away from damaged buildings.

Figure 1.4. A man with a head injury is escorted away from buildings damaged in the earthquake in Petrinja. Photo by Antonio Bat (EPA).

1.2 Affected Population

While the magnitude 6.4 earthquake occured in central Croatia, HINA reported that twelve countries experienced shaking and felt the earthquake. However, the most affected town is Petrinja with a population of just over 20,000, followed by Glina, Sisak, and small neighboring villages, around 30 miles south of the country's capital Zagreb. Many residents in these areas have sought temporary living arrangements because their homes have been destroyed or damaged to the point that it is no longer safe to remain inside, or due to fear from future earthquakes. Residents took shelter in mobile homes, housing containers, winter tents, cars, relatives' homes in other areas, and even stranger's homes all across Croatia (BBC 2020). Figure 1.5 shows a woman sitting in her yard where a tent has been erected for her to shelter. The Croatian military even set up military barracks, where about 200 people sheltered. Prime Minister Plenković stated that the army set up 500 places ready in barracks to house people saying that "no one must stay out in the cold tonight" in the days after the magnitude 6.4 earthquake (ABC News 2020). Unfortunately, as Figure 1.6 shows, many individuals did have to stay out in the cold in the nights immediately following the earthquake. Prime Minister Plenković declared January 2, 2021 a national day of mourning for earthquake victims and on January 4, 2021 declared a state of disaster in the earthquake-impacted areas (MIA 2021).

Economically, this earthquake is a bitter blow for the region and its population, which has faced a long and difficult rebuilding process after the war for independence in the 1990's, compounded with recent economic challenges due to the decline of traditional industries in the area (BBC 2020c).

Figure 1.5. A woman sits in her yard as men erect a tent in front of a damaged house in the village of Majske Poljane. Photo by AP.

Figure 1.6. Displaced residents warm up around a fire after the earthquake in Petrinja. Photo by Antonio Bronić (Reuters).

In 2020 Croatia has plunged into a deep recession due to COVID-19 mitigation measures, lockdowns, and travel restrictions. The March 22, 2020 and the December 29, 2020 events will only deepen the economic impacts, especially for communities in the epicentral area which may take many years to fully recover. Petrinja's Mayor Darinko Dumbović said that his residents were "going through hell" and of the city said, "I feel that both its center and its soul have been destroyed" (CNN 2020). Figure 1.7 shows just a glimpse of the destruction to which Mayor Dumbović was referring.

Figure 1.7. Aerial photo showing extent of damage in an area of Petrinja. Photo by Antonio Bronić (Reuters).

1.3 Rescue and Relief

Hundreds of residents from Petrinja, Sisak, and neighboring villages were displaced in the days immediately following the December 29 earthquake (CNN 2020). Figure 1.8 shows an example of a married couple who cannot return to their home. As of January 3, a total of 751 people were reported as homeless and placed in organized temporary shelters with the number expecting to rise (B92 2021). Firefighters rescued over 30 people badly injured and in dangerous condition from crumbling buildings (BBC 2020a). In addition to the firefighters, police forces, Croatian army, and ordinary citizens were rescuing people buried under the debris of collapsed buildings and vehicles in the days following the earthquake, in Petrinja and neighboring villages (BBC 2020c, and Reuters 2020). More than 165 HGSS (Croatian Mountain Rescue Service) members from 16 stations were deployed to Petrinja and the surrounding areas. More than 91 interventions with 200 tasks, and 120 locations were performed and visited respectively in the days after the earthquake (N1 2020d). Local residents with smaller injuries and wounds were treated on site, while those with more serious injuries were taken to hospitals. Residents whose homes were damaged were transported to the "Colonel Predrag Matanović" army barracks, where food, water, and other necessities were distributed. In the Sisak-Moslavina County alone, over 800 firefighters and 220 fire trucks, coming from neighboring counties including Zagreb, took part in the rescue and relief efforts (N1 2020d). In Sisak, all school buildings were made available as shelter for people who lost their homes in the earthquake, while in Glina temporary living arrangements were organized shortly after the earthquake.

Figure 1.8. Maria Pavlović and her husband Tomislav, who were unable to return to their damaged home, sit on a bench in Petrinja. Photo by Damir Senčar (Getty Images).

Of grave concern to the local residents and government officials was the fact that the largest hospital in the Petrinja and Sisak area was largely out of operation due to earthquake-induced damage. Although injured people were brought to the hospital on the day of the earthquake, Prime Minister Plenković announced that patients had to be evacuated from local hospitals in army helicopters, vehicles, and ambulances (ABC News 2020). Figure 1.9 shows an example of the Croatian military evacuating a woman from a local hospital. Figure 1.10 depicts an injured woman requiring assistance to evacuate, while nurses and the army personnel are in the background. The COVID-19 situation in Croatia at the time of the earthquake has made the situation all the more precarious, with COVID-19 patients being forced to evacuate to other hospitals in the country (Reuters 2020). From December 29 to 31, the Dubrava Hospital in Zagreb received 55 COVID-19 patients from the area of Sisak and Petrinja, out of which eight required a ventilator (N1 2020a). Likewise, the Arena sports hall in Zagreb, which was previously adapted into an emergency healthcare facility for COVID-19 patients, began to receive COVID-19 patients from Sisak-Moslavina County (CNN 2020). However, some of the hospitals in Zagreb, for example the Sveti Duh Hospital, were also forced to evacuate patients and medical staff due to the December 29 earthquake. Many patients were forced to sit in chairs outside the hospital and were wrapped in blankets, while waiting to be transported to other facilities, as shown in Figure 1.11. Health officials reported that even a baby was forced to be delivered in front of the hospital in a tent after the earthquake. Because of the extent of destruction caused by the earthquake, and large number of displaced people and evacuations, the Croatian government lifted travel restrictions which were previously in place in the country due to the COVID-19 pandemic, in order to facilitate rapid assistance to the affected areas and enable displaced residents to find shelter and assistance in neighboring communities (NY Times 2020).

Figure 1.9. Croatian soldiers evacuating a woman from a local hospital. Photo by Antonio Bronić (Reuters).

Figure 1.10. A woman pushes her walker outside a hospital as patients are evacuated after the December 29 earthquake. Photo by Antonio Bronić (Reuters).

Figure 1.11. Patients and medical staff were evacuated from the Sveti Duh Hospital in Zagreb after the December 29 earthquake. Photo by Goran Stanzl (Reuters).

1.4 Building Damage

Several towns were left in ruins after the December 29 earthquake. Petrinja, Glina, Sisak and Lekenik sustained the greatest damage. The damage was also observed in Donji Kukuruzari, Sunja, Hrvatska Kostajnica, Majur, Dvor Topusko, Gvozd and Martinska Ves (B92 2021). All of the previously mentioned locations are located in Sisak-Moslavina County, however according to media reports the damage was also observed in other counties in Croatia (Index.hr 2020).

Furthermore, damage was also reported in neighboring countries, including Bosnia and Herzegovina and Slovenia (BBC 2020b; BBC 2020c).

A significant portion of the Petrinja town was destroyed. As shown in Figure 1.12, many unreinforced masonry (URM) buildings experienced severe damage. Several schools were also damaged, in addition to the Petrinja hospital, as well as the St. Lawrence church and Petrinja Town Hall. Most houses in Majske Poljane, one of the most affected villages, were URM buildings constructed without seismic provisions and they experienced severe damage or collapse. Additionally, a majority of houses in Glina were damaged to varying extents, while in Sisak mostly older URM buildings located in the city center experienced damage. The damage was also observed in the nation's capital, Zagreb, where the Parliamentary building, the Cathedral, churches, and many other buildings experienced damage (Wikipedia 2021).

Figure 1.12. Croatian soldiers, firefighters, and residents next to heavily damaged buildings located in the center of Petrinja. Photo by Damir Senčar (Getty Images).

According to the Croatian HCPI data, as of January 8, 2021, only 12,500 buildings were inspected out of approximately 30,000 buildings that required inspection based on reported damage by the citizens. Out of all inspected buildings, 1.25% were tagged as not functional due to external influences, 13.91% were not in use due to damage, 11.16% were temporarily out of use until a detailed inspection is performed, 12.78% were temporarily out of use and urgent repairs were needed, 2.66% were undamaged, 22.24% were functional without limitations, while the remaining 36% were functional but with recommendations (HCPI 2021). In addition to many severely damaged residential buildings, news agencies have also reported about 825 damaged commercial buildings, and 700 damaged mixed-function buildings with commercial shops (B92 2021; N1 2021). Furthermore, it was reported that out of 74 schools and kindergartens in Sisak-Moslavina County, 5 needed to be rebuilt, 9 were severely damaged, and 13 suffered minor damage, but could still be used after necessary repairs (srednja.hr 2020). The retirement home in Sisak remained occupied and functional, while the residents of the retirement homes in Petrinja and Glina had to be relocated (B92 2021; N1 2021).

As documented in prior figures in this report, the streets were full of debris, stones, and tiles in the immediate aftermath of the earthquake (Reuters, 2020). Many vehicles in the affected areas sustained heavy damage due to debris from collapsed buildings (BBC, 2020a). Many people reported damage to non-structural elements and contents, including falling Christmas trees, pictures falling off the walls, broken glasses, items falling from the shelves, broken tiles in the bathrooms, etc. (BBC 2020b; BBC 2020c). Some people also reported that the earthquake was followed by a strong sound. The 6.4 magnitude earthquake on December 29, 2020 was followed by a large number of aftershocks, which caused further damage to the buildings (BBC 2020d).

1.5 Infrastructure/Power Loss

Power losses were experienced by residents of the earthquake-affected area. In Zagreb, electric power supply was restored within a day after the earthquake, while for the majority of users in Petrinja, Sisak, Glina and nearby villages, power outages lasted less than three days. However, some parts of Petrinja did not have power for at least 8 days after the earthquake (B92 2021, BBC 2020a, BBC 2020d, N1 2020b, N1 2020c, CNN 2020). Water supply for the majority of users in the affected region was restored within 7 days. In the immediate aftermath of the earthquake, Petrinja's Mayor said, "We have no electricity, no water. Everything is broken. We are here in darkness, in ruin, searching for people (CNN 2020)."

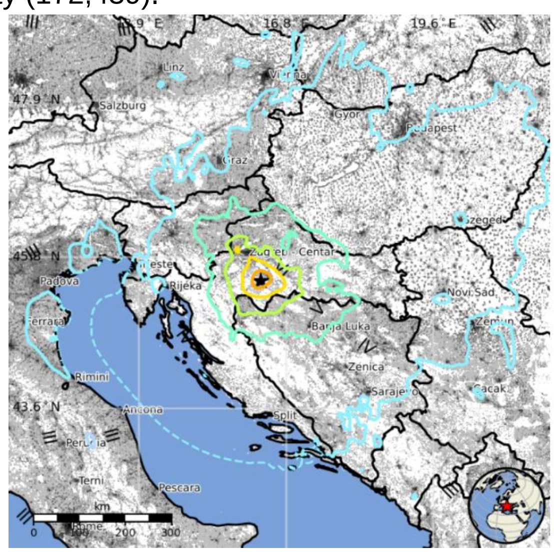
The Krško nuclear power plant in Slovenia was shut down following the earthquake following standard safety protocols (BBC 2020a, CNN 2020, NY Times 2020).

1.6 External Assistance

Many Croatians from outside the earthquake-affected area, non-governmental organizations, the Croatian government, and foreign countries have shown solidarity with earthquake victims and offered various forms of assistance, including food, hygiene supplies, and financial aid (Total Croatia News 2020, CNN 2020). Numerous volunteers from all over Europe have been assisting with repairs of the damaged buildings in order to enable a safe and quick return of residents in the affected areas (B92 2021). Prime Minister Plenković even stated in the immediate aftermath of the earthquake that the Croatian government had secured 120 million kuna ($19 million) from the state budget to assist with the response. Interior Minister Davor Božinović also mentioned that Croatia has activated the EU Civil Protection Mechanism, which aids in providing disaster relief (CNN 2020).

1.7 Earthquake consequences predicted by the USGS PAGER

PAGER (Prompt Assessment of Global Earthquakes for Response), a product of the USGS, is an automated system that produces rough estimates of the impact of significant earthquakes around the world, informing emergency responders, government and aid agencies, and the media of the scope of the potential disaster. PAGER rapidly assesses earthquake impacts by comparing the population exposed to each level of shaking intensity with models of economic and fatality losses based on past earthquakes in each country or region of the world (USGS 2020a, 2020b). Figure 1.13 shows isoseismals based on the Modified Mercalli Intensity (MMI) scale and the population exposed to various shaking intensities, as estimated by PAGER for the December 29 earthquake. According to the PAGER estimates, about 456,000 people were exposed to the highest shaking intensities (MMI VII and VIII combined), while additional 1.08 million people were exposed to a lower intensity MMI VI (strong intensity); this results in the total population exposed to shaking intensities VI to VIII of 1.54 million. Based on the most recent national census (Croatian Bureau of Statistics 2011), the population of the Sisačko-Moslavička county, which was most severely affected by the earthquake, is 172,439. It is expected that the entire population of that county was exposed to MMI shaking intensities VII and VIII. In addition to that, Zagrebačka country (population 317,606) and the City of Zagreb (population 790,016) were also exposed to the earthquake, but at lower intensities. It should be noted that the entire population of Croatia is approximately 4,284,889, hence approximately 30% of the Croatian population was exposed to the earthquake (based on the census data). Based on the above discussion, the total population exposed to the December 29 earthquake can be estimated as 1.28 million, which is comparable, but somewhat lower than the PAGER estimate (1.54 million). In terms of the population exposed to the highest shaking intensities (MMI VII and VIII), the PAGER estimate (456,000) is multi-fold higher than the population of the Sisačko-Moslavička county (172,439).



MMI	Shaking	Population
I	Not Felt	0 k*
II-III	Weak	43,447 k*
IV	Light	21,214 k
V	Moderate	2,105 k
VI	Strong	1,080 k
VII	Very Strong	393 k
VIII	Severe	63 k
IX	Violent	0 k
X	Extreme	0 k

*Estimated exposure only includes population within map area (k = x1,000)

Population per ~1 sq. km. from LandScan

Figure 1.13. Isoseismals based on the MMI scale estimated for the December 29th, 2020, M_w 6.4 earthquake (USGS 2020a).

PAGER also estimates probability density functions for the number of fatalities and economic losses in U.S. dollars. More specifically, these approximate probability density functions provide estimates of the probabilities of the order of magnitude of the number of fatalities and economic losses by providing probabilities within specific ranges, each varying an order of magnitude from the previous one. The number of shaking-related fatalities in this event was projected as most likely (with 40% probability) between 10 and 1000 according to the USGS (Figs. 1.14a). At the time of the writing of this report, seven fatalities had been reported. The USGS PAGER tool estimated 1 to 10 fatalities, 10 to 100 fatalities, 100 to 1000 fatalities, and 1000 to 10000 fatalities with probabilities of 17%, 40%, 31%, and 8%, respectively, for the December 29 earthquake event. PAGER estimated most likely economic losses due to damage to be between $100 million and $1000 million (with 35% probability) (Figure 1.14b).

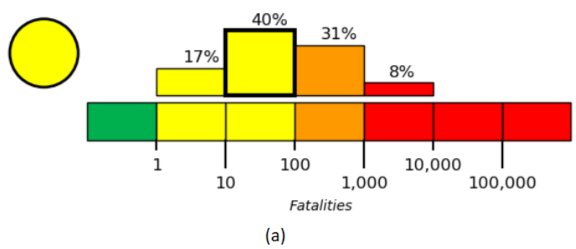


Figure 1.14. PAGER estimates: a) probability of fatalities and b) estimated economic losses for the December 29, 2020, M_w 6.4 earthquake (USGS 2020a).

2.0 Seismological Aspects

2.1 Tectonics of the Region

Croatia is located in the Alpine-Mediterranean seismic region. Tectonics of the Mediterranean are primarily governed by the convergent boundary region between the African and Eurasia plates. This convergence began approximately 50 Ma (millions of years) and was associated with the closure of the Tethys Sea, whose modern remnant corresponds to the Mediterranean Sea (USGS 2020). The tectonics of Croatia, in particular, are governed by the thrusting of the Adriatic (Adria) microplate under the European lithosphere (Figure 2.1). The region is complex as there are multiple microplates and regional-scale structures, originating numerous crustal faults (Figure 2.2). The collision between the Adria and Eurasia plates is still not yet fully understood, and it is the subject of study of numerous ongoing investigations (Ivančić 2018).

The major tectonic units that control the seismicity of Croatia (Figure 2.3) are the Pannonian Basin to the north, the Eastern Alps, the Dinarides, the Dinarides-Adriatic Platform transition zone, and the Adriatic Platform (Markušić 2008). The interaction between these units causes earthquakes in the upper crust, distributed along the numerous active faults in the region (Stanko et al. 2020). Most earthquakes occur in the west (coastal) area due to the collision between the Adriatic Platform and the Dinarides. The seismogenic faults in this region are primarily reverse faults, with tectonic movements that have predominantly tangential components. The seismicity of the Pannonian Basin is typical interplate, characterized by rare occurrences of large events, and whose tectonic motions are primarily vertical on steep dipping faults (Markušić 2008).

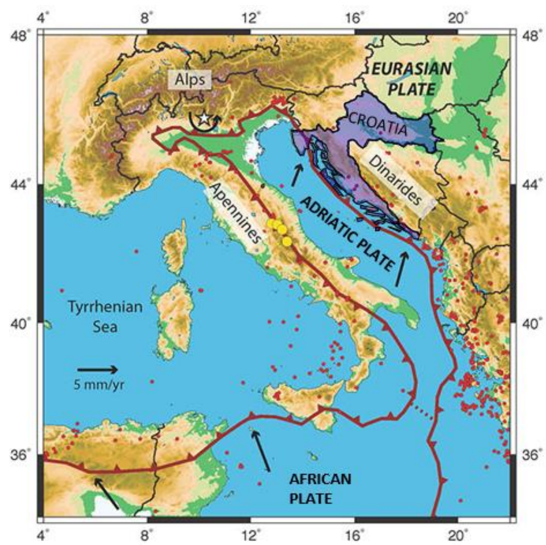


Figure 2.1. Tectonic plates in the Alpine-Mediterranean region (adapted from Physics Today 2016).

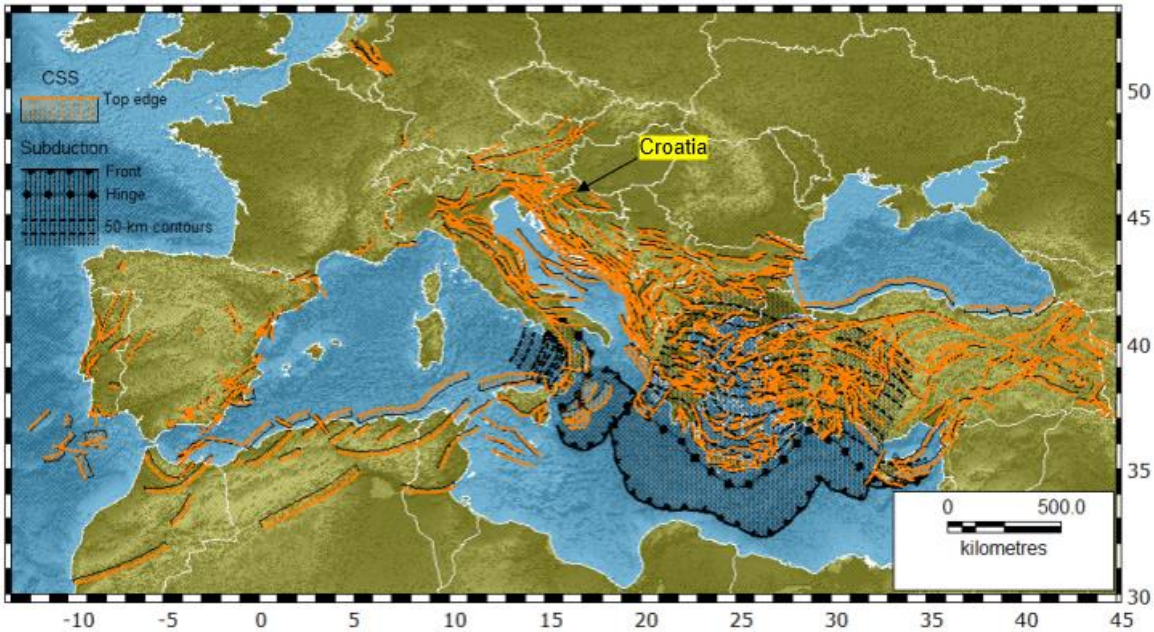


Figure 2.2. Seismogenic faults in Europe (adapted from Basili et al. 2016).

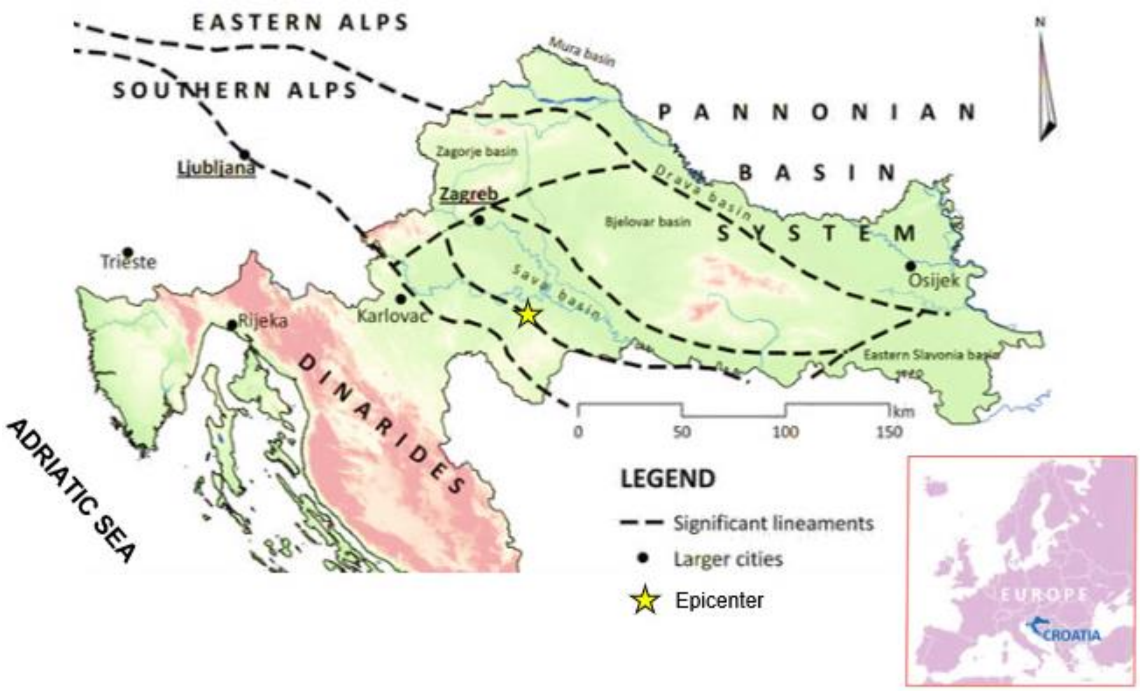


Figure 2.3. Position of Croatia in relation to major European tectonic units (adapted from Borović et al. 2016).

2.2 Seismicity of the Region

Figure 2.4 depicts the epicenters of around 30,000 earthquakes that occurred in Croatia from BC to 2015, with the average number of 45 earthquakes felt each year. Similarly, Figure 2.5 presents the epicenters of earthquakes with magnitudes over 3.0 in Croatia and its surroundings since 1950. Some of the strongest seismic events that affected Croatia from the 17th century onwards are listed in Table 2.1.

The seismicity of the wider Zagreb area is defined by four seismic zones, namely Zagreb, Novo Mesto-Krško, Karlovac-Metlika, and Pokupsko-Petrinja (Figure 2.6).

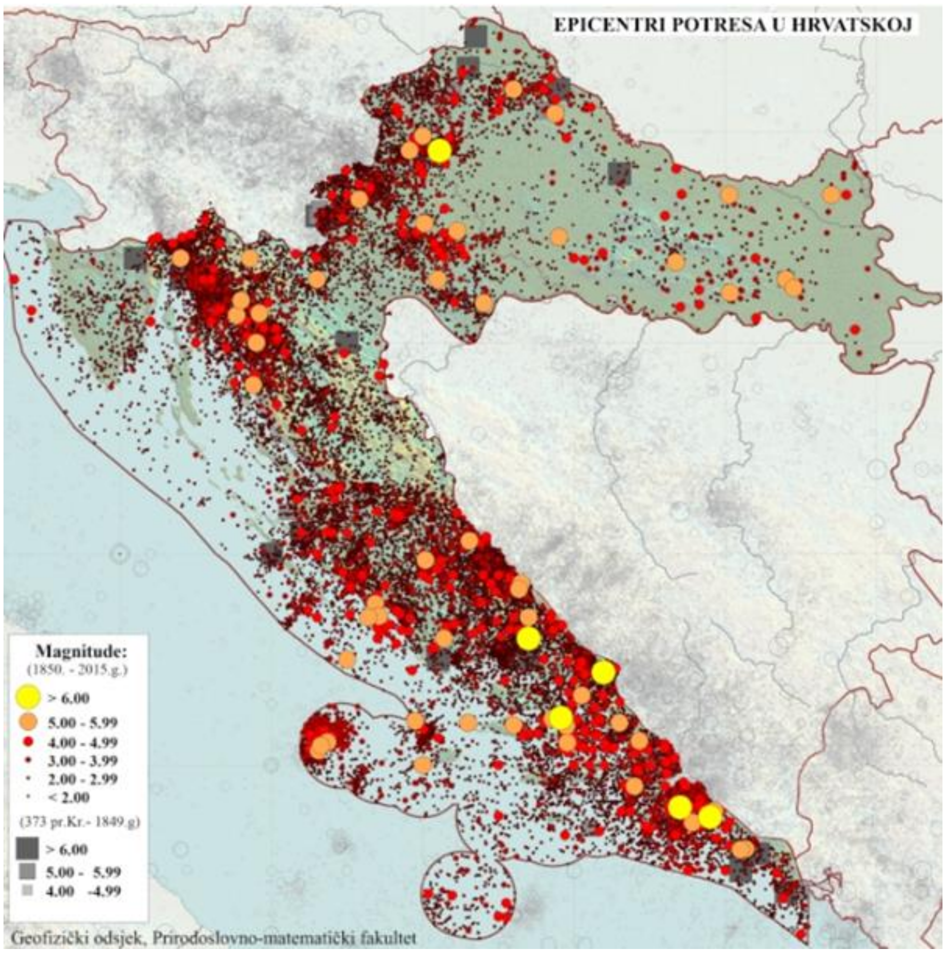


Figure 2.4. Map of earthquake epicenters in Croatia in the period from BC to 2015 according to the Catalog of Earthquakes in Croatia and the Neighboring Areas (*Archives of the Department of Geophysics, Faculty of Science, University of Zagreb*; *Herak et al. (*1996*); Markušić et al. (*1998*); Ivančić et al. (*2001, 2006*))*. Source: Seismological Service of Croatia (2021).

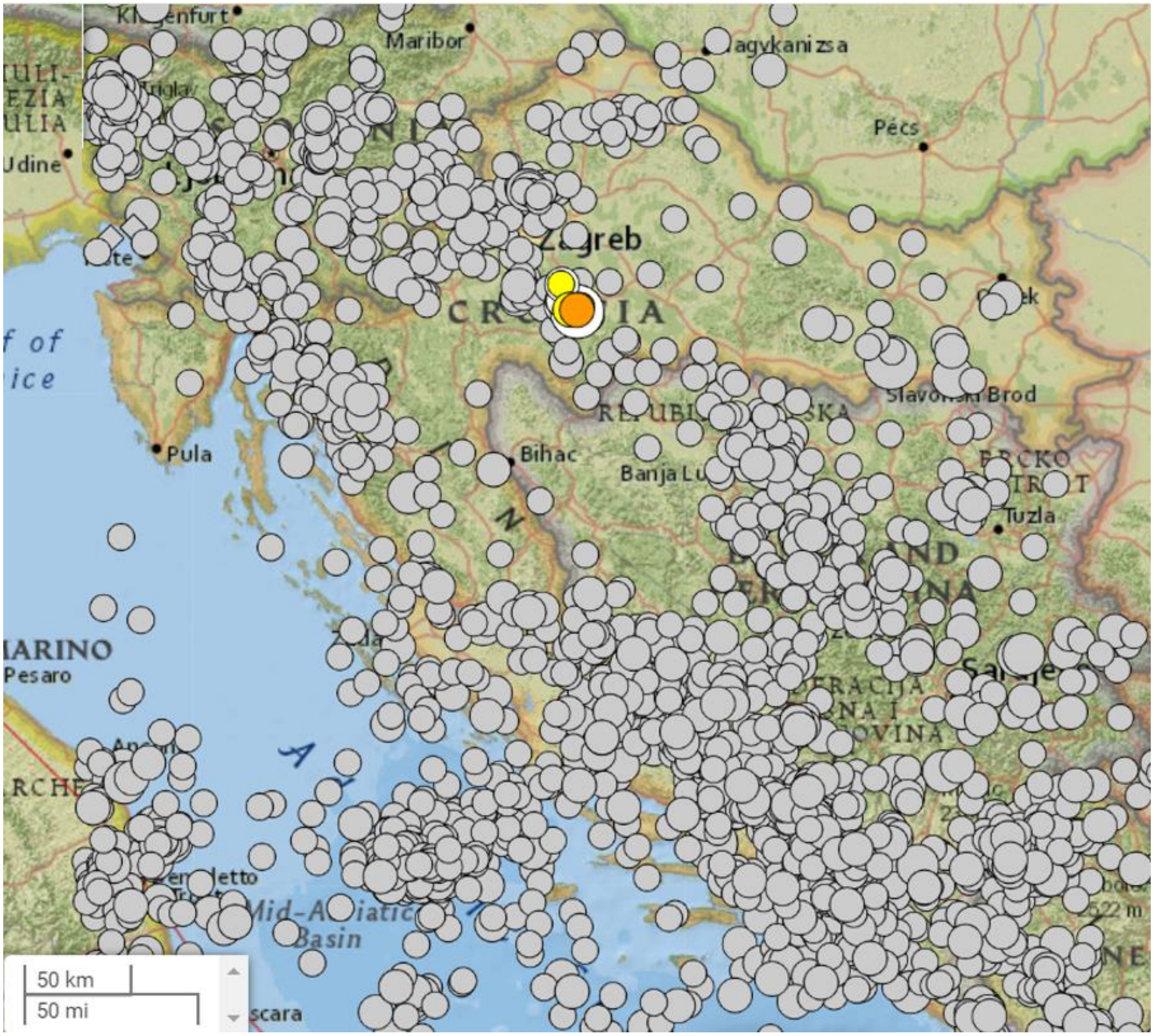


Figure 2.5. Epicenters of earthquakes with moment magnitudes M>3 in Croatia since 1950. Source: USGS ComCat. (USGS 2021).

The strongest seismic events associated with the Zagreb seismic zone have been mainly located on the north-western slopes of the Medvednica Mountain. The event of November 9, 1880 (Table 2.1) was the strongest one that occurred in that zone and is also the first Croatian earthquake whose characteristics (such as intensity and focal depth) were determined through macroseismic investigations and more detailed analyses. This event is commonly referred to as the 'Great Zagreb earthquake' as it resulted in great material damage including complete destruction of 13% of all buildings in Zagreb. The March 22, 2020 Zagreb earthquake is the strongest earthquake that struck the nation's capital more recently (Stanko et al. 2020).

Before the occurrence of the December 29, 2020 Petrinja earthquake, the strongest instrumentally recorded earthquake in the Pokupsko-Petrinja seismic zone (Figure 2.6) was the

October 8, 1909 Pokupsko earthquake (Table 2.1). The studies and analyses of this earthquake, performed by the Croatian scientist Andrija Mohorovičić, resulted in the discovery of the boundary between the crust and the mantle (known today as Mohorovicic or Moho discontinuity in his honor) (Stanko et al. 2020, Herak & Herak 2010). The 2020 Petrinja earthquake has a magnitude equal to that of the 1942 Imotski earthquake which makes these two the strongest instrumentally recorded seismic events in Croatia (Prevolnik 2021).

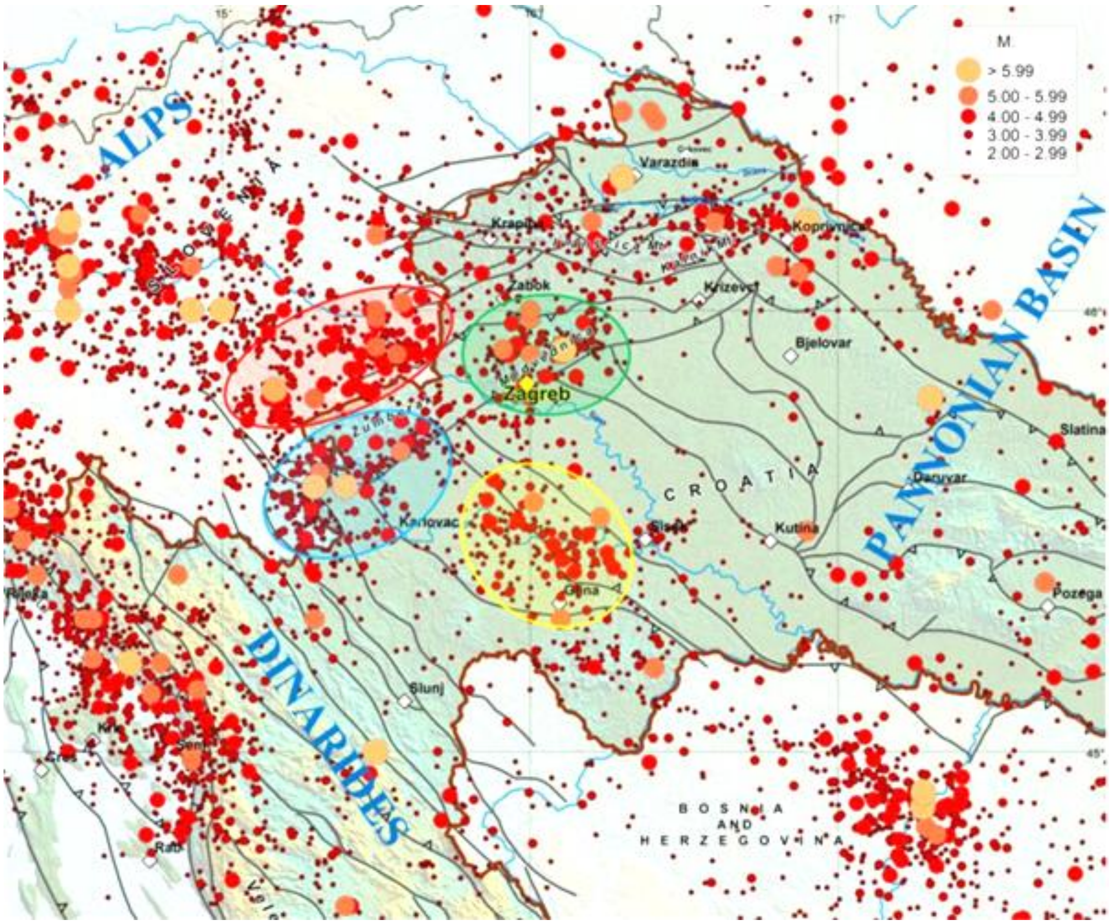


Figure 2.6 Spatial distribution of earthquake locations in the investigated area (373BC–2019), according to the Croatian earthquake Catalogue-CEC, the updated version first described in Herak et al. (1996). Seismic zones are marked as: Zagreb-green, Novo Mesto-Krško-red, Karlovac-Metlika-blue and Pokupsko-Petrinja-yellow. Faults are marked with black lines (Ivancic et al. 2006; Ivancic et al. 2018). From Stanko et al. (2020).

Table 2.1. List of the strongest earthquakes that occurred in Croatia since the 17th century (adapted from Ines Ivančić, Seismological Service of Croatia (2021)).

Date	Location	Estimated Magnitude (M_L)	Intensity (MCS)
6 April 1667	Dubrovnik	/	IX-X
9 November 1880	Zagreb	6.3	VIII
2 July 1898	Trilj	/	IX
8 October 1909	Pokuplje	5.8	VIII
12 March 1916	Vinodol	5.8	VIII
27 March 1938	Novigrad Podravski	5.6	VIII
29 December 1942	Imotski	6.2	VIII-IX
11 January 1962	Makarska	6.1	VIII-IX
13 April 1964	Dilj Gora	5.7	VIII
5 September 1996	Ston-Slano	6.0	VIII
22 March 2020	Zagreb	5.5	VII
29 December 2020	Petrinja	6.2	VIII-IX

2.3 October 8, 1909 Earthquake

The October 8, 1909 M_S 6.0 Kupa Valley earthquake has been instrumental in the field of geophysics for more than 100 years. Specifically in Croatia, this event has potentially significant implications for further understanding of the December 29, 2020 Petrinja earthquake. The following paragraph, along with Figure 2.7, were taken from a paper written by Herak and Herak (2010) on the anniversary of this important event:

"The Kupa Valley (Croatia) earthquake of 8 October 1909 belongs to a group of milestone events in the history of geophysics and seismology. Also known as the Kupa Valley, Pokuplje or the Pokupsko earthquake, it is often mentioned in textbooks, encyclopedias, and historical overviews of science as the earthquake whose seismograms provided key data for Andrija Mohorovičić's proof of the existence of the crust-mantle boundary that was later named after him. The Kupa Valley earthquake occurred only a year after the first Wiechert seismograph was developed. The earthquake occurred close to Zagreb (about 30 km to the south) where Mohorovičić lived and worked, and it was strong enough to cause some damage in the city. Earthquakes had been of interest in Zagreb for some time, as seismicity around the capital was at its long-time maximum ever since the large earthquake of 1880. After the earthquake, Mohorovičić exchanged correspondence with phase readings and comments with many prominent seismologists of that time. All together, Mohorovičić received data from 41 stations, of which he used 36. The Kupa Valley earthquake is cited in seismological literature almost exclusively in the context of the discovery of the Moho. However, it was the strongest event known to have ever been noted in the Kupa Valley epicentral region, and it plays a key role in defining the hazard there."

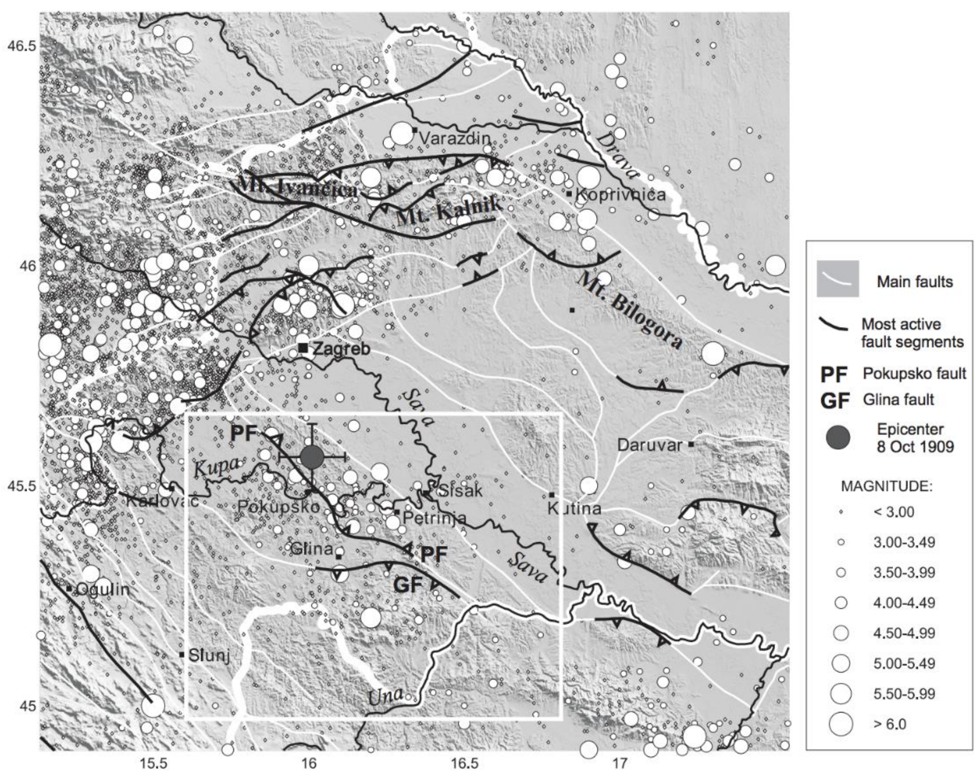


Figure 2.7. Overview map of northwest Croatia, with the Pokupsko epicenter area marked by a white rectangle. Epicenters are from the Croatian Earthquake Catalogue (relocated here for the Pokupsko area). The 1909 mainshock is shown as a dark gray circle with one standard deviation error bars. (From Herak and Herak 2010, Figure 1).

2.4 March 22, 2020 Zagreb Earthquake

On March 22, 2020, at approximately 6:24 am local time, a moment magnitude 5.3 (M_L = 5.5 according to the Croatian Seismological Survey of the University of Zagreb) earthquake struck the city of Zagreb, Croatia. The epicenter was located 10 km north of the center of the city, with coordinates 45.907°N, 15.970°E and a depth of 10 km (USGS 2020b). Figure 2.8 shows the epicenter of the earthquake. The earthquake was felt across Croatia, and even in the adjacent countries of Slovenia, Bosnia and Herzegovina, Serbia, and Hungary.

The earthquake mechanism corresponds to a reverse (thrust) faulting mechanism, characteristic of earthquakes in the Medvednica Mountain region. The rupture plane found by Markušić et al., (2020) had a strike of 263° and a dip angle of 43° to the south-southeast. Meanwhile, the rupture plane found by USGS also had a strike of 263° but a dipping angle of 39°. Furthermore, the axis of maximum tectonic pressure (P) was predominantly horizontal with plunge angle of 4° in the SSE-NNW direction, while the axis of maximum tension (T) was almost vertical with a plunge angle of 84° (Markušić et al. 2020). Figure 2.9 shows the moment tensor solution for the March 22, 2020 earthquake according to the Markušić (2020).

The USGS ShakeMap (see Figure 2.10) indicates Peak Ground Accelerations (PGA) in the range of 0.2g and Modified Mercalli Intensity levels of VII. This high level of shaking is consistent with the observed damage including the collapsed buildings (USGS 2020b).

Figure 2.8. Epicenter of the Zagreb, Croatia earthquake on March 22, 2020 (USGS 2020b).

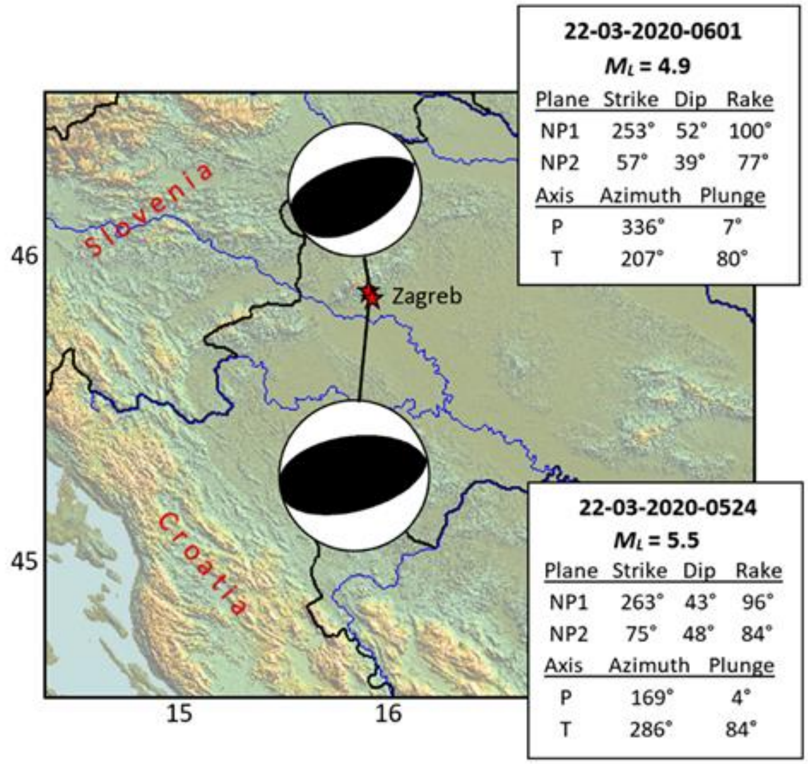


Figure 2.9. Fault plane solution of the Zagreb, Croatia earthquake on March 22, 2020 (adapted from Markušić et al. 2020).

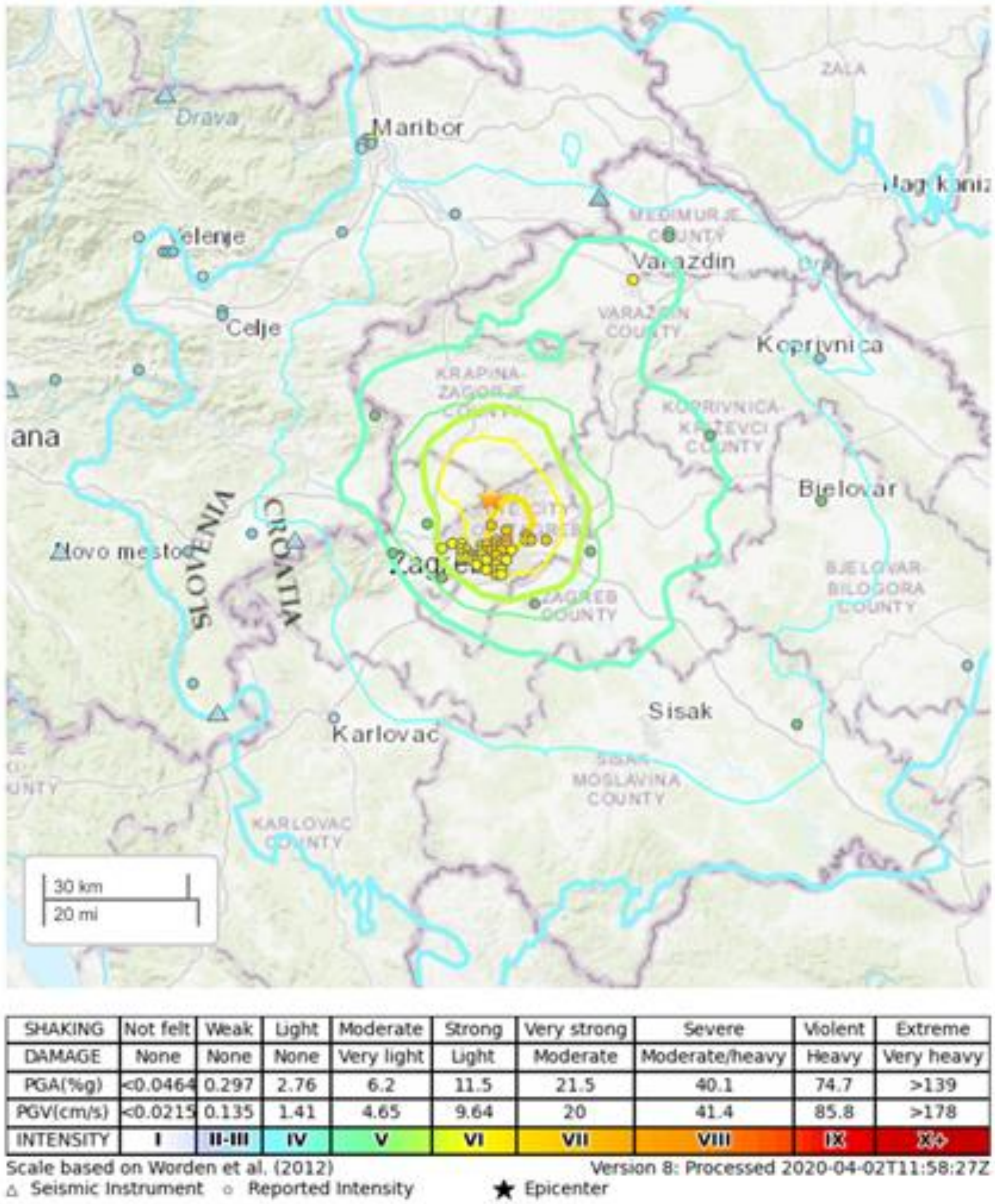


Figure 2.10. PGA contours and intensities estimated from ShakeMap (USGS 2020b) for the March 22, 2020 earthquake.

2.5 December 29, 2020 Earthquake

On December 29, 2020, at approximately 12:20 pm local time (11:20 am UTC), a moment magnitude 6.4 (M_L = 6.2 according to the Croatian Seismological Survey of the University of Zagreb) earthquake struck 3 km southwest of Petrinja, 12 km southwest of Sisak, and 47 km south of Zagreb, hitting the Sisak-Moslavina County of Croatia, as shown in Figure 2.11 (EMSC-CSEM 2020, IRIS 2020, Seismological Service of Croatia 2020a, USGS 2020). The USGS

(2020) located the hypocenter at 45.422°N 16.255°E, with a depth of 10 km, whereas the Croatian Seismological Survey (2020a) located the hypocenter at 45.400°N 16.219°E, with a depth of 11 km. The location of the hypocenter suggests that the rupture occurred within the central portion of the Petrinja Fault (Figure 2.12). Moreover, preliminary geological analysis performed by the Croatian Geological Survey (Korbar 2021) indicate that the December 29, 2020 earthquake also activated a more complex fault system in the underground of the wider area of Sisak, Petrinja, and Glina (Figure 2.13).

The mainshock of December 29, 2020, was preceded by two foreshocks with moment magnitudes 5.2 and 4.7 on the day before (December 28). At the time of this writing, there have been more than a hundred aftershocks with moment magnitudes over 2.0, with two of them (both on December 30, 2020) having moment magnitudes 4.7 and 4.8, and one (January 6, 2021) having a moment magnitude 4.9 (M_L = 5.0) (Seismological Service of Croatia 2020b). As shown in Figure 2.14, most of the aftershocks have occurred within the northern portion of the Petrinja Fault, and some of them have occurred within the adjacent Jastrebarsko and Podsljeme Faults. It should be noted that the aftershocks within the Jastrebarsko and Podsljeme Faults might correspond to aftershocks of the M5.3 March 22, 2020 earthquake. The Seismological Service of Croatia at the Department of Geophysics, Faculty of Science, University of Zagreb, produced an illustrative animation showing the epicenters of the foreshocks and aftershocks (until December 30, 2020) of the December 29, 2020 earthquake, which can be watched at this link: http://youtu.be/OSvZhrpIVng.

Figure 2.11. Location of the December 29, 2020 earthquake in Croatia (source: New York Times 2020).

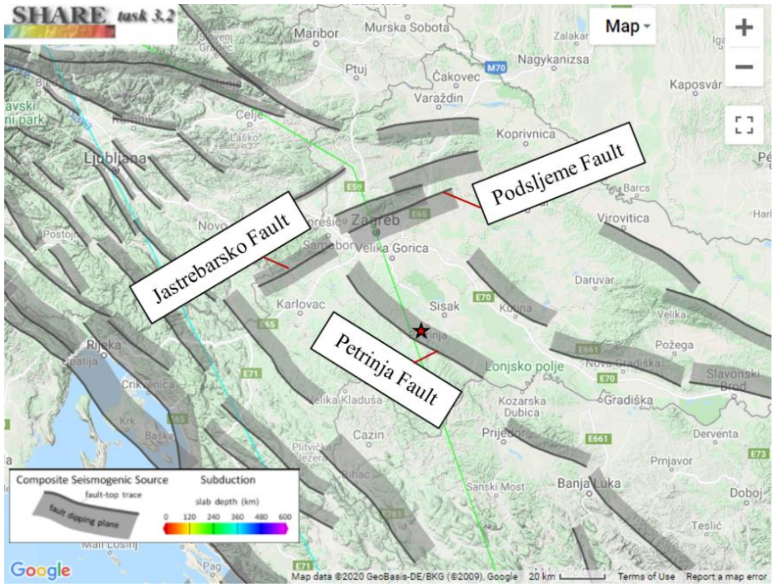


Figure 2.12. Map of active crustal faults in Croatia. The red star marks the epicenter of the December 29, 2020 earthquake (adapted from Basili et al. 2013).

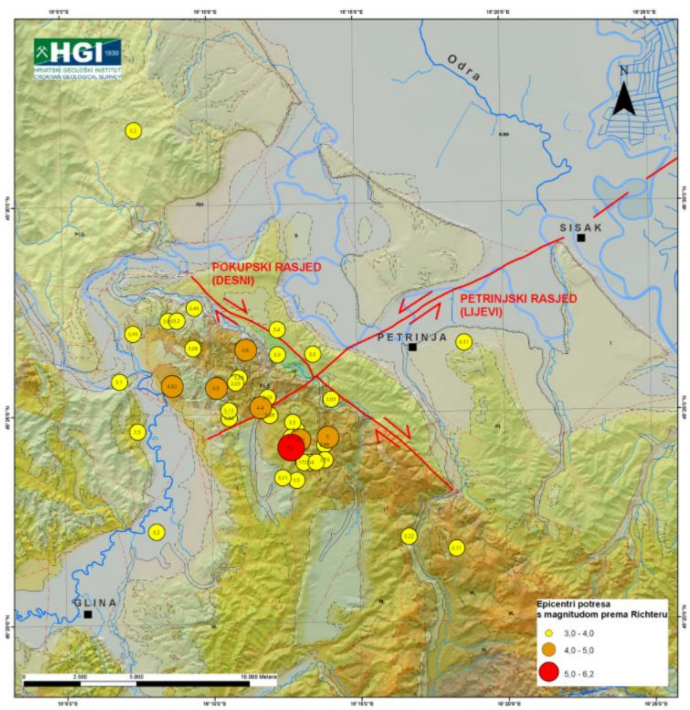


Figure 2.13. Geological map of the epicentral region of the December 29, 2020 earthquake, highlighting the activated fault systems according to preliminary geological analyses. Korbar (2021).

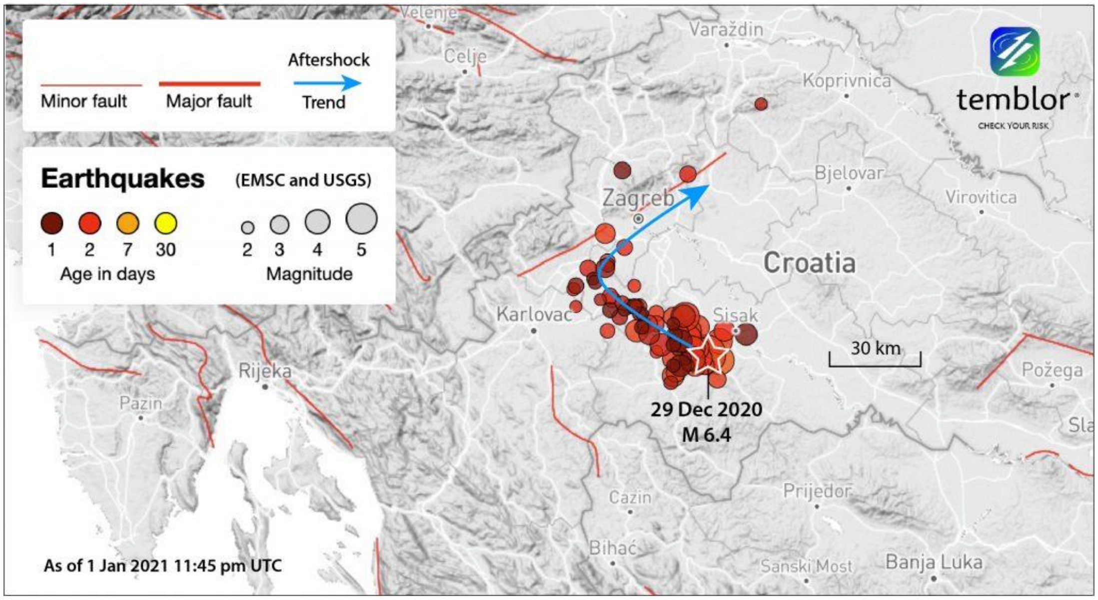


Figure 2.14. Aftershocks with moment magnitudes M>2 of the December 29, 2020 earthquake. Temblor (2021).

The moment tensor inversion solution for the December 29, 2020 earthquake, as reported by the USGS (2020), indicates a strike-slip focal mechanism (Figure 2.15). As shown in Table 2.2, one nodal plane corresponds to left-lateral movement with a slight thrust component on a fault striking in the NE-SW direction, while the other indicates right-lateral movement on a fault striking SE-NW and dipping sub-vertically to the southwest. It is likely that the latter fault plane solution (Fault Plane 2) defines the causative fault as it conforms with the SE-NW direction of the Petrinja Fault (Figure 2.12).

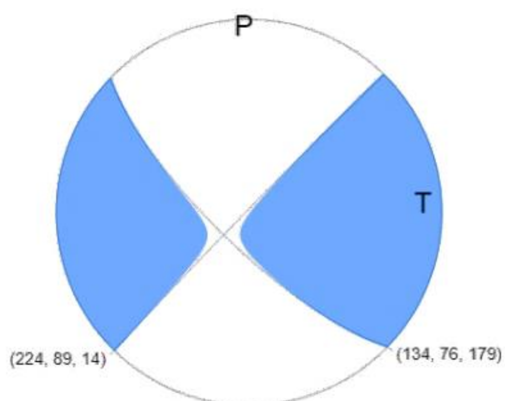


Figure 2.15. Moment tensor solution for the December 29, 2020 earthquake according to the USGS (2020).

Table 2.2. Fault plane solutions from USGS (2020). The causative plane is more likely to correspond to the Fault Plane 2 solution marked in grey.

Fault Plane 1			Fault Plane 2		
Strike	Dip	Rake	Strike	Dip	Rake
224	89	14	134	76	179

2.6 Ground Motion Intensities

As shown in Figure 2.16, the USGS ShakeMap estimates and Modified Mercalli Intensity of VIII and a PGA of approximately 0.4g in the epicentral region (USGS 2020). Similarly, the Croatian Seismological Survey (2020a) reported an intensity in the epicentral region of VIII-IX on the EMS-98 scale.

Table 2.3 provides a list of seismic stations reported by the USGS that recorded the event within a distance of 250 km from the epicenter. Among this list, the maximum instrumental PGA and PGV were recorded at the Cresnjevec (CRES) station of the Seismic Network of Slovenia, in its North-South direction: the PGA was 24.7 cm/s^2 (0.0252 g), whereas the PGV was 2.24 cm/s. The source-to-site distance of the CRES station was 70.55 km, being, among the list in Table 2.3, the closest seismic station to the rupture.

Table 2.4 presents preliminary information on six seismic stations located in Zagreb that recorded the event (Prevolnik 2021). Among these stations, the maximum PGA and PGV were 243.16 cm/s^2 (0.248 g) and 9.59 cm/s; both were recorded at the QKAS station in its North-South direction. Interestingly enough, although this station recorded the maximum PGA and PGV among those listed in Table 2.4, it is not the closest station to the epicenter. According to Prevolnik (2021), this observation might suggest ground motion amplification due to local soft soil conditions and/or topographic effects.

Figure 2.17 provides a map showing the geographical location of the seismic stations listed in Tables 2.3 and 2.4, along with the epicenter of the December 29, 2020 earthquake.

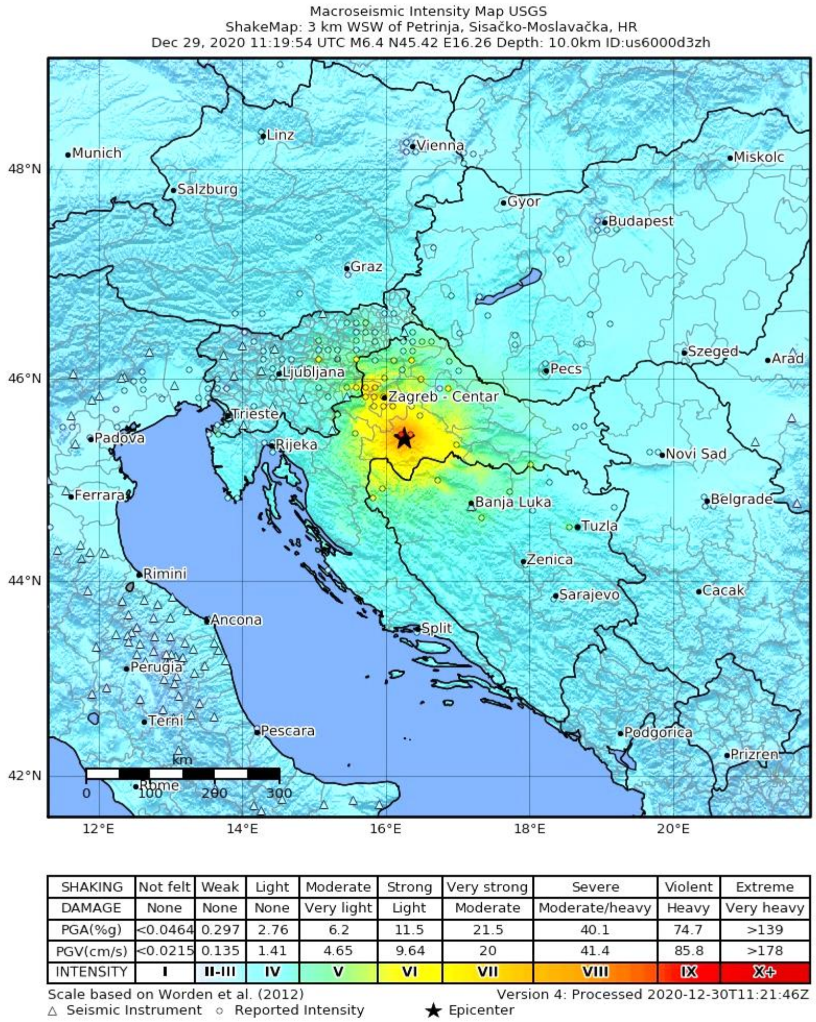


Figure 2.16. Intensity map estimated from ShakeMap. (source: USGS 2020).

Figure 2.18 compares ground motion intensities (PGA, PGV, and 5%-damped pseudo-acceleration spectral ordinates at periods 0.3s and 1.0s, Sa(0.3s) and Sa(1.0s), respectively) recorded at the stations listed in Tables 2.3 and 2.4 with the intensities estimated by using the Boore et al. (2014) ground motion prediction equation, using a time-averaged shear wave velocity in the upper 30 m, V_{s30}, of 760 m/s. It should be noted that this value of V_{s30} was selected as a generic value for comparison purposes and might not reflect the real V_{s30} of the sites where the seismic stations are located. For PGA and PGV, most of the recorded intensities fall within the estimated 2.5/97.5th percentiles, evidencing a good agreement between the recorded and the estimated ground motion intensities. In the case of Sa(0.3s) and Sa(1.0s), most of the recorded intensities fall below the median estimated value, even with some cases below the estimated 2.5th percentile, which suggests a negative inter-event residual in these ground motion intensities.

Table 2.3. List of seismic stations that recorded the event within a distance of 250 km from the epicenter, according to the USGS (2020).

Station	Station Coordinates	R [km]	PGA [%g]		PGV [cm/s]	
			EW	NS	EW	NS
CRES Cresnjevec, SL	45.826°N 15.457°E	70.55	1.68	2.52	1.51	2.24
BOJS Bojanci, SL	45.504°N 15.252°E	72.65	0.93	0.98	0.72	1.26
BLY Banja Luka, Bosnia and Herzegovina	44.749°N 17.184°E	97.61	1.21	0.94	2.17	1.70
KOGS Kog, SL	46.448°N 16.250°E	106.98	2.30	1.93	1.13	1.56
VISS Visnje, SL	45.803°N 14.839°E	110.84	1.02	1.29	0.59	1.09
VNDS Vrh nad Dolskim, SL	46.102°N 14.701°E	134.65	1.10	0.95	0.99	1.23
CEY Cerknica, SL	45.738°N 14.422°E	139.26	0.74	0.58	0.41	0.97
LJU Ljubljana, SL	46.044°N 14.528°E	143.12	1.10	1.39	1.05	1.53
CRNS Crni vrh, SL	46.081°N 14.261°E	163.19	1.08	0.99	0.85	1.25
SKDS Skadanscina, SL	45.546°N 14.014°E	167.24	0.26	0.28	0.32	0.52
DST2 DST-Trieste_station	45.659°N 13.801°E	184.73	0.57	0.87	0.35	0.98
VOJS Vojsko, SL	46.032°N 13.888°E	187.67	0.36	0.30	0.47	0.66
GORS Gorjuse, SL	46.317°N 14.000°E	192.73	0.38	0.29	0.50	0.53
CADS CADRG, SL	46.228°N 13.737°E	206.37	0.48	0.49	0.55	0.66
RC01C Raspberry Shake Citizen Science Station	45.941°N 13.047°E	247.23	0.44	0.59	0.76	1.09

Table 2.4. List of six seismic stations in Zagreb that recorded the event (Prevolnik 2021).

Station	Station Coordinates	R [km]	PGA [%g]		PGV [cm/s]	
			EW	NS	EW	NS
QARH	45.777°N 15.993°E	45.46	8.15	9.52	8.49	7.79
QUHS	45.808°N 15.999°E	48.50	9.77	12.67	6.23	5.96
QZAG	45.827°N 15.987°E	50.78	10.86	9.96	6.40	5.24
QGAJ	45.811°N 15.879°E	52.75	13.01	11.48	7.48	6.73
QKAS	45.914°N 16.103°E	57.80	16.60	24.80	6.07	9.59
QPTJ	45.907°N 15.968°E	59.65	2.84	3.96	2.34	1.78

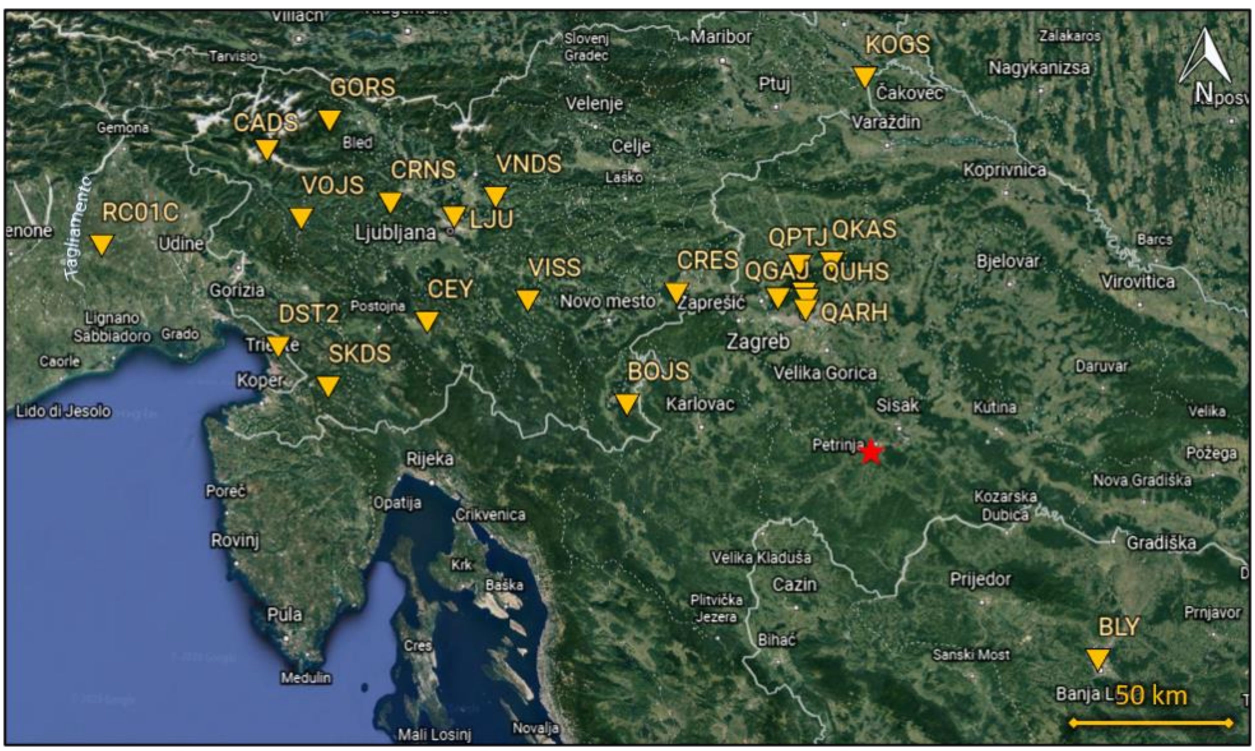


Figure 2.17. Map of publicly reported seismic stations (source: Google Earth). The epicenter of the December 29, 2020 earthquake is shown with a red star.

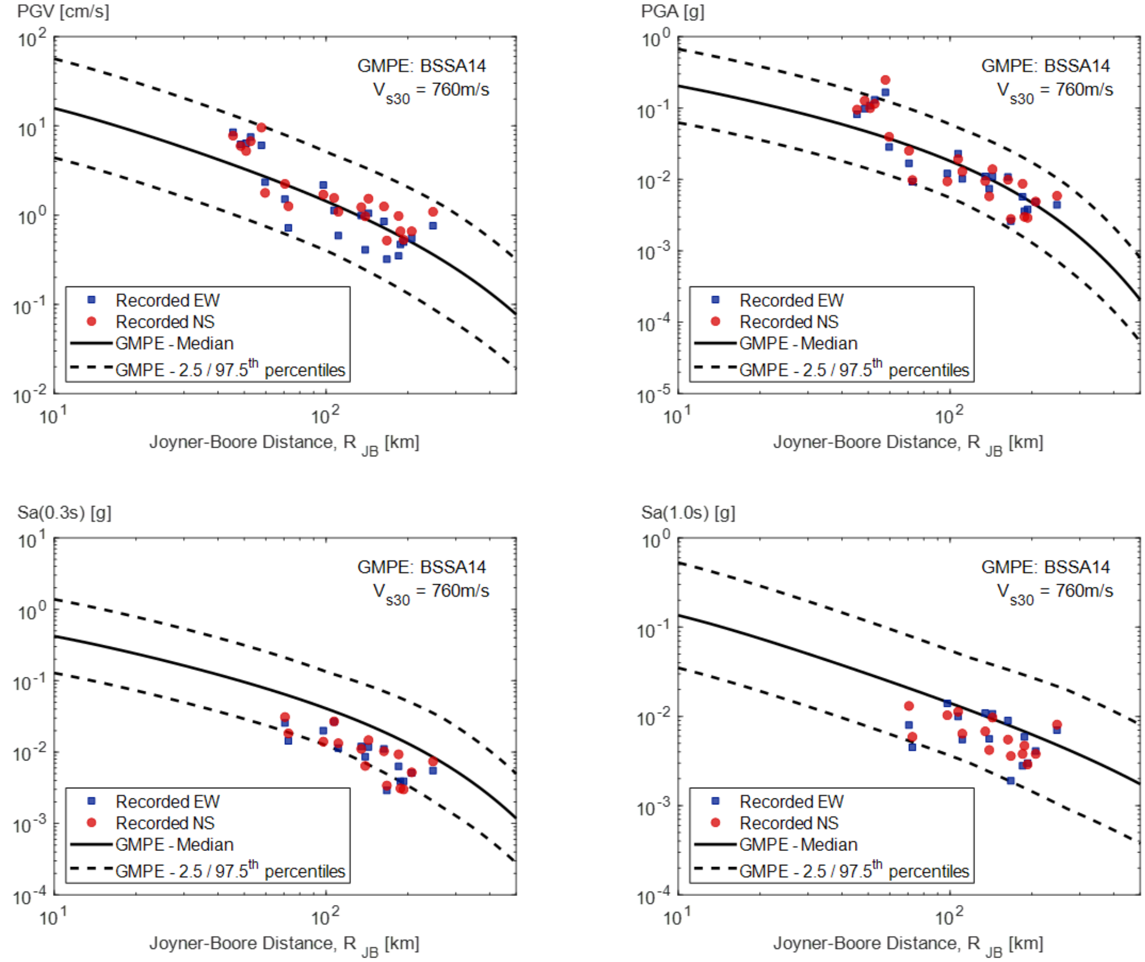


Figure 2.18. Comparison of recorded and estimated ground motion intensities using the Boore et al. (2014) ground motion prediction equation for the M_w 6.4 December 29, 2020 earthquake.

3.0 Local Codes and Construction Practices

This chapter provides information on the existing building stock in Croatia and the evolution of seismic codes in the past decades.

3.1 Existing Building Stock

In a historical context and from a construction material and techniques point of view, there are seven characteristic periods regarding the most common types of buildings in the National Building Stock of the Republic of Croatia (Pavić et al. 2020a):

Prior to 1940: Most of the buildings constructed in this period were Unreinforced Masonry Buildings (URM) with brick or stone masonry walls of thickness ranging from 25 to 50 cm (Figure 3.1). Until 1920, these buildings had wooden floors, but subsequently semi-prefabricated reinforced concrete floor systems were used (Pavić et al. 2020b). It is noted that the buildings of pre-1920 vintage had solid clay brick walls in lime mortar (Pavić et al. 2019). Most of these buildings currently constitute parts of historic town centers throughout Croatia. Some of these buildings have been classified as historical heritage. These buildings experienced moderate to severe damage in the December 29, 2020 earthquake. It is estimated that about a third of all dwellings in Croatia are from this era, i.e., they were built before seismic design codes (Šavor Novak et al. 2019).

1941-1970: This is the period where reinforced concrete (RC) structures and light-weight structures with large glazed frames were built alongside the use of traditional techniques. After the 1963 Skopje earthquake, the first national seismic code was published. For the first time, use of reinforcement was introduced in masonry buildings, in the form of vertical RC confining elements characteristic for confined masonry (Hadzima-Nyarko and Kalman Šipoš 2017).

1971-1980: During this period, RC structures, mostly moment resisting frames and structural wall systems with transverse concrete load-bearing walls, were widely used in urban areas. Masonry walls were constructed using hollow clay blocks (clay tiles) with minimum thicknesses of 19 to 25 cm. Prefabricated RC systems (walls and frames) were also common in that period (Manual for Energy Certification of Buildings 2010).

1981-1987: All available materials on the market at that time were used for construction.

1988-2005: Buildings constructed in this period included masonry, RC, steel, and laminated wood.

2006-2009: This period was mostly dominated by RC construction (Figure 3.1).

2010-Present: All available construction materials and techniques have been used in this period.

Since neither a taxonomy nor a database of buildings have been developed for the Republic of Croatia, appropriate conclusions can only be drawn about the construction types of buildings, materials used, and applicable regulations by trying to relate the data from the census and the knowledge of the construction tradition. The characteristics of building structures in various regions as well as the construction practices may change over time, but some of the main characteristics of the materials, the construction technology and quality of construction are the same for each period (Pavić et al. 2020b).

Figure 3.1. Examples of construction practices in Croatia: a URM building constructed prior to 1940 (left), and an RC building constructed between 2006 and 2009 (right) (Pavić et al. 2020a).

Based on data from the Croatian National Statistical Institute (DSZ RH), there are about 900,000 buildings in Croatia (Pavić et al. 2020a). The corresponding number of dwellings is 2,246,910, out of which 1,912,901 are permanent residences, with a total area of 168,651,195 m^2 (Croatian Bureau of Statistics 2011). A majority (86%) of the total national building stock comprise residential buildings; out of these, 34% are multi-family (apartment) buildings while the reimaining 66% are single-family houses. A small fraction (9%) of the total building stock are commercial buildings while the remaining 5% are public (government) buildings. A breakdown of the residential building stock according to the construction materials and lateral load resisting system is shown in Figure 3.2 (Crowley 2019).

About 25% of the Croatian population lives in the four largest urban centers. Approximately 40% of all settlements in the country account for 2.7% of the overall population, due to very low population density. Some of these settlements are small villages with less than 100 inhabitants (Hadzima-Nyarko et al. 2020). A breakdown of the dwellings in rural areas according to the type of construction materials and lateral load-resisting system obtained as a result of the NERA project is shown in Figure 3.3. It can be seen from the chart that the majority (76%) of dwellings in rural areas are masonry buildings, while only 12% of dwellings are RC buildings (Hadzima-Nyarko et al. 2020). The classification of dwelling types in urban areas, determined through rapid field surveys and questionnaires, is presented in Figure 3.4. It can be observed from the chart that URM buildings account for approximately 25% of the urban building stock, while the remaining 75% are RC frames or shear wall systems.

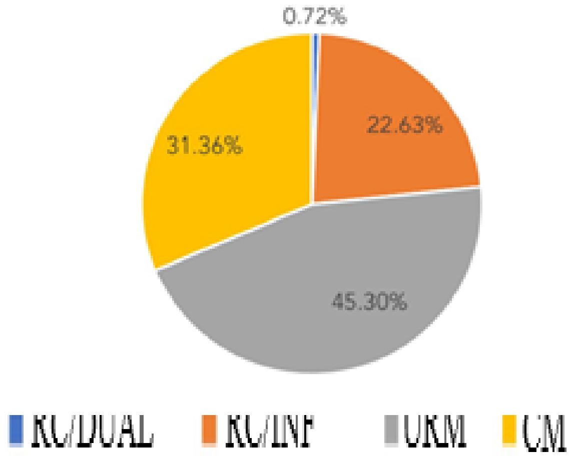


Figure 3.2. National residential building stock in Croatia according to construction material and lateral load-resisting system [RC/DUAL: reinforced concrete shear wall/frame dual systems, RC/INF: reinforced concrete frames with infill walls, URM: unreinforced masonry, CM: confined masonry] (Crowley 2019).

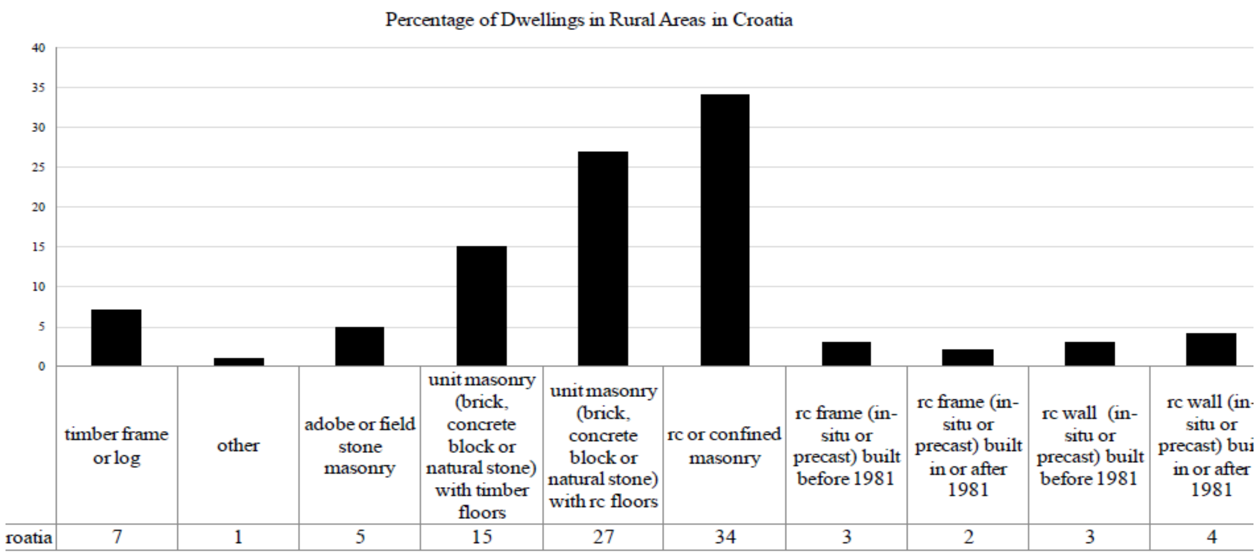


Figure 3.3. Classification of rural dwellings in Croatia according to project NERA (2011) according to construction materials and lateral load-resisting systems (Hadzima-Nyarko et al. 2020).

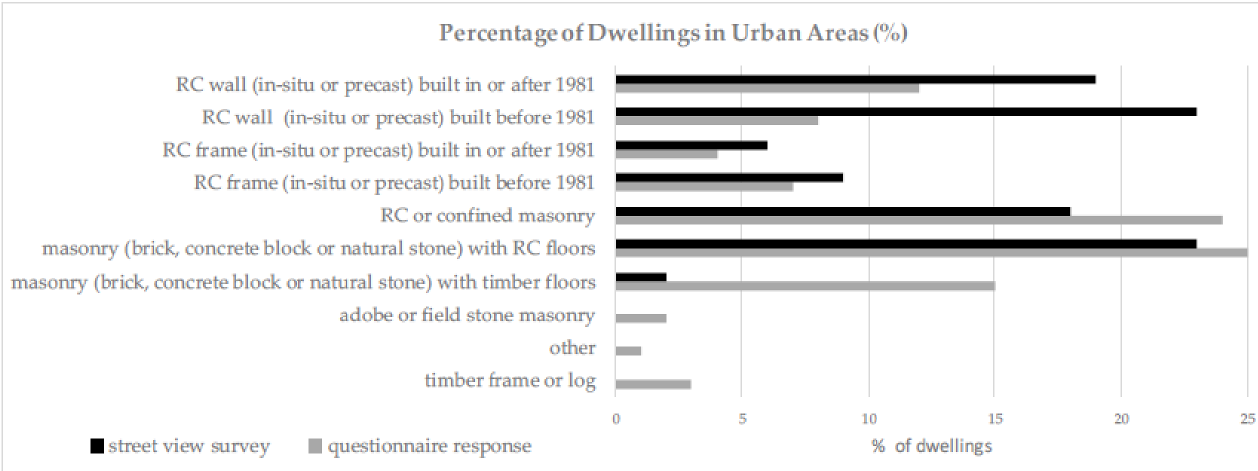


Figure 3.4. Classification of urban dwellings in Croatia according to project NERA (2011) (Pavić et al. 2020b).

Out of the 2,246,910 total dwellings in Croatia, 61,770 dwellings, corresponding to 2.7% of the entire stock, are located in Sisak-Moslavina County close to the epicentral region. A chart showing the breakdown of dwellings according to the year of construction of these dwellings is presented in Figure 3.5. According to the preliminary damage assessment conducted within 10 days after the earthquake, 54% of these dwellings were directly affected by the earthquake.

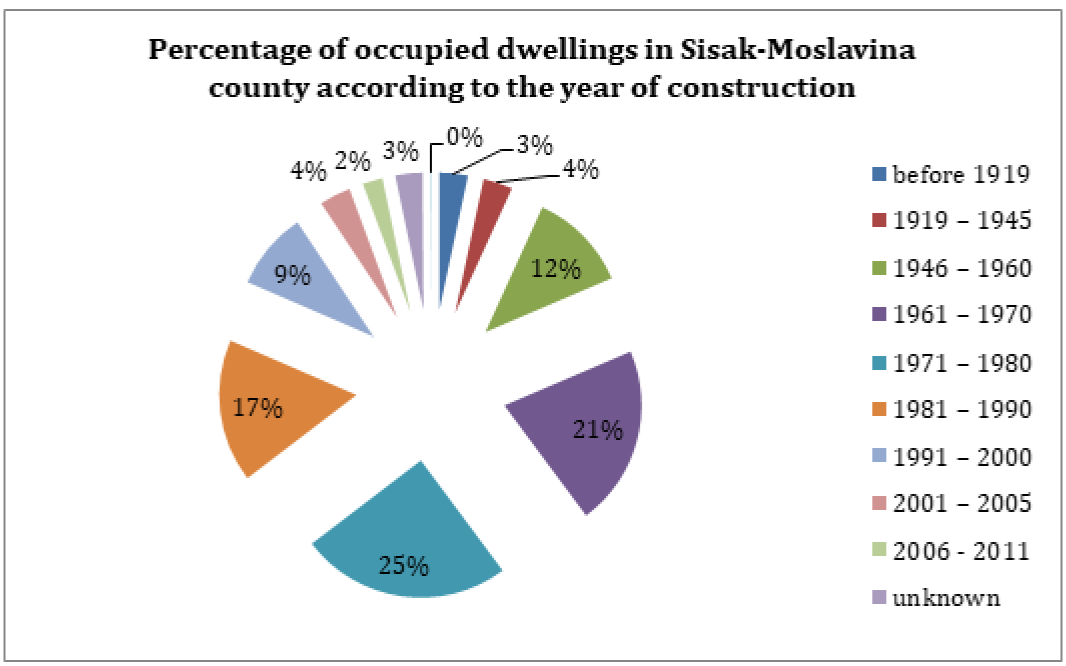


Figure 3.5. Classification of dwellings in Sisak-Moslavina County according to the year of construction (Croatian Bureau of Statistics 2011).

According to Hadzima-Nyarko et al (2020), building typologies in the small rural areas (such as the villages around Sisak and Petrinja), can be classified as follows according to the taxonomy developed by Giovinazzi (2015): M2 – adobe (earthen construction), M5 – unreinforced masonry structures (URM) with flexible floors, M6 – unreinforced masonry structures (URM) with rigid floors, and M7 – masonry structures with horizontal and vertical ties (confined masonry). Based on the data collected by Hadzima-Nyarko et al. (2020) for rural areas around the city of Osijek, it can be concluded that low-rise URM buildings up to two-story high are prevalent in rural areas, but midrise masonry buildings (up to 5-story high) could be found in larger villages or smaller towns. Older buildings did not have more than 5 floors because elevators would have been required, thereby increasing the initial construction cost. Newer buildings constructed after 2005 according to Eurocode 8 (CEN 2004) are often limited to a maximum of 5 floors in order to avoid additional costs related to elevators and they are typically built using confined masonry technology.

As discussed in Chapter 4, commonly observed damage patterns in the December 29 earthquake are those experienced by URM buildings with flexible wood diaphragms which are subjected to multiple deformation patterns when subjected to ground shaking (Figure 3.6, Kim and White 2004), namely out-of-plane bending in both directions and shear raking. These buildings are inherently vulnerable to both in-plane and out-of-plane earthquake effects. In particular, excessive lateral displacements of flexible floor diaphragms cause damage or failure of walls subjected to out-of-plane earthquake shaking; this is typically the case with gable walls which are common in older buildings in Croatia. Components of a typical flexible wooden floor structure in Croatia are shown in Figure 3.7 (Koški et al. 2012).

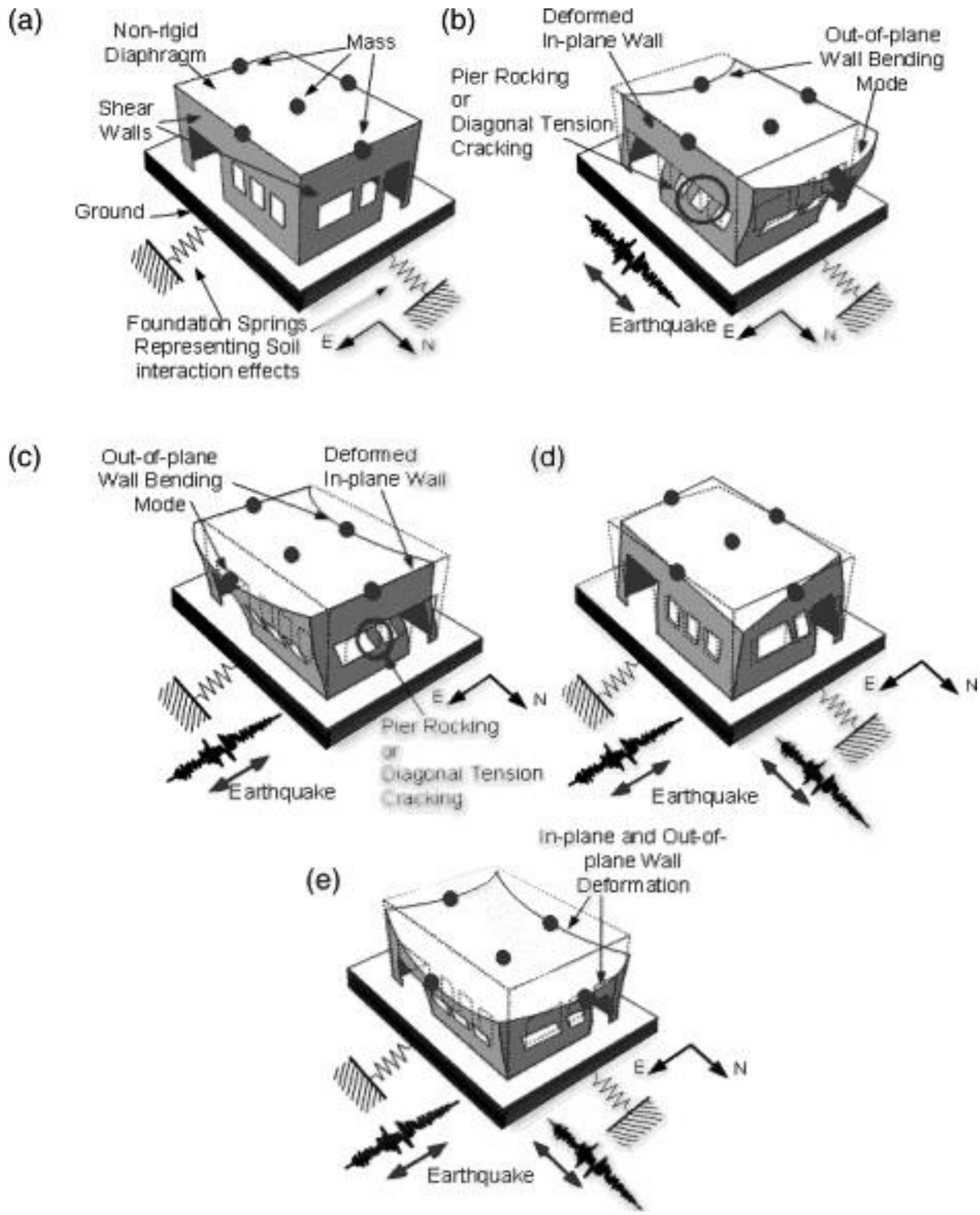


Figure 3.6. Schematics of a single-story URM building with a flexible diaphragm: (a) structural components and undeformed shape, (b, c) bending in two orthogonal directions, (d) shear racking in both directions, and (e) combined bending and shear racking (Kim and White 2004).

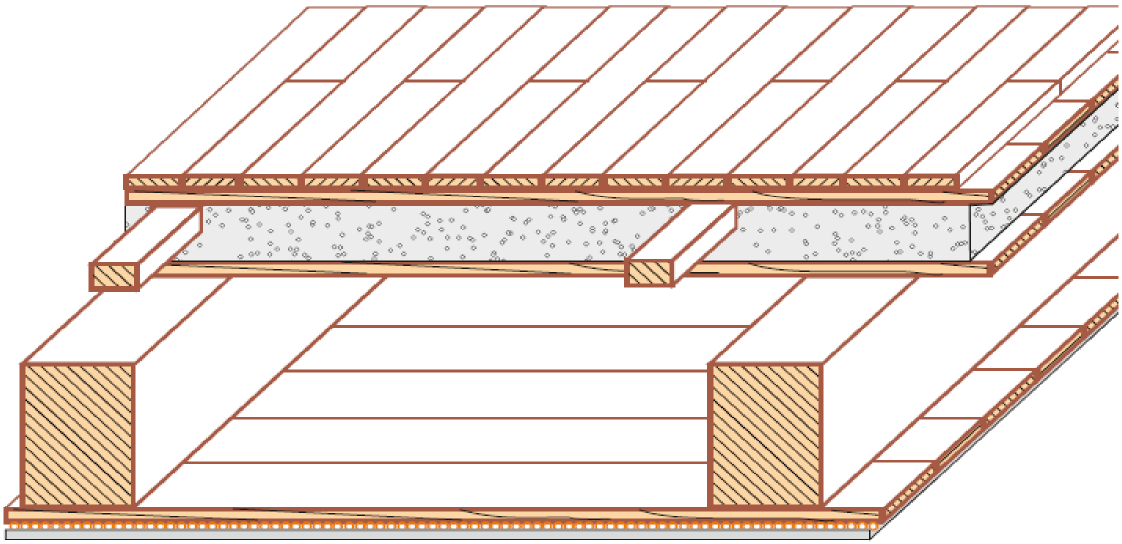


Figure 3.7. Components of a typical flexible wooden floor of a URM building in Croatia (Koški et al. 2012).

3.2 Building Codes

The design and construction of buildings in Croatia are regulated by the Construction Act, the Technical Regulation for Building Structures, the Physical Planning Act, and the Law on the Protection and Preservation of Cultural Property (Pavić et al. 2020a). The first building code in Croatia contained basic seismic design provisions and was published in 1948 (PTP0 1948). After the 1963 M_w 6.1 Skopje earthquake, a significant wealth of knowledge was acquired on the seismic response of buildings in former Yugoslavia. The first national seismic design code was published in 1964 (PTP 1964). The code was substantially revised after the 1979 Montenegro earthquake and a new edition was published in 1981 (PTN 1981). Both the 1964 and 1981 codes were applied throughout the former Yugoslavia (SFRY), which existed as a country until 1991. Subsequently, the former states from the SFRY territory became independent countries, including Croatia, Slovenia, North Macedonia, Bosnia and Herzegovina, Montenegro, and Serbia. It should be noted that, except for Slovenia and Croatia which adopted Eurocodes in the early 2000s, other countries have been following the 1981 code (PTN 1981) until recently, hence there is a substantial stock of existing buildings in the region designed according to that code. Fajfar (2018) provided a historic overview of the development of seismic design codes published in former Yugoslavia and a comparison with international codes. The Eurocode 8 (CEN 2004) standard was gradually introduced in Croatia as pre-standard starting from 2005, and was officially adopted in 2011 (EC8 2011). The evolution of building regulations related to earthquake design and construction of buildings in Croatia from 1945 to date is shown in Table 3.1.

Table 3.1. Evolution of seismic design codes in Croatia (adopted from Pavić et al. 2020a).

	PERIOD					
	Until 1948	**1948-1964**	**1964-1981**	**1981-2005**	**2005-2012**	**2010-Present**
SEISMIC DESIGN STANDARD	Not available	Provisional Technical Regulations for Loading of Structures, Part 2	Provisional Technical Regulations for Construction in Seismic Regions (PTP 1964)	Technical Regulations for the Design and Construction of Buildings in Seismic Regions (PTN 1981)	Pre-standards HRN ENV 1998-1 (EC8)	Standards HRN EN 1998-1:2011 (EC8)
SEISMIC DESIGN RIGOR	Not considered	Considered by equivalent lateral force applied to the top of the building	First set of seismic design codes and a seismic hazard map	Simplified design	State-of-the-art design according to Eurocode 8	Seismic hazard map updated in 2012
DOMINANT CONSTRUCTION TYPE	URM with wooden and concrete floors	URM without ties, RC frames	Confined masonry, monolithic RC frames and prefabricated RC walls and frames	Confined masonry, RC frames, shear walls, dual systems	Masonry, RC, steel, laminated wood, others	

Seismic hazard maps of Croatia in terms of peak ground acceleration (PGA) have been updated recently using probabilistic seismic hazard assessment (PSHA) (Herak et al. 2011; Atalić et al. 2019) according to modern seismic hazard assessment approaches followed in Europe. These maps were mainly developed for use along with Eurocode 8 (EC8) spectra. Seismic maps have been developed for two intensity levels. The first intensity level is for a return period of 95 years, i.e. with 10% probability of exceedance in 10 years, while the second intensity level is for a return period of 475 years, i.e., with the 10% probability of exceedance in 50 years, corresponding to the design-basis earthquake (DBE) according to ASCE 7-16 (ASCE 2016). The seismic hazard map for the 95-year return period event is intended for the EC8 so-called "damage limitation" requirement, while the seismic hazard map for the 475-year return period event is intended to meet the "no-collapse" or life-safety requirement. The maps are representative of ground shaking at site classes corresponding to rock and similar formations and need to be amplified using soil factors for other soil conditions (Šipoš and Hadzima-Nyarko 2017; Pavić et al. 2020b). Maps updated in 2011 corresponding to the 95 year and the 475-year events are shown in Figure 3.8, and PGA values for different cities in Croatia are listed in Table 3.2 from previous and current seismic hazard maps. The 1990 values were estimated using empirical relationships between MCS intensity and PGA (Trifunac et al. 1991), and the shown ranges represent estimates for the 16th and 84th percentiles (Pavić et al. 2020b). Note that the revision of the next generation of EC8 seismic provisions, including updates on the seismic hazard maps, is currently underway.

The acceleration response spectra used for design purposes are constructed using the PGA values according to EC8 Article 3.2.2.2, where the shape of the response spectrum depends on the site class and magnitude of the earthquake (Type 1 for M_w<5.5, and Type 2 otherwise).

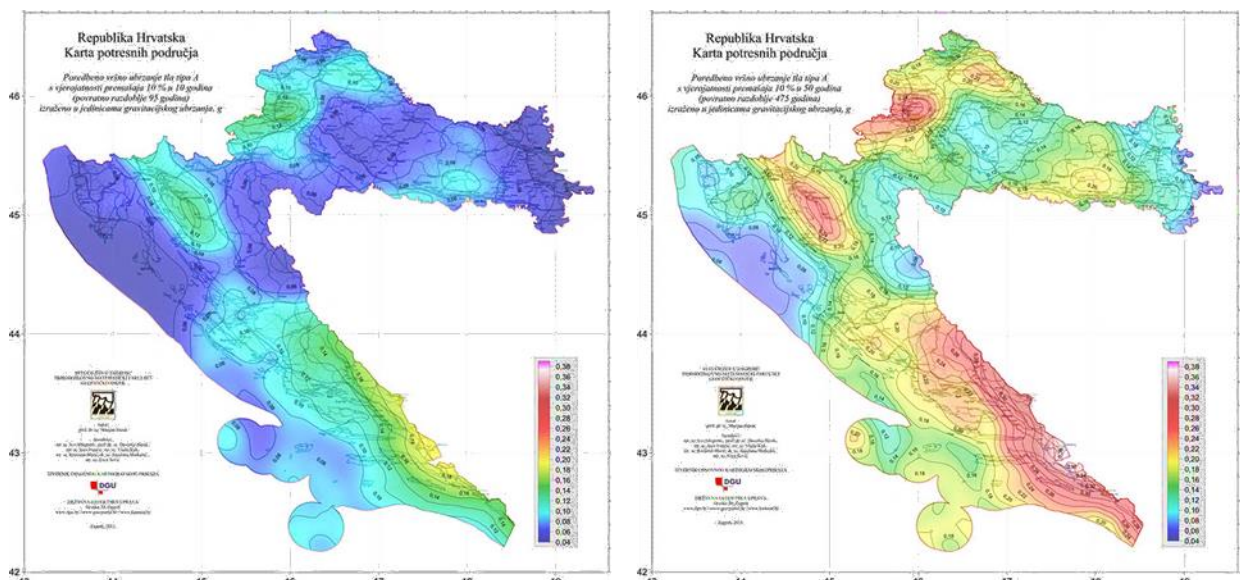


Figure 3.8. Seismic hazard maps of Croatia for 95-year (left) and 475-year (right) return period events (Herak 2011).

Table 3.2. PGA values at different seismic hazard levels for several cities in Croatia (Pavić et al. 2020b).

City Name	1990		2011			
	100 yrs.	500 yrs.	Tr = 95 yrs.		Tr = 475 yrs.	
			Rock	Soil	Rock	Soil
Zagreb	0.081–0.199	0.159–0.388	0.12–0.14	0.168–0.196	0.22–0.26	0.308–0.364
Rijeka	0.081–0.199	0.159–0.199	0.1	0.14	0.18–0.20	0.252–0.28
Split	0.081–0.102	0.159–0.199	0.12	0.168	0.22	0.308
Osijek	0.081–0.102	0.159–0.199	0.04–0.06	0.072–0.108	0.10–0.12	0.18–0.216
Zadar	0.081–0.102	0.159–0.199	0.08	0.112	0.18	0.252

To put things into international perspective, the seismic hazard at Petrinja and Zagreb are compared against three locations in California (Napa, Sacramento, and San Diego) using the PGA seismic hazard curves in Figure 3.9 and the 475 year (10% probability of exceedance in 50 years) uniform hazard spectra in Figure 3.10. The seismic hazard curves and uniform hazard spectra are computed for rock sites by using the seismic hazard tools of the European Facilities for Earthquake Hazard and Risk (EFEHR 2000) for Petrinja and Zagreb and by using OpenSHA (Field et al. 2003) for the selected locations in California.

Referring to Figures 3.9 and 3.10, it is clear that the intensity of the seismic hazard in Petrinja is similar to that of Sacramento, especially when comparing the Design-Basis Earthquake (DBE) uniform hazard spectra in Figure 3.10. San Diego (specifically La Jolla) has a similar hazard curve to the one in Petrinja, however, due to the flat slope of the hazard curve around that portion, the PGA corresponding to 10% probability of exceedance is larger, which is also reflected on the corresponding uniform hazard spectrum. The DBE uniform hazard spectrum at San Diego is similar to the one in Zagreb for short periods at the acceleration sensitive region. The seismic hazard level at Napa, where a M_w 6.0 earthquake occurred on August 24, 2014, is comparatively much larger than that of both Petrinja and Zagreb as observed both in Figures 3.9 and 3.10.

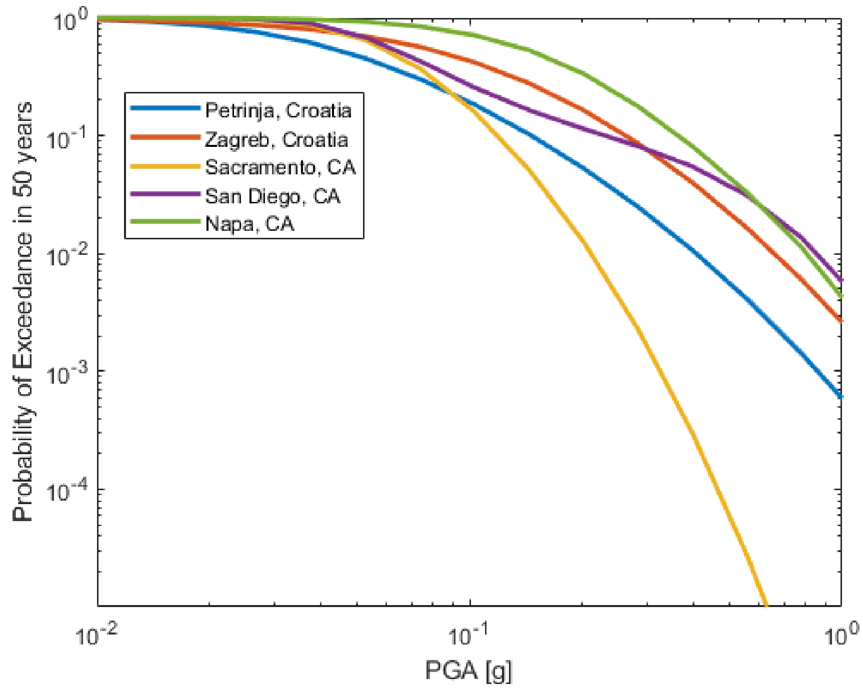


Figure 3.9. PGA hazard curves at Petrinja and Zagreb for a span of 50 years compared with those at three locations in California.

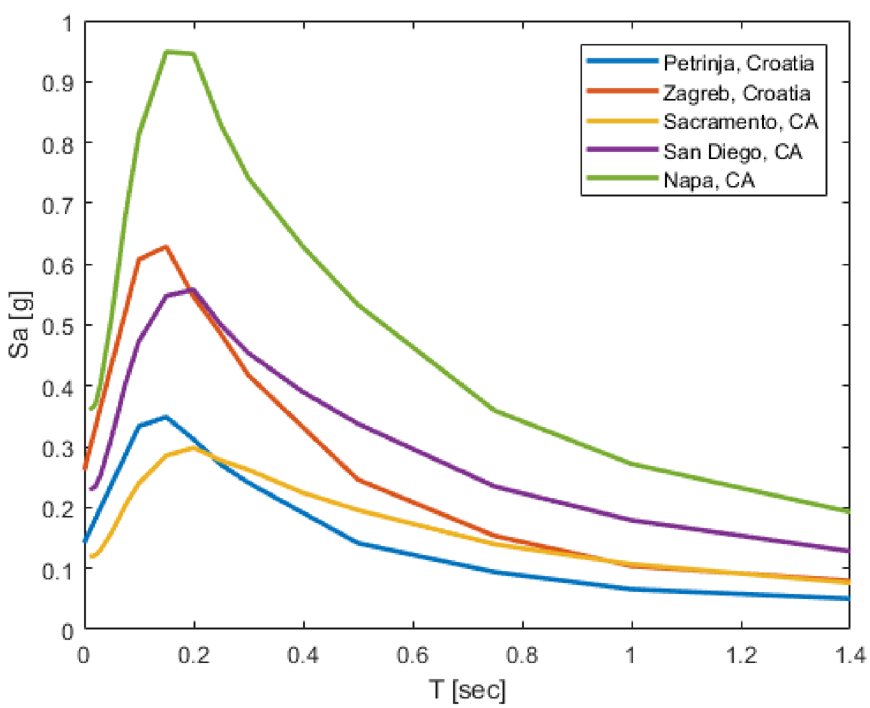


Figure 3.10. Comparison of uniform hazard spectra at Petrinja and Zagreb with several locations in California for the 475-year return period event.

It is noted that the uniform hazard spectra shown in Figure 3.10 are not currently used in the U.S. or Croatia for design purposes. As mentioned, the design spectra used in Croatia are based on Eurocode (CEN 2004), which is computed as a function of PGA that is obtained from the seismic hazard maps shown in Figure 3.8. This is expected to be harmonized with the current approach in the U.S. standards, e.g., ASCE7-16 (ASCE 2016) in the upcoming version of Eurocode 8, which is currently under review. The design spectra specified in ASCE7-16, on the other hand, use the spectral accelerations at the short-period and at 1 sec. Multi-point spectra, similar to the uniform hazard spectra shown in Figure 3.10, are planned to be used in the U.S. starting with ASCE7-22 and ASCE41-23, which are the upcoming versions of these standards.

4.0 Damage to Buildings

The December 29, 2020 Petrinja earthquake affected several thousands of buildings, including residential buildings, schools, hospitals, historical and religious buildings, commercial and industrial buildings. Moreover, widespread damage to nonstructural elements and building contents was quite common. This chapter comprises ten sections and provides a detailed overview of the effects of this earthquake on various building types in several urban and rural communities within the earthquake-affected area. Petrinja, a small town located close to the epicenter, was significantly affected by the earthquake, hence the focus is mostly on this area. A map of downtown Petrinja is shown in Figure 4.1 together with the location of several buildings that are analyzed in this chapter.

Sections 4.1 and 4.2 focus on residential buildings and illustrate the damage of older unreinforced masonry (URM) buildings, which were severely affected by the earthquake (e.g., #1 in Figure 4.1), but also the good performance of modern confined masonry buildings (e.g., #2 in Figure 4.1). Although most of the population in the earthquake-affected area lives in low-rise dwellings, several mid-rise apartment buildings were also subjected to the earthquake, such as a 5-story URM building (#3 in Figure 4.1). Section 4.3 discusses the effect of the earthquake on commercial buildings, such as the KTC supermarket (#4 in Figure 4.1). Section 4.4 discusses healthcare facilities, such as hospitals and health centers (e.g., #5 in Figure 4.1), as well as retirement homes. Section 4.5 discusses educational facilities, including primary and high schools (e.g., #6 and #7 in Figure 4.1, respectively), as well as university buildings. Several government buildings also experienced damage due to the earthquake, such as the Petrinja Town Hall and the Chamber of Crafts building (#8 and #9 in Figure 4.1, respectively), as discussed in Section 4.6. Section 4.7 discusses some historical buildings affected by the earthquake, although several of those are described in various other sections of this chapter (depending on their respective function). Section 4.8 discusses religious buildings, such as the Church of St. Lawrence (Sveti Lovro), the saint protector of Petrinja (#10 in Figure 4.1). Section 4.9 discusses the effect of the earthquake on industrial facilities, such as a timber production facility on the outskirts of Petrinja. Finally, Section 4.10 discusses damage to nonstructural components and building contents, ranging from chimneys and ceiling systems to contents.

Figure 4.1. Map showing downtown Petrinja and several of the buildings discussed in this chapter (source: Google Earth).

4.1 Low-Rise Residential Buildings

This section provides an overview of damage to low-rise residential buildings (either single-family or multi-family buildings), which are the most common form of housing in the earthquake-affected area. These buildings are usually up to two stories high, and very rarely have three stories. The buildings are located in Petrinja, Sisak, and surrounding villages. In two-story buildings, there are often shops or offices on the ground floor level and apartments on the upper floor(s). Single-story buildings are mostly found in rural areas.

Most of the low-rise residential buildings are masonry structures that can be classified into i) earthen construction, ii) URM with flexible wooden floors (constructed before the Second World War), iii) URM with rigid floors (usually composite masonry and concrete systems), and iv) confined masonry with horizontal and vertical reinforced concrete (RC) confining elements. Earthen buildings usually date back to the 19th century and are mostly single-story buildings with thick walls. Figure 4.2 shows typical older URM buildings in Petrinja before the earthquake. It should be noted that, although most of the buildings appear to have been well maintained, some older buildings were in poor condition (dilapidated) before the earthquake. Most of the older masonry buildings (constructed before the 1960s) have walls constructed using solid clay bricks and lime or cement-lime mortar. The walls are usually at least 36 cm thick, mostly due to thermal comfort considerations at the time of the original construction. Exterior walls in most of these buildings have been plastered; in certain cases, the walls were exposed due to poor maintenance prior to the earthquake. Wooden floors are common in older buildings (constructed before the 1960s). Like many other URM buildings in other countries, wall-to-floor or wall-to-roof connections are usually inadequate, with floor or roof structures simply supported by the walls. These buildings have sloped wooden roofs with rafters and purlins and clay tile roofing. Figures 4.3 and 4.4 show typical floor and roof details characteristic for these types of buildings.

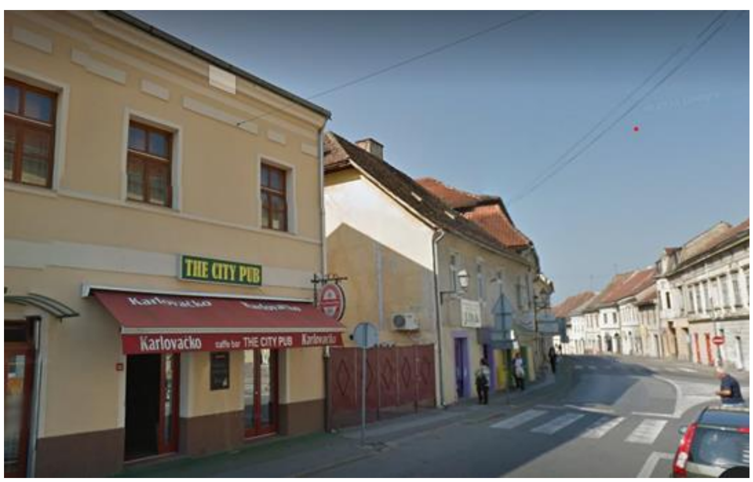


Figure 4.2. Typical older URM buildings in Petrinja (source: Google Earth).

Figure 4.3. Typical wall and floor construction in older URM buildings, characterized by thick clay brick masonry walls, timber floors, and roofs. This building in Petrinja (adjacent to the KTC supermarket) was not significantly damaged in the December 28 M_w 5.2 earthquake but experienced gable wall and roof collapse in the December 29 M_w 6.4 earthquake (source: Joško Krolo).

(a) (b)

Figure 4.4. Details of older URM buildings: (a) floor-to-wall support area exposed due to floor collapse (source: Instagram account go.where.you.feel.most.alive) and (b) wooden roof truss structure with exposed wall-to-roof connection (source: Marko Bartolac).

After the Second World War, the construction of masonry buildings in Croatia was performed according to pertinent national codes. Starting in 1948, a national design code (PTP0 1948) prescribed the provision of horizontal RC tie-beams (ring beams) for masonry buildings in seismic zones. However, it appears that the provision was not followed until 1964, when a more comprehensive seismic design code was issued (PTP 1964). The 1964 code prescribed the application of reinforcement and rigid floors for masonry buildings. The code also restricted building heights. For instance, it allowed the construction of masonry buildings up to 5 stories with horizontal RC tie-beams in seismic zone VIII (and up to 3 stories in zone IX). The 1981 code (PTN 1981) was more relaxed in terms of the required reinforcement provisions in low-rise masonry buildings compared to the 1964 code. For instance, the construction of URM buildings up to 3 and 2 stories was permitted in zones VII and VIII, respectively (but not in zone IX).

Confined masonry construction technology, which is characterized by horizontal and vertical RC confining elements (tie-beams and tie-columns) at prescribed locations in a building, was first introduced by the 1964 code (PTP 1964); however, its application was not mandatory except for buildings that exceeded the height limits set for masonry buildings with horizontal RC tie-beams. The 1981 code contained the following height restrictions for confined masonry buildings: up to 3 stories for zone IX, up to 4 stories for zone VIII, and up to 5 stories for zone VII.

The earthquake-affected area is classified as seismic zone VIII according to the seismic code of 1981 (PTN 1981). Therefore, reinforcement was not required for 1- and 2-story buildings constructed before 2005, but it was required for taller buildings (as discussed above). After 2005, seismic design provisions for masonry buildings were prescribed by Eurocode 8 (CEN 2004), including both URM and confined masonry.

Until the 1970s, most masonry buildings in Croatia were constructed using solid clay bricks, but subsequently, hollow clay blocks started to be widely used and phased out solid clay bricks. Masonry has remained the most common construction technology for low-rise residential buildings to date, and it was also used for the reconstruction of single-family dwellings after the war in the 1990s. Examples of low-rise residential masonry buildings of recent construction are shown in Figure 4.5.

(a) (b)

Figure 4.5. Modern masonry buildings in the earthquake-affected area: (a) two-story confined masonry building before the earthquake (source: Google Earth) and (b) single-story URM building with a rigid floor after the earthquake (source: Nenad Bijelić).

The December 29, 2020 earthquake and its aftershocks affected low-rise masonry housing significantly, and many buildings experienced damage or collapse. Older two-story URM buildings with wooden floors experienced damage or failure of walls due to out-of-plane seismic effects. Excessive horizontal displacements of flexible floors caused these out-of-plane walls to act as vertical cantilevers and experience damage or collapse (toppling). In some cases, wall collapse induced the roof collapse. Figure 4.6 shows collapsed older URM buildings in Petrinja and their appearance before the earthquake.

(a) (b)

Figure 4.6. Collapsed URM buildings in downtown Petrinja (a) before the earthquake (source: Google Earth) and (b) after the earthquake (source: Nenad Bijelić).

In many cases exterior walls at the top floors of buildings with wooden floors and roofs collapsed, as happened in the buildings shown in Figure 4.7.

(a) (b)

Figure 4.7. Out-of-plane failure of walls at the upper portion of buildings with wooden floors and roofs due to flexible diaphragm and the absence of adequate wall-to-floor connections: (a) older 2-story URM building in downtown Petrinja (source: Nenad Bijelić) and (b) rear wall of a 2-story building in Sisak (source: Kristijan Freiberger).

Figure 4.8 shows different stages of out-of-plane failure mechanism, from the development of vertical cracks at wall intersections to cracking in the gable wall.

(a) (b)

Figure 4.8. Out-of-plane damage of masonry walls: (a) vertical cracks (source: Damir Lazarević) and (b) cracking and onset of failure in gable walls (source: Nenad Bijelić).

(a) (b)

Figure 4.9. Performance of gable walls: (a) collapsed gable wall in a partially confined masonry building (with discontinuous RC tie column) and without a RC ring beam along the wall-to-roof interface (source: Sanjin Strukic/Pixel) and (b) good performance of a gable wall in a form of light-weight wooden panel (source: Nenad Bijelić).

Damage of gable walls in URM buildings was observed both in older buildings and in new construction, due to inadequate construction details (Figure 4.9).

Properly constructed confined masonry buildings performed very well in the earthquake, particularly in comparison with URM buildings, as illustrated in Figures 4.10 and 4.11.

(a) (b)

Figure 4.10. Examples of good performance of confined masonry buildings in Petrinja: (a) a two-story confined masonry building remained undamaged while an adjacent older URM building experienced severe damage; and (b) an undamaged single-story confined masonry building (source: Marko Bartolac).

Figure 4.11. Performance comparison between confined masonry and URM buildings in Mečenčani village. The URM building with brick masonry walls (left) experienced damage in the earthquake while a similar confined masonry building (right) remained intact (source: Sonja Zlatović).

Several confined masonry buildings of relatively recent construction (1990s) were damaged during the earthquake. These are single-story buildings with RC floors, sloped roofs, and walls constructed using hollow clay blocks (clay tiles). Several deficiencies were observed in the construction of these buildings. In most cases, these buildings were lacking tie-columns at the corners, which was a major deficiency. Confining elements were provided at the level above the floor slab, and they were effective in reducing damage to the upper portion of the building (attic and roof). However, ground floors experienced significant damage, including crushing of masonry at the corners due to excessive flexural compression and vertical cracking at the wall interface. Inclined (diagonal) cracks were also observed in the piers due to high seismic demand and lack of confining elements. It appears that some of these buildings were constructed during the post-war recovery in the 1990s (Jutarnji List 2021b). Damage patterns observed in these buildings are illustrated in Figures 4.12 and 4.13.

Figure 4.12. Damage of a partially confined masonry building due to the absence of RC tie-columns at the ground floor level (sources: J. Miskovic/Cropix (left) Hrvatska Danas 2021 (right)).

Figure 4.13. Damage of a partially confined masonry building in the Graberje village due to the absence of RC tie-columns at wall intersections. The damage is in the form of wide vertical cracks along the wall intersection and stepped shear cracks expanding from the ground to the second floor slab (source: Hrvoje Ljubojević, Tenzor d.o.o).

The ground floor of a 2-story masonry building in Prekope village collapsed, as shown in Figure 4.14. This is an example of a building with a vertical extension. The ground floor was constructed as an URM construction (solid clay bricks) whereas the upper floor was a partially confined structure constructed at a later stage. The photos show that the upper floor had a vertical confining element at the left corner, but was lacking such element at the other corner. It is interesting to observe that an adjacent unreinforced single-story masonry building did not experience any damage. Poor performance of this building can be attributed to the use of different masonry materials (i.e., bricks and hollow clay blocks) and construction technologies (unreinforced and confined masonry) at different floors.

(a) (b)

Figure 4.14. Collapsed partially confined masonry building in Prekope village, close to Glina (sources: (a) Damir Sencar AFP Getty and (b) Krešimir Micić).

The main causes of damage and failure in low-rise residential buildings can be summarized as follows:

1. Out-of-plane damage or failure of exterior masonry walls at the upper/top floors of older URM buildings (constructed before the Second World War) were caused by excessive lateral displacements of flexible wooden floors. In most cases, these walls acted as vertical cantilevers due to inadequate wall-to-floor and wall-to-roof connections, and were prone to collapse due to out-of-plane inertial forces. In some instances, wall failures triggered roof failure.

2. Masonry buildings of more recent construction have rigid floors, but also experienced damage due to the absence of vertical reinforcement at the ground floor level. The in-plane damage pattern was in the form of diagonal tension cracks in the walls due to excessively high seismic demand. Earthquake-induced principal tensile stresses in the walls exceeded the masonry tensile strength and caused the development of inclined cracks (diagonal tension cracks). The quality of masonry materials and construction appears to be inadequate in some cases, and is also a cause of damage.

3. Vertical cracks along the wall intersections in URM buildings with rigid floors were caused by out-of-plane seismic effects and insufficient overall integrity (box action) of the building.

4. Partially confined masonry buildings, with URM walls at the ground floor and RC tie-columns at the upper floor, experienced damage that is characteristic of URM buildings. This is expected, since the provision of RC confining elements at the ground floor level is critical for satisfactory seismic performance.

5. Damage or collapse of gable walls in confined masonry buildings was caused by inadequate construction details, e.g., absence of inclined RC tie-beams along the wall-to-roof interface and/or intermediate RC tie-columns extended up to the roof level.

4.2 Multi-Family Residential Buildings

This section provides an overview of the seismic performance of mid-rise apartment buildings. Most of these buildings were constructed after World War II, either as individual buildings in urban areas or within settlements which were systematically developed as urban development projects after the 1960s. However, it should be noted that older mid-rise apartment buildings also exist in the earthquake-affected area. In most cases, these buildings were originally owned by one family, but over time they were converted into multi-family residential buildings. These are URM buildings with wooden floors and roofs, and their structural features and damage patterns are similar to the low-rise residential buildings described in Section 4.1. Figure 4.15 shows the collapse of exterior walls at the top floors of a 4-story building in Petrinja and the appearance of the facade prior to the earthquake (see Figure 4.15a).

(a)

(b)

(c)

Figure 4.15. Collapse of exterior walls at the upper portion of a building in Petrinja: (a) before the earthquake (source: Google Earth), (b) damaged condition after the earthquake (source: Aeroklub Petrinja drone footage), and (c) detail of the exposed building interior and roof structure (source: Getty).

Several low- to mid-rise apartment buildings in the epicentral area were also affected by the earthquake, particularly in Petrinja and Sisak; however, the earthquake also affected buildings in Zaprešić, which is located approximately 50 km away from the epicenter. Typically, these are mid-rise buildings (up to five stories high). Until the 1960s URM buildings with rigid floors were widely used for the construction of apartment buildings. Subsequently, RC frames with masonry infills were used. These multi-family (apartment) buildings are up to 5 stories high and do not have elevators (according to the building code elevators had to be installed for buildings with more than 5 stories). Apartment buildings constructed before 1964 (when the first seismic code was published) were not designed using seismic provisions. Confined masonry construction technology was introduced in the 1960s and was required for buildings with more than one story by the 1964 code.

A 3-story apartment building located near the marketplace in Petrinja, an area where several low-rise URM buildings experienced heavy damage or collapse, is shown in Figure 4.16 (facade view in longitudinal direction). The building, which was probably constructed in the 1960s, had rigid floors and clay brick masonry walls (approximately 230 mm thick). The building experienced shear cracks in the walls at the ground floor level that were caused by high in-plane seismic demand and excessively high tensile stresses. The most extensive damage was observed at the right end of the building, where the connection between the longitudinal and transverse walls failed, causing crushing and falling out of masonry; this can be explained by inadequate structural integrity characteristic for URM buildings, and could have been prevented had RC tie-columns been provided.

Figure 4.16. Damage in a 3-story residential building in Petrinja (source: Marko Bartolac).

A five-story apartment building at Vladimira Nazora Street in Petrinja is an example of an older apartment building that was affected by the earthquake (Figure 4.17). Based on the architectural style, it appears that the building was constructed in the 1960s, hence it was most likely designed without any seismic provisions. This is the tallest building in downtown Petrinja and is located close to several damaged two-story URM buildings. The building has a rectangular plan with a length of 25 m and a width of 15 m (approximately). It is a load-bearing wall structure with brick masonry walls and rigid floor and roof slabs. A few RC columns were constructed at the ground floor level, which was intended for commercial use. There is also a passage for vehicles, which causes a decrease in strength and stiffness at the ground floor level and can be characterized as a vertical irregularity. At the rear side there is an adjacent single-story building and another adjacent two-story URM building at the street level. Based on a survey of the building exterior, it was observed that wide in-plane shear cracks developed in the transverse direction at the ground floor level.

Figure 4.17. Five-story apartment building in the center of Petrinja (source: Nenad Bijelić and Marko Bartolac).

A few apartment buildings were severely damaged in Zaprešić, located approximately 50 km from the epicenter (Jutarnji List 2020c). These are URM buildings constructed in the 1960s with brick masonry walls and rigid floors and roofs. The buildings are shown in the map in Figure 4.18. Buildings 1 to 3 are identical, except for a slightly different orientation, as seen in the map. These buildings have an L-shaped plan view and consist of two separate wings connected by a steel staircase. Note that the floors in the connected wings are offset in terms of elevation (Figure 4.19). One wing has a covered terrace at the top with the roof slab supported by columns on one side and by L-shaped walls on the other. Severe damage was observed in the walls at the top floor level of Building 2 (Figure 4.20). This can be explained by high spectral accelerations, compounded by an absence of vertical confinement or stabilizing flanges at the wall ends. Identical patterns of in-plane shear cracking were observed at the ground floor level in Buildings 1 and 2. Building 4 has a rectangular plan shape and 5 stories plus a vertical extension – the top story was added after the original construction was completed. The building experienced in-plane shear cracking in the transverse direction at the ground floor level (a similar pattern to that observed in Buildings 1 and 2) (Figure 4.21). It appears that other buildings in the vicinity of these 4 buildings did not experience significant damage, including an adjacent single-story URM building and some 10-story-plus high-rise buildings (Figure 4.22). The damage can be explained by low frequency content of the ground motions at this site.

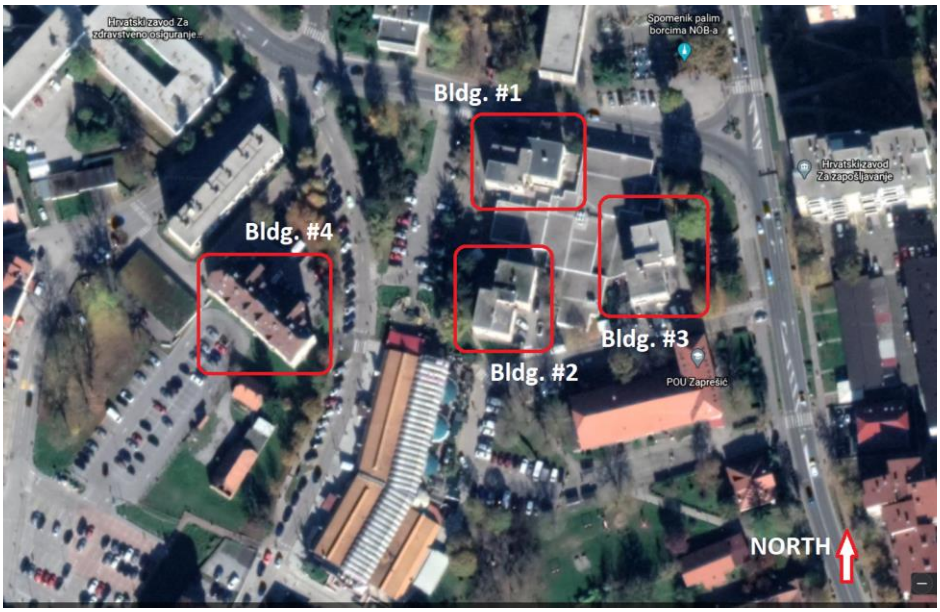


Figure 4.18. Map of four damaged buildings in Zaprešić (source: Google Earth).

Figure 4.19. Damaged Building 3: exterior view and cracking pattern at the ground floor level (source: Nenad Bijelić).

Figure 4.20. Extensive cracking experienced at the roof/terrace level of Building 2 (source: Nenad Bijelić).

Figure 4.21. Damage to Building 4, a 5-story building with a vertical extension (source: Marko Bartolac).

(a) (b)

Figure 4.22. Undamaged buildings in the same neighborhood of Zaprešić: (a) a single-story URM building adjacent (within a 10-m distance) to Building 4 (source: Marko Bartolac) and (b) 10-story-plus high-rise apartment buildings (source: Google Earth).

Mid-rise RC apartment buildings performed well during the earthquake. Figure 4.23 shows a 5-story RC building in the "Brzaj" settlement in Sisak that was constructed in 1986. RC structural walls are the main elements of the lateral load-resisting system in this building. It can be seen from the figure that the building did not experience any visible structural damage. However, the buildings in the same settlement experienced nonstructural damage due to collapsed chimneys (Figure 4.24).

Figure 4.23. Buildings with RC structural walls that did not experience any damage, "Brzaj" settlement in Sisak (source: Maja Freiberger).

Figure 4.24. Removal of the chimneys from the roof of an RC building, "Brzaj" settlement in Sisak (source: Maja Freiberger).

In general, mid-rise residential buildings were less severely affected by the earthquake compared to low-rise buildings. The main causes of damage and failure of these buildings can be summarized as follows:

1. Out-of-plane damage or failure of exterior masonry walls at the upper/top floors of older URM buildings (constructed before World War II) were caused by excessive lateral displacements of flexible wooden floors. In general, this failure mechanism is very similar in low-rise and mid-rise buildings.

2. In many instances, older URM buildings were not adequately maintained, and as a result their condition was poor before the earthquake. It is believed that the deterioration of construction materials and components (such as wooden floors and roofs) and the use of weak mortar also influenced the extent of damage.

3. Masonry buildings with rigid floors constructed in the 1960s experienced in-plane shear cracking at the base of the building due to excessively high seismic demand. Earthquake-induced principal tensile stresses in the walls exceeded the masonry tensile strength and caused the development of inclined cracks (diagonal tension cracks). This damage pattern was observed both in the epicentral area (e.g., Petrinja) and areas further away from the epicenter (e.g., Zaprešić).

4. Reinforced concrete buildings did not experience structural damage due to the earthquake; however, minor damage of nonstructural components, such as chimneys, occurred in some buildings.

4.3 Commercial Buildings

In Zagreb, there was little reported damage to store fronts. For example, Figure 4.25 shows a view looking east on Ilica Street in Zagreb, a large shopping area. Although fallen façades can be seen in the photo, there was no damage to glass store fronts.

Figure 4.25. Photo taken looking east on Ilica Street in Zagreb showing fallen debris (source: Santora and Orovic, 2020).

Damage was reported at the KTC supermarket, an RC structure located in downtown Petrinja, which is shown in Figure 4.26. There was damage to the hung ceiling assembly (Figure 4.27) and products fell off shelves (Figure 4.28); however, structural damage was not documented nor reported. The building also has an elevator that did not lose functionality due to the earthquake.

Figure 4.26. KTC supermarket in Petrinja before the earthquake (source: Google Maps).

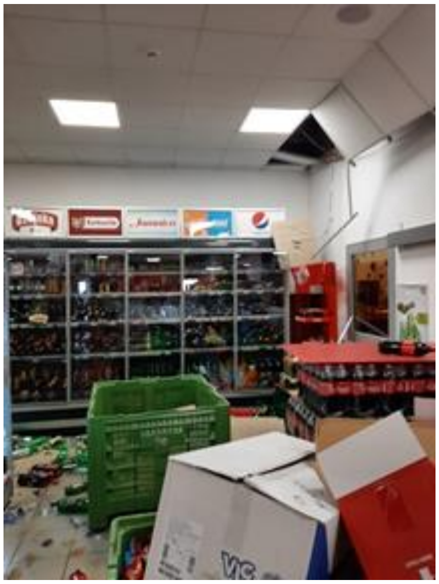


Figure 4.27. Damage to hung ceiling assembly in the KTC supermarket (source: Sonja Belovarac Radenovic).

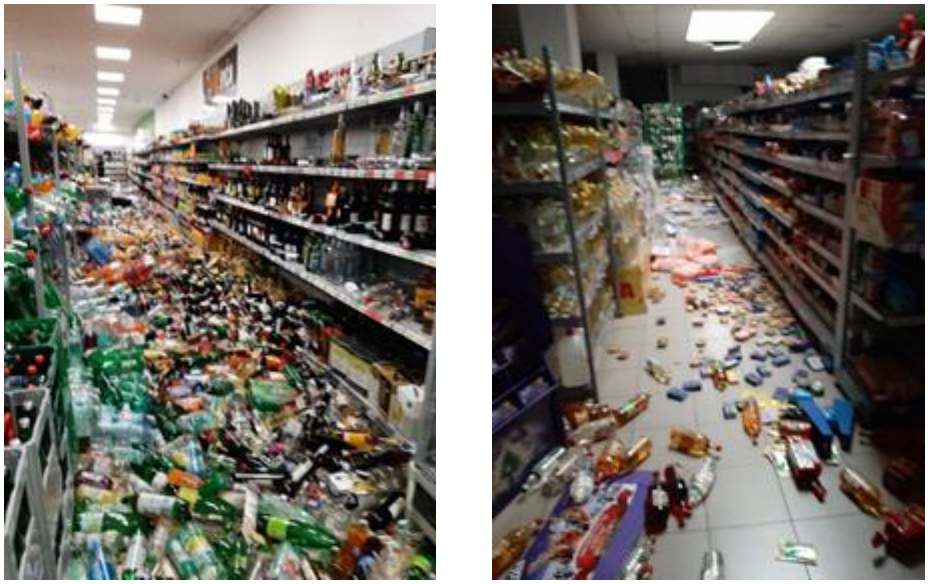


Figure 4.28. Products on the floor of the KTC supermarket due to the earthquake (source: Sonja Belovarac Radenovic).

4.4 Healthcare Facilities

This section provides an overview of the damage to three healthcare facilities: a retirement home and a health center in Petrinja, and the General Hospital of Sisak. Healthcare facilities are critically important after disaster events, and particularly important given the COVID-19 pandemic that was ongoing during this earthquake sequence, which had already significantly impacted the population physically and psychologically.

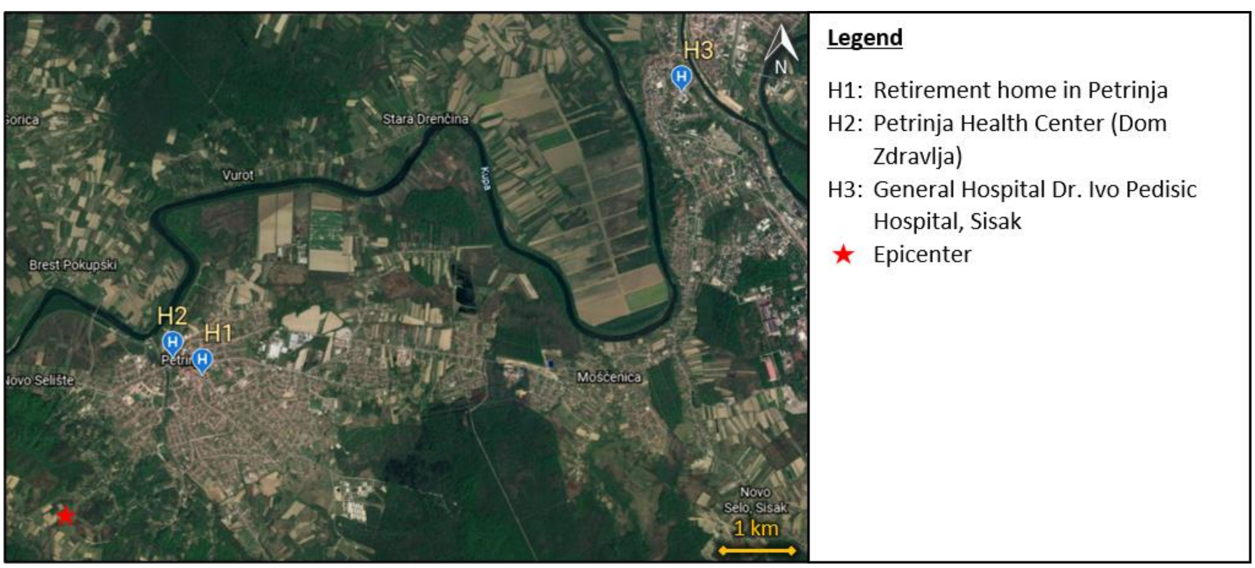


Figure 4.29. Location of the healthcare facilities discussed in this report (source: Google Earth).

4.4.1 Retirement home in Petrinja

The retirement home in Petrinja is located at Trg Narodnih učitelja 7 and is shown in Figure 4.30 before the earthquake. This four-story building consists of RC moment resisting frames with masonry infills. The plan view, which consists of two rectangular sections with dimensions 40.4 m x 18.3 m and 35.8 m x 20 m, is shown in Figure 4.30.

Figure 4.30. Retirement home in Petrinja: outside view (left) and dimensions in plan (right) (source: Google Earth).

The observed damage in the retirement home was mostly to nonstructural elements such as interior masonry infills and partition walls, hung ceilings, tiles on the walls, and tiles on the floors. Shear cracks in masonry infill walls are common due to the stiffness and deformation incompatibility of the infills with the reinforced concrete frame. Several of these cracks occurred throughout the retirement facility in Petrinja. Figure 4.31 shows diagonal shear cracks originating from the corners of the windows in the infill walls of a hallway. Along the length of the hallway, large shear cracks originated from the corners of doorways and propagated through the single wythe partition walls, made of hollow clay blocks, as shown in Figure 4.32. Cracks along the interface between a masonry infill wall and a reinforced concrete column are seen in Figure 4.33. Besides large diagonal shear cracks in the plaster, cracks at the end of RC beams also occurred (Figure 4.34). Damage to other nonstructural components was also observed, such as hung ceiling assemblies in the form of exposed piping and fasteners for the hung ceiling (Figure 4.35) and cracks in wall and floor tiles (Figure 4.36).

Figure 4.31. Shear cracks in infill masonry walls of the retirement home in Petrinja (source: Damir Lazarević).

Figure 4.32. Damage to partition wall in the retirement home in Petrinja (source: Damir Lazarević).

Figure 4.33. Cracks along the interface between a masonry infill and an RC column (source: Damir Lazarević).

Figure 4.34. Damage to a reinforced concrete beam in the retirement home in Petrinja (source: Damir Lazarević).

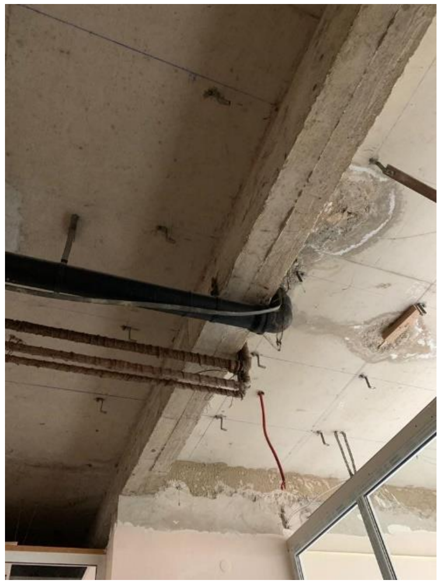


Figure 4.35. Exposed piping and fasteners for the hung ceiling (source: Damir Lazarević).

Figure 4.36. Cracks in the floor tiles (left) and tiles detached from the kitchen walls (right) (source: Damir Lazarević).

4.4.2 Petrinja Health Center (Dom Zdravlja)

The health center in Petrinja (Dom Zdravlja) was heavily damaged by the earthquake. The building, shown in Figure 4.37 before the earthquake, has a clay tile roof and stucco façade. Due to the level of earthquake damage, the health center shut down and no one was allowed inside, including engineers who wanted to inspect the damage. All of the medical equipment and supplies were left inside the building.

Figure 4.37. Outside view of the health center in Petrinja before the earthquake, showing its clay tile roof and stucco facade (source: Google Earth).

Figure 4.38 shows large shear cracks through the exterior walls of the building and large cracks at the interface of what is assumed to be masonry infill and a reinforced concrete frame. These cracks have a significant width, which could contribute to prevent reoccupation of the building, even to retrieve critical medical equipment.

Figure 4.38. Photos showing the exterior of the health center in Petrinja with large shear cracks in the exterior walls (source: Domagoj Damjanović).

4.4.3 General Hospital Dr. Ivo Pedisic, Sisak

The General Hospital Dr. Ivo Pedisic located in Sisak has a capacity of 408 beds and provides attention to approximately 1,000 patients daily (Croatia Week 2021, Jan 5). This hospital complex has several buildings with a wide range of dimensions in plan, heights, construction materials, structural configurations, and building ages. For example, the Internal Medicine building is shown in Figure 4.39. A plan view of the complete hospital complex is shown in Figure 4.40 and Table 4.1 summarizes the condition of each building after the earthquake. Several patients from the damaged buildings needed to be re-accommodated, while all COVID-19 patients were transferred to hospitals in Zagreb.

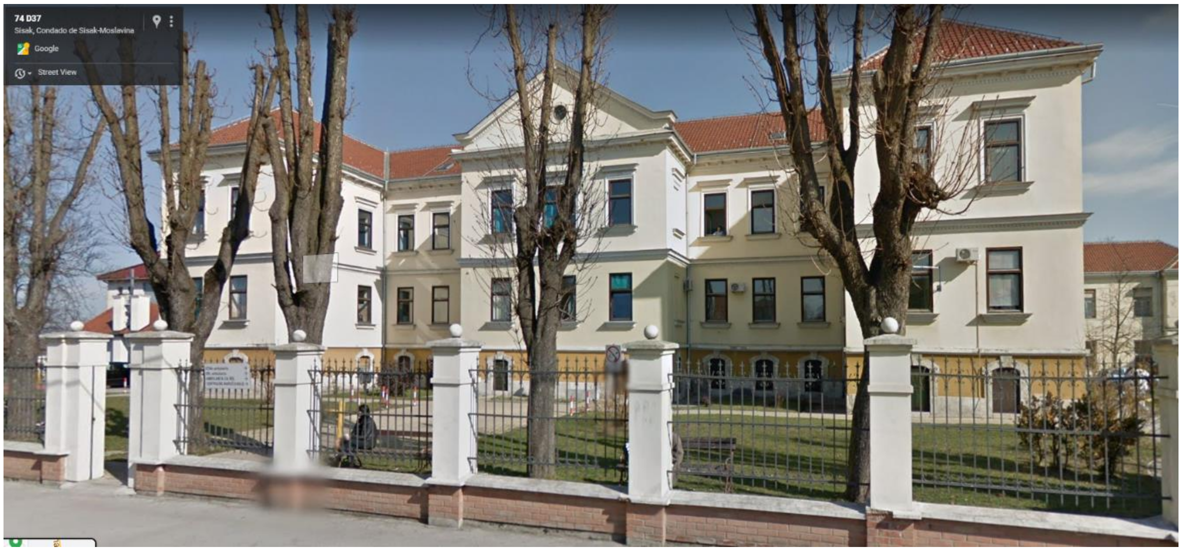


Figure 4.39. Internal Medicine building of the General Hospital Dr. Ivo Pedisic in Sisak before the earthquake (source: Google Earth).

Figure 4.40. Plan view of the Dr. Ivo Pedisic General Hospital in Sisak. Buildings are enumerated for damage reporting purposes (source: Google Earth).

Table 4.1. Condition of each building in the Dr. Ivo Pedisic Hospital after the earthquake.

Bldg. #	Description	Condition after earthquake
1	Pediatrics, Neurology, Ophthalmology and Laboratory	1st floor and lower level operational. 2nd and 3rd floor, temporarily non-operational. Failures of heating pipes
2	Internal Medicine	Non-operational, Failure of water pipes
3	Gynecology and Obstetrics	Operational, Failure of heating station
4	Administration	Non-operational
5	Surgery	Operational, Failure of sterilization device
6	Internal Medicine	Non-operational, Failures of heating pipes
7	Under construction.	-
8	Cytology	Temporarily non-operational
9	IT services	Operational
10	Pathology	Operational
11	Psychology (outpatient)	Operational
12	Clinic for Eyesight	Operational
13	Boiler Room	Operational
14	Entrance (security)	Operational
15	Oxygen storage	Operational
16	Technical Services and Procurement	Operational
17	Laundry	Operational
18	Waste Management	Operational
19	Dialysis	Operational

Building #1 (Pediatrics) has three-stories and it consists of RC moment resisting frames with masonry infills and approximate plan dimensions of 53 m by 15 m. As shown in Figure 4.41, masonry infills presented cracks with horizontal and diagonal patterns, usually due to incompatibility between the deformation capabilities of concrete and masonry. Damage also occurred in the elevator shafts and stairs. The 2nd and 3rd floor of this building were declared unusable due to this damage.

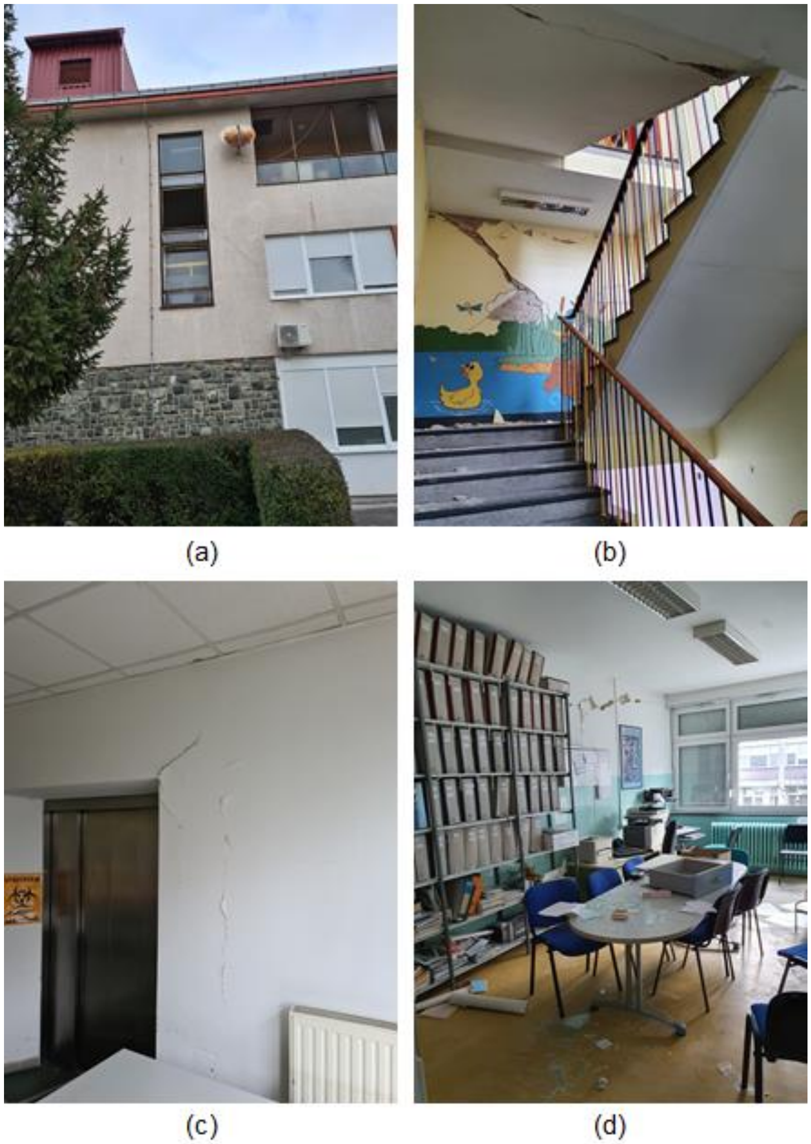


Figure 4.41. Building #1: (a) external view, (b) diagonal cracks in masonry infills, (c) cracks near elevator shafts, and (d) horizontal cracks along masonry-concrete joints (source: Nenad Bijelić).

Building #2 (Internal Medicine) is an old C-shaped three-story RC and masonry building with main plan dimensions of 42 m by 17 m. The roof of this building partially collapsed, as shown in Figure 4.42. The building also presented massive cracking in different areas and was, therefore, declared unusable.

(a) (b)

Figure 4.42. Building #2: (a) front view and (b) back view (source: Croatia Week 2021, Jan 5).

Building #4 (Administration) is an old rectangular three-story RC and masonry building with approximate plan dimensions of 25 m by 10 m. It presented cracking with different geometric patterns and fallen stucco facades, as shown in Figure 4.43, and was also declared unusable.

(a) (b)

Figure 4.43. Building #4: (a) front view, and (b) back view (source: Nenad Bijelić).

Building #5 (Surgery) is a seven-story RC structure with plan dimensions of approximately 63 m by 14 m. The building exhibited different types of damage, including construction joint openings, tiles detaching, fallen ceiling tiles, and broken windows, some of which are presented in Figure 4.44. The sterilization equipment was also damaged. However, the building remained operational.

Figure 4.44. Building #5: (a) Outside view, (b) joint opening, (c) concrete wall cracking, and (d) fallen ceiling tiles (source: Nenad Bijelić).

4.5 Schools

There are a total of 53 schools in Sisak-Moslavina County, which include 37 primary, 13 secondary, and three music schools. These schools house 14,705 students. Due to the earthquake, five of these schools require complete reconstruction, nine were significantly damaged, and 13 will require minor repairs of their nonstructural components. The Minister of Science and Education, Radovan Fuchs, said that 3,489 students do not have a school to attend in Sisak and 1,843 do not have a school in Petrinja (Pauković 2020a, 2020b). This section discusses the damage observed in the eight schools shown in Figure 4.45.

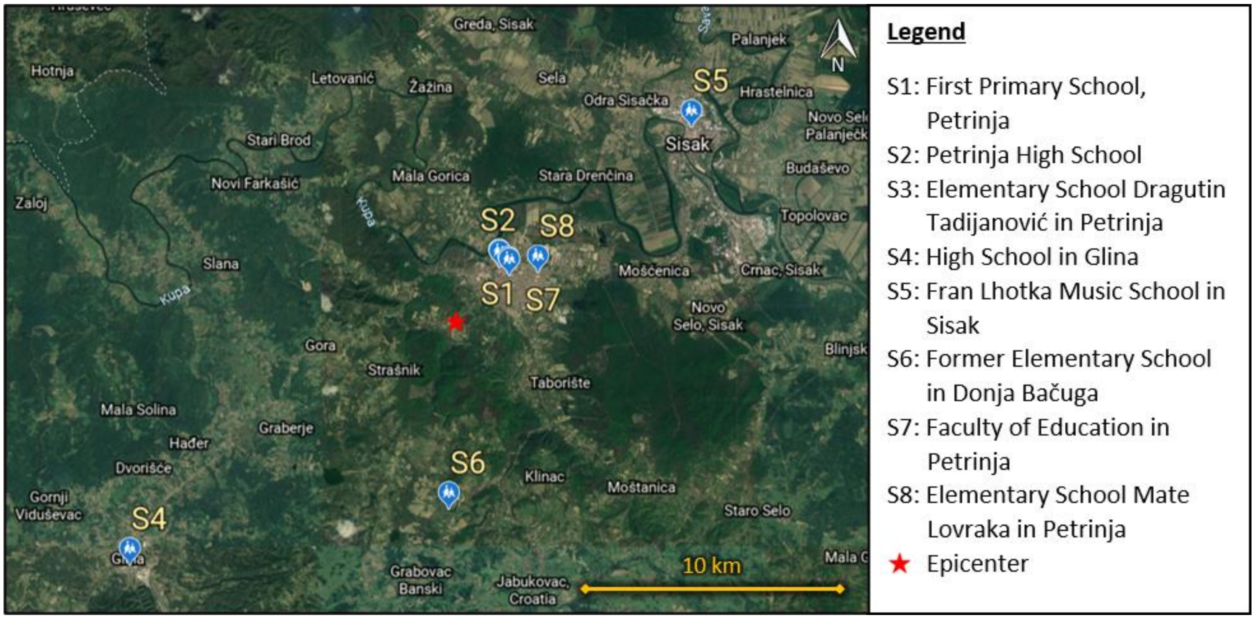


Figure 4.45. Location of schools discussed in this report (source: Google Earth).

In Petrinja, the First Primary School and High School suffered partial collapses. The other schools in the Sisak-Moslavina County that will require complete reconstruction are the Fran Lhotka Music School in Sisak, the Sisak Vocational School, the Farkašić and Letovanić Regional Schools of the Mladost Primary School in Lekenik, the Ivan Goran Kovačić Primary School in Gora, and the Nebojan Regional School (Pauković, 2020a).

Schools in Zagreb did not experience significant damage and their students will return to in-person classes on January 18, after the winter break (Pauković 2020a). However, some schools that were not yet repaired from the March 2020 earthquake, such as the Women's General Gymnasium, experienced additional damage due to the December earthquakes.

4.5.1 First Primary School, Petrinja

The First Primary School in Petrinja was originally built around 1860; however, it may have been expanded over time. The school is a U-shaped building, as shown in the plan view of Figure 4.46. The structural system of the building consists of URM walls and jack arch slabs. The roof is timber-framed with clay tiles and partially collapsed after the earthquake, as shown in Figure 4.47.

Figure 4.46. First Primary School in Petrinja: outside view before the earthquake (left) and U-shape plan view with dimensions (right) (source: Google Earth).

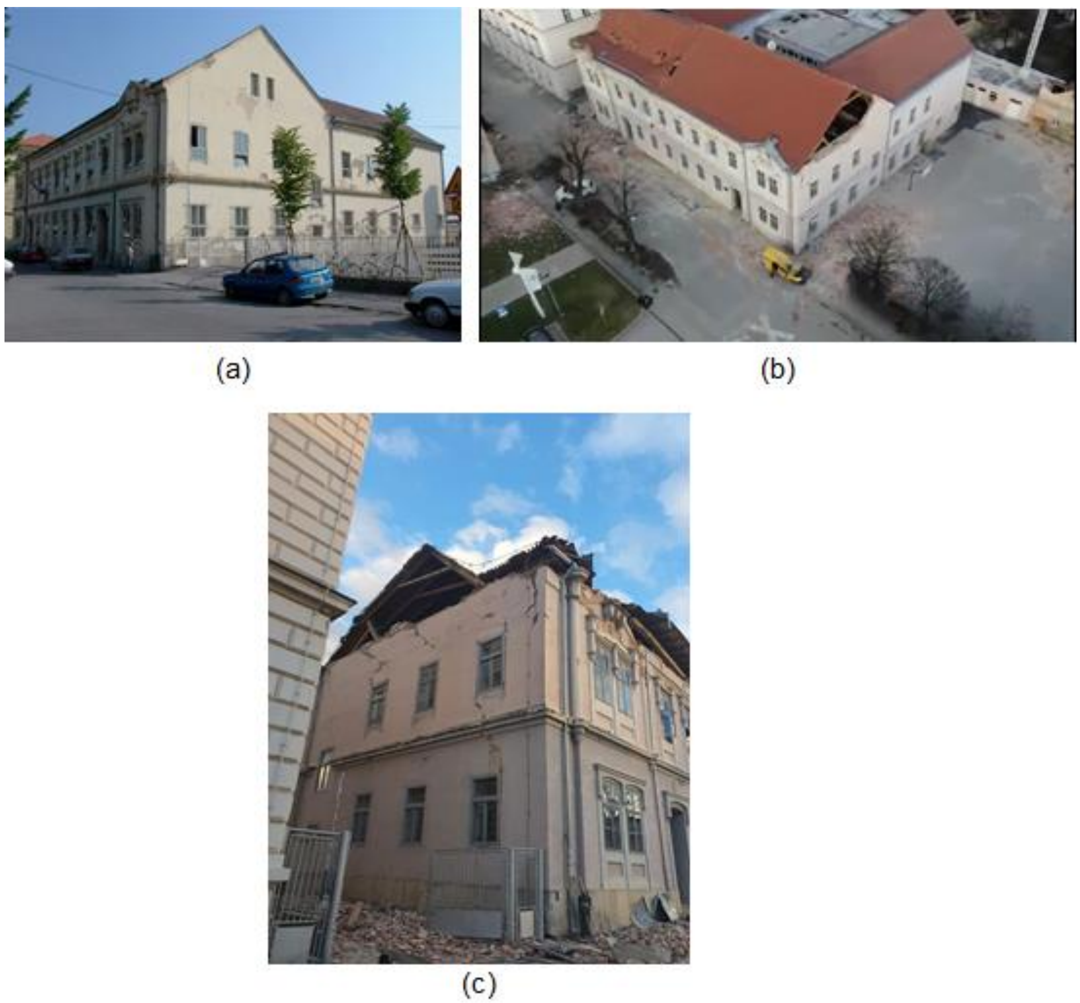


Figure 4.47. Exterior damage to the Primary School in Petrinja: exterior view (a) before and (b) after the earthquake, and (c) damage to the timber-framed roof, where masonry from the gable fell to the street (sources: (a) Google Earth; (b) Twitter 2021a and c) Nenad Bijelić).

The First Primary School in Petrinja also experienced significant nonstructural damage, especially to interior partition walls, which were apparently constructed recently. These walls are hollow clay tiles, as shown in Figure 4.48a. The observed damage included partial or total collapses likely due to out-of-plane seismic effects and the lack of connection between the walls and the floor structure, such as seen, for example, in Figure 4.48a where the tile fell out of the wall. Some cracks were also observed at the interface of the wall tiles and structural elements, as shown in Figures 4.48b and 4.48c. Moreover, a water pipe was damaged causing water leakage, which can be seen in Figure 4.49.

(a) (b) (c)

Figure 4.48. Interior damage to the First Primary School in Petrinja: (a) partial collapse of an interior partition wall showing its hollow clay tile construction, (b) damage to the interior walls, and (c) shear crack propagating from the corner of the window opening, highlighting the brittle nature of the construction (source: Nenad Bijelić).

(a) (b)

Figure 4.49. Leaking water pipe in the First Primary School in Petrinja: (a) water on the floor and (b) broken water pipe (source: Nenad Bijelić).

4.5.2 Petrinja High School

The Petrinja High School was originally built around 1860 and likely received several modifications and additions over time. The high school building, shown in Figure 4.50, has URM walls, jack-arch floors, and its roof has hollow clay tiles similar to those in the First Primary School located next door. While Petrinja High School did not collapse, reports from the principal of the High School indicate that the building has interior damage that requires repairs prior to re-occupation by staff and students. As shown in Figure 4.51b there is a shear crack on the outside of the building on the transverse wall and localized damage above the windows. Figure 4.52 shows the longitudinal wall that is parallel with the street. There are also cracks in the façade above the windows that are rather small in comparison to the total wall area, thus experiencing just localized wall damage. A possible explanation for having more damage in the transverse direction is that the building has fewer walls in the transverse direction than in the longitudinal direction. Another possible explanation is that the transverse direction of the high school seems to be parallel to the fault normal direction of the Petrinja Fault whereas the longitudinal direction of the high school seems to be parallel to the fault parallel direction.

After the earthquake that happened on December 28, there was only minor damage in the interior of the building (Figure 4.53a). However, the earthquake of December 29 caused significant cracking to the structural walls and damage to the floor/wall contacts (Figure 4.53b).

Figure 4.50. Petrinja High School before the earthquake (source: Google Maps).

Figure 4.51. Transverse wall of Petrinja High School (a) before the earthquake (source: Google Street View) and (b) after the earthquake (source: Nenad Bijelić).

(a) (b)

Figure 4.52. Longitudinal wall of Petrinja High School (a) before the earthquake (source: Google Street View) and (b) after the earthquake (source: Nenad Bijelić).

(a) (b)

Figure 4.53. Interior of Petrinja High School: (a) minor damage caused by the December 28 earthquake (source: Domagoj Damjanović) and (b) significant damage caused by the December 29 earthquake (source: Marko Bartolac and Nenad Bijelić).

4.5.3 Elementary School Dragutin Tadijanović in Petrinja

Unlike the First Primary School, the Elementary School Dragutin Tadijanović in Petrinja (Figure 4.54) only experienced minor damage to structural components. The building consists of RC moment-resisting frames with masonry infill walls, as evidenced in Figure 4.55 and 4.56. In the former the plaster is completely detached from the wall. A significant number of cracks were observed at the intersection of the masonry infill walls and the RC frame, as shown in Figure 4.56. Several infill walls experienced this type of cracking, especially between RC beams and the top of infill walls (Figure 4.56). Furthermore, some items fell off shelves and out of cabinets, as shown in Figure 4.57. No other type of nonstructural damage was observed throughout the school.

Figure 4.54. Elementary School Dragutin Tadijanović in Petrinja before the earthquake (source: Google Earth).

Figure 4.55. Plaster fell off of the wall exposing masonry infill (source: Nenad Bijelić and Damir Lazarević).

Figure 4.56. Cracks forming at the contact between reinforced concrete frames and masonry infills (source: Nenad Bijelić and Damir Lazarević).

Figure 4.57. Items that fell off shelves and out of cabinets (source: Nenad Bijelić and Damir Lazarević).

The sports hall of the school features RC moment resisting frames with infill walls and a roof constructed of light-gage steel joists with a timber roof deck, which is shown in Figure 4.58. No damage was observed in structural elements in this area of the school.

Figure 4.58. Sports hall at Elementary School Dragutin Tadijanović in Petrinja (source: Nenad Bijelić and Damir Lazarević).

4.5.4 High School in Glina

The Glina High School experienced damage to interior walls, as documented through the Facebook page of the school. Figure 4.59 shows the high school before the earthquake and Figure 4.60 shows damage to interior partition walls due to the earthquake. At this stage, it is not clear whether there was structural damage.

Figure 4.59. Glina High School before the earthquake (source: Google Maps).

Figure 4.60. Earthquake damage in Glina High School (source: Facebook Page - Srednja škola Glina).

4.5.5 Fran Lhotka Music School in Sisak

The building that houses the Fran Lhotka Music School in Sisak was originally a synagogue constructed around 1880 and converted into a music school in 1967 (Terbovc 2021). The building is shown before the earthquake in Figure 4.61a and after the earthquake in Figure 4.61b, which shows out-of-plane failure of the masonry in the gable. This masonry fell on top of cars parked in front of the building. There were no reports of casualties due to damage to this building. The interior of the building experienced damage to nonstructural components such as decorative ceiling and instruments, as shown in Figure 4.62. From this photograph, it appears that the floor diaphragms are made of timber and the walls are constructed of masonry.

The building represents the architectural style of the famous Viennese architect Ludwig von Förster (Terbovc 2021). The building is not protected as a cultural asset of Croatia. During the conversion of the building from a synagogue to a music school, the interior of the building received a large renovation. The school is located within the central park/square of Sisak and brings awareness to the contribution of the Jewish community within the town (Terbovc 2021).

(a) (b)

Figure 4.61. Fran Lhotka Music School (a) before the earthquake (source: Google Maps) and (b) after the earthquake (source: Facebook page - Glazbena škola Frana Lhotke, Sisak).

Figure 4.62. Photo taken inside of the Fran Lhotka Music School (source: Roberts 2020).

4.5.6 Former Elementary School in Donja Bačuga

Damage to a former elementary school in Donja Bačuga was only observed from the outside (the reconnaissance team did not go inside). The building is now the Center for Plum and Chestnut, a public institution for continuing education focused on fruit growing and eco-agriculture. The damage included the brick facade falling off (Figure 4.63), broken glass at the entrance doors (Figure 4.64), and shear cracks to the exterior RC columns due to the column/infill interaction causing “short column” effects (Figure 4.65).

Figure 4.63. Brick facade detached from building (source: Nina Čeh).

Figure 4.64. Broken glass in entryway door (source: Nina Čeh).

Figure 4.65. Shear cracks to exterior RC columns (source: Nina Čeh).

4.5.7 Faculty of Education in Petrinja

The Faculty of Education in Petrinja, shown in Figure 4.66, was built in 1962 and is an RC building with masonry infill walls. No significant damage was observed from the outside; however, widespread damage occurred in interior infill walls. Several walls experienced complete detachment of the plaster, which fell down causing damage to building contents (Figure 4.67). In-plane loading on infill walls due to RC frame deformation caused damage in the form of diagonal cracks, which can be seen in Figure 4.68. This figure also shows overturned shelves and fallen items. Horizontal cracks were also observed at the contact between masonry infill walls and RC beams (Figure 4.69). Due to in-plane/out-of-plane interaction, several infill walls experienced high out-of-plane displacements (Figure 4.70). Some infill walls were heavily damaged with significant gapping in head joints (Figure 4.71). Severe collapse of the ceiling in one of the classrooms in the faculty building is shown in Figure 4.110 (see Section 4.10.1).

Figure 4.66. Faculty of Education before the earthquake (source: Google Earth).

Figure 4.67. Plaster detached from the wall (source: Damir Lazarević and Marko Bartolac).

Figure 4.68. Diagonal cracks in infill walls and overturned shelves (source: Marko Bartolac).

Figure 4.69. Horizontal cracks between the RC beams and the top of infill walls (source: Damir Lazarević).

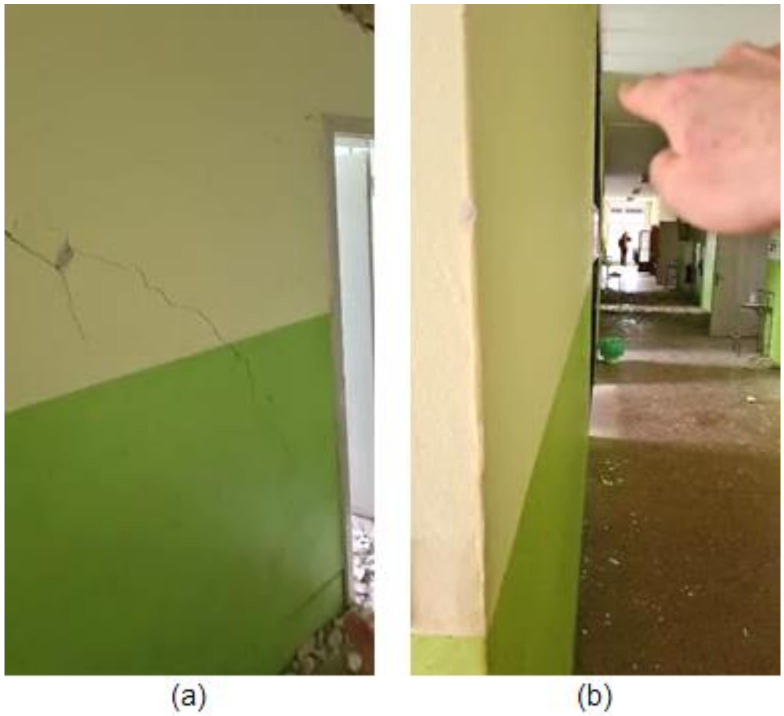


Figure 4.70. (a) Diagonal cracks due to in-plane loading and (b) out-of-plane infill failure due to in-plane/out-of-plane interaction (source: Nenad Bijelić and Damir Lazarević).

Figure 4.71. Gapping in head joints of infill walls (source: Nenad Bijelić).

4.5.8 Elementary School Mate Lovraka in Petrinja

The Mate Lovraka Elementary School, located in Petrinja and shown in Figure 4.72, was constructed in three different stages. The south part, which is the oldest of the three, is a timber single-story building; the middle portion, which was built at a later stage, is a single-story steel building; and the northern part is a 2-story building, mostly made of RC moment resisting frames, as shown in Figure 4.73.

Figure 4.72. Mate Lovraka Elementary School in Petrinja (source: Google Earth).

(a) (b)

Figure 4.73. RC moment resisting frames of the northern part of the Mate Lovraka Elementary School in Petrinja (source: Susana Ereiz).

Besides structural damage to an old chimney, overall, the building behaved really well without any visible signs of structural damage. Some minor nonstructural damage was observed in the perimeter of a ceiling system (see Section 4.10.1, Figure 4.109b). However, all classrooms (Figure 4.74a) and corridors (Figure 4.74b) were operational after the earthquake. Opposite to the building entrance there are two reinforced masonry two-story residential buildings that did not experience any noticeable structural damage. All these buildings are nice examples of good structural performance during the December 29 earthquake.

(a) (b)

Figure 4.74. (a) Classrooms and (b) a corridor of the Mate Lovraka Elementary School in Petrinja (source: Susana Ereiz).

4.6 Government Facilities (Public Buildings)

4.6.1 Petrinja Town Hall Building (Grad Petrinja)

The Petrinja town hall building is located in the southwestern corner of the central park. The park was originally a square for military parades, typical for the towns in "Vojna Krajina" ("War Frontier"). As the town of Petrinja was transformed from the late 18th up to the late 19th century, the square was turned into a park and civil buildings were constructed around its borders

(Matijašević and Cindrić 2005). The layout of the square dating back from 1863, as shown in Figure 1, already comprised the town hall. The town hall building is therefore a representative example of 19th century architecture of Petrinja. The building is composed of a main part which has a rectangular shape with approximate outer dimensions of 58 m x 15 m, and two annexes on the northwestern and southwestern sides, which have rectangular layouts and dimensions of 7.5 m x 7.5 m. It consists of a basement and two stories. Based on initial surveys it was concluded that the masonry walls were built using solid brick and lime mortar. The floors of the first and second story were constructed with masonry vaults and timber beams, respectively. The two annexes seem to be already present on the map of 1863, which is the earliest that shows the town hall.

Figure 4.75. City plan of Petrinja dating to 1863, showing the Town Hall building in the southwest corner of the park (source: Matijašević and Cindrić 2005).

(a)

(b)

Figure 4.76. Petrinja town hall building: (a) Front façade before the earthquakes (source: Petrinja Virtual Tour) and (b) Front façade after the earthquakes (source: Nenad Bijelić).

The longitudinal direction of the building is aligned in north-south direction. Photos of the front façade before and after the earthquakes are shown in Figure 4.76. These photos show mainly cracking in the spandrels. Photos that were taken inside the building show extensive cracking of both the load bearing walls in the transverse direction (Figure 4.77a) and the masonry vaults of the first floor (Figure 4.77.b), which suggest that the masonry vault developed a mechanism. Similar damage has been observed throughout the building.

Figure 4.77 (a) and (b)

Figure 4.77. Details of Town Hall building damage: (a) In-plane shear crack in a load-bearing wall in the transverse direction (source: Nenad Bijelić) and (b) Cracking of a masonry vault, indicating a potential formation of an arch mechanism (source: Nenad Bijelić).

Damage was also detected at the floors of the 2nd story, where the cracks indicate that the floor beam had been sliding on the supports, shown in Figure 4.78.

Figure 4.78. Damage at a floor-wall connection at the 2nd story. The crack at the connection is potentially a result of beam sliding at supports (source https://www.index.hr/vijesti/clanak/video-pogledajte-kako-izgleda-petrinja-ogromna-steta-na-zgradi-gradske-uprave/2242131.aspx).

The two annexes at the northwestern and southwestern side suffered even more widespread damage than the main building, showing multiple wide shear cracks in piers and flexural cracks in spandrels as shown in Figure 4.79. The overall condition of the building was rather poor, and it was marked as red.

(a) (b)

Figure 4.79. Town hall annexes after the earthquake: (a) Southwestern annex with widespread damage in the transverse wall (source: Nenad Bijelić) and (b) Northwestern annex with the widespread damage in the transverse wall (source: Nenad Bijelić).

4.6.2 Chamber of Crafts Building (Društvo obrtnika Petrinja)

By the end of the 18th century, the so-called "Vojna krajina" ("War frontier") region had lost its defensive purpose, becoming a burden for the central government in Vienna. To reform the region and make it more economically sustainable the central authorities supported the development of the crafts and trade. In turn, the towns such as Petrinja became attractive centers, leading to immigration from other parts of Habsburg Monarchy and wider. The largest stream of immigrants was arriving from Czechia, Italy, Germany and Austria. The immigrants brought their traditional craftsmanship skills leading to further development. The long tradition of craftsmanship is continued via the Chamber of Crafts whose building is located adjacent to the central park. The Chamber of Crafts of Petrinja building has a rectangular shape with approximate outer dimensions of 14 m x 10 m. It consists of a high basement and two floors. The building before and after the earthquakes can be seen in Figure 4.80. The Building suffered extensive damage, mostly marked by the characteristic in-plane shear failure of the piers, and the horizontal crack at the roof level. Considering the fact that the building suffered extensive in-plane damage, and considering the position of the building shown in Figure 4.81, we can note that the location of the building in-plane damaged façade is perpendicular to the façades of the buildings that suffered the out-of-plane collapse. This suggests that the strong motion direction was in the direction of the damaged façade, being approximately east-west.

(a) (b)

Figure 4.80. Chamber of Crafts building: (a) before the earthquakes (source: Google Maps) and(b) after the earthquakes. All central piers developed deep in-plane shear cracks. A wide continuous horizontal crack extends throughout the façade at the roof level (source: Nina Čeh).

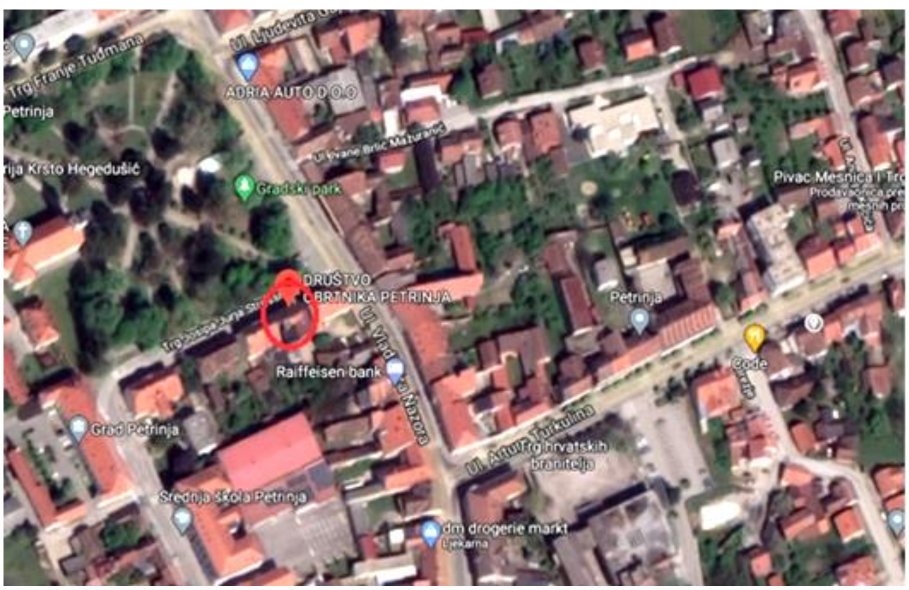


Figure 4.81. Chamber of Crafts building location. Considering that the building suffered predominately in-plane damage, it indicates a possibility of strong motion direction being the same as the building aggregate span direction (west-east) (source: Google Maps).

4.7 Historical Buildings

Thanks to its geographical position, Petrinja was important to various rulers throughout history. The first record of the name Petrinja, was in 1240, but it referred to the area of the today's village Jabukovac.The city that is today known as Petrinja was founded on the confluence of river Petrinjčca and river Kupa in 1592, where Ottoman Bosnian military commander, Hasan Pasha Predojevic built a fortress named Petrinja. Over the years, Roman Catholic and Orthodox churches in this region presented not only great artistic value, but also witnessed numerous sociological and historical processes.

The nearby town Sisak was originally named Segesta and was in a Celtic and Illyric region. Then, the town on two navigable rivers belonged to the Roman empire and was from the beginning a strongly fortified town. Its 16th century fortress of the Old Town is well-preserved and has been turned into a museum, becoming the main tourist attraction in Sisak.

Unfortunately, most of the historical buildings and the sacral architecture in this region were severely damaged by the Petrinja earthquake. The damage to the Sisak fortress complex and to some of the churches in the area is reported in the following section.

4.7.1 Sisak Fortress (Stari grad Sisak)

Sisak Fortress is an early modern fortification completed in 1550 and situated on the bank of the Kupa river in Sisak. Its structure is triangle-shaped and is made of brick and hewn stone (ashlar). Each of the three corners is reinforced with a round tower covered by conical roof. The towers are connected by thick walls with loopholes. From the aerial view it is possible to see that another long and narrow structure ending in a tower is connected to the fortress. In the past the fortress has been damaged but immediately repaired. The west wing of the old town Sisak was retrofitted in 2003, where the floor slab of the 2nd floor was replaced and the horizontal reinforced concrete ring beam was added around the structure. Also, the roof of the fortress was replaced in relatively recent years. Nowadays, the fortress hosts some collections of the Sisak Town Museum.

Figure 4.82. Aerial view of the Sisak Fortress (source: Pinterest 2021).

The main damage is concentrated in the structure connected to the fortress and in particular in the small tower. Figure 4.83a shows the structure in 2011 (Google). In Figure 4.83b and 4.83c, it is possible to observe the collapse of the entire chimney probably added to the original construction later and the presence of cracks in the masonry structure. Some cracks were already present before the earthquake. The fortress reported damage to the tiles of the conical roof.

Figure 4.83. (a) Small tower connected to the Sisak fortress in 2011 (source: Google), (b, c) collapsed chimney in the small tower, and (d) damage to the tiles of the conical roof of one of the tower of the fortress (source: Instagram account starigradsisak and dvorcistarigardovi).

4.8 Religious Buildings

Most of the churches in the affected area were made of URM, being among the most vulnerable structures when subjected to seismic loading. Churches that were rebuilt after the war in the 1990s typically were built as confined masonry buildings. These churches demonstrated good behavior under the seismic actions on December 29, 2020. However, one of the churches that was reconstructed in the past 25 years as an unreinforced masonry structure, exhibited poor seismic response, particularly showing high sensitivity to out-of-plane loading. Apart from the churches that are the main focus of this section, a number of parish houses were also damaged.

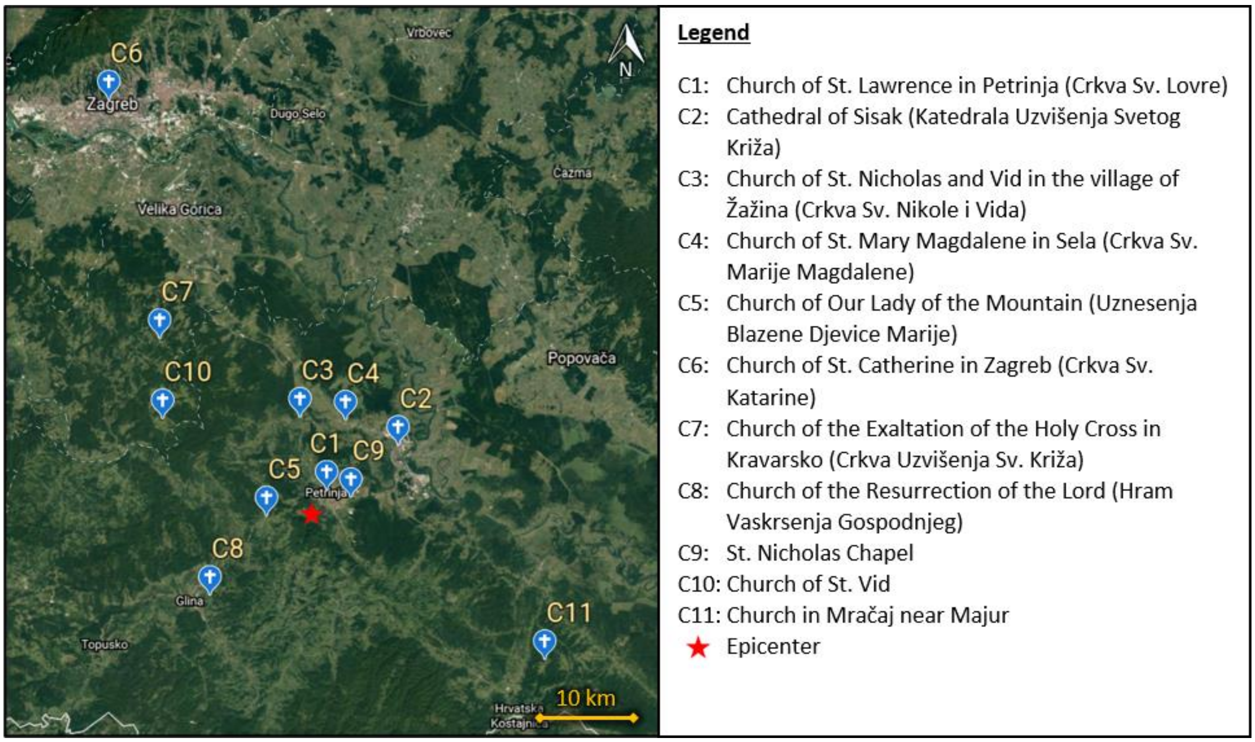


Figure 4.84. Location of churches discussed in this report (source: Google Earth).

4.8.1 Church of St. Lawrence in Petrinja (Crkva Sv. Lovre)

The dominating building on the main square in Petrinja is the Church of St Lovre, originally built in 1780 under the rule of Maria Theresa and Austro-Hungarian Empire. It was destroyed during the war in the 1990s. On its foundations, the new Church was built in 2000, replicating fully the original architectural design and the decorations. Figure 4.86a depicts that during the earthquake on December 29, 2020, it did not suffer any damage of structural elements mostly due to the good seismic behavior of confined masonry. However, the roof tiles are displaced, as indicated in Figure 4.85b, as well as the cross from the top of the Church. Plaster inside is cracked and statues are damaged. Cracks in the plaster are visible in the exterior of the bell tower.

(a) (b)

Figure 4.85. (a) St. Lawrence Church before the earthquake (source: petrinjaturizam.hr/upoznaj-petrinju/kultura) and (b) after the earthquake, roof tiles were displaced (source: Nenad Bijelić).

(a) (b)

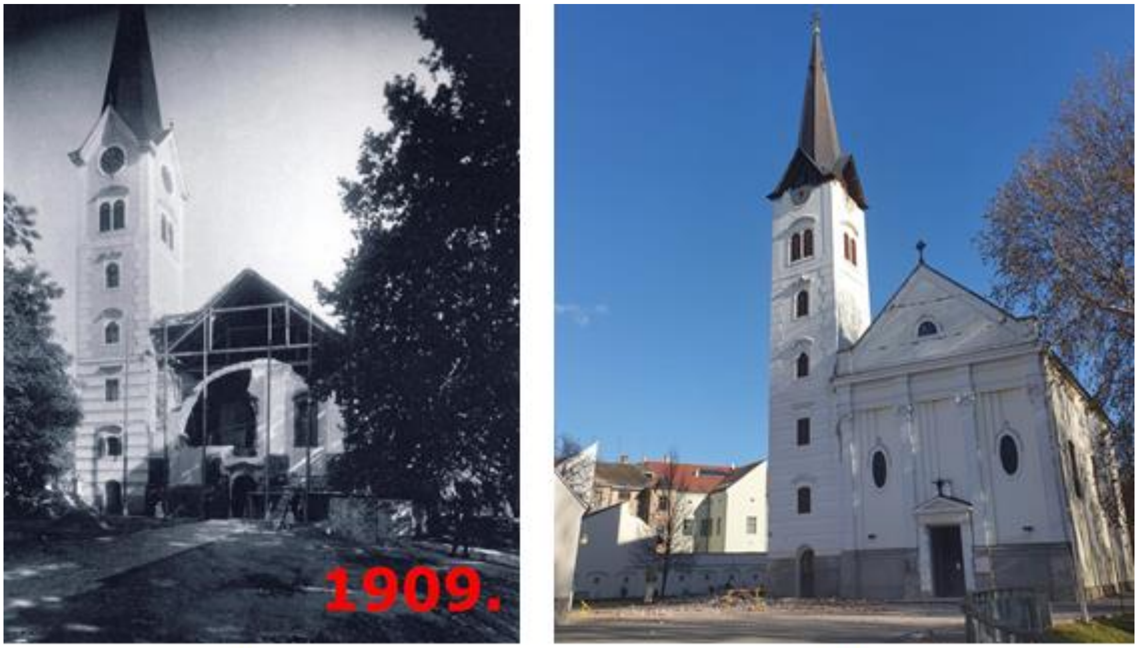
Figure 4.86. (a) Inside the campanile - confined masonry and (b) thin cracks in the exterior of the bell tower (source: Marko Bartolac).

(a) (b)

Figure 4.87. St. Lawrence parish church rectory that was built in 1783 in late Baroque style: (a) Façade shows diagonal cracks in the piers. Overall response was good. It is possible that small openings to the total area of walls had a beneficial effect. Chimneys collapsed. (b) Cracked vault inside the house (source: Marko Bartolac).

4.8.2 Cathedral of Sisak (Katedrala Uzvišenja Svetog Križa)

The Cathedral in Sisak was built during the first half of the 18th century. The bell tower was erected in 1760, and the church was consecrated in 1765. In 1909, an earthquake hit the Cathedral, leaving extensive damage. As a consequence, the old baroque façade was replaced by a neoclassical one, with elements of secession. The Cathedral suffered damage during both World War II and War in the 1990s and it was repaired afterwards. Reinforced concrete horizontal ring beams were added in the 1990s. After the earthquake on December 29, 2020, triangular gables at the top of the bell tower collapsed out-of-plane, as shown in Figures 4.88b and 4.89. The roof above the entrance to the choir and the connection between façade and the bell tower are also damaged but to a lesser extent. Moreover, the interior of the Cathedral showed numerous cracks and plaster detachment. The ceiling above the sanctuary and the sacristy was damaged as well as the connection between the bell tower and the portal, which had already been damaged during the earthquake in 1909.



(a) (b)

Figure 4.88. Sisak Cathedral: (a) after the earthquake in 1909 (source: svetikrizsisak.hr/i/141/zupa/zupna-crkva/) and (b) after the earthquake in 2020, local out-of-plane failure of gables at the top of the bell tower (source: Damir Lazarević).

Figure 4.89. Sisak Cathedral after the earthquake in 2020: (a) a detail of the top of the bell tower showing local out-of-plane failure of gables (source: Marko Todorov/CROPIX) and (b) after the bell tower was removed (source: Nina Čeh)

4.8.3 Church of St. Nicholas and Vid in the village of Žažina (Crkva Sv. Nikole i Vida)

The Parish Church of St. Nicholas and St. Vid, located on the edge of the village in Žažina, was built between 1778 and 1788. Despite the elements of classicism, the Baroque floor plan, in the shape of a square, dominates the Church. An arch separates the nave from a narrower sanctuary and shallow elliptoid apse. After severe damage in World War II, the exterior of the Church was renovated. However, the bell tower remained in poor static condition and strengthening was necessary. The earthquake on December 29, 2020 affected the Church severely, leading to the collapse of the bell tower, as seen in Figure 4.90. Thick load bearing unreinforced masonry walls remained standing, but they are heavily cracked. A church organist was found dead in the wreckage of the collapsed St. Nikola and Vid Church in the village of Žažina. Media reported that three other people were in the church during the earthquake but managed to escape with only minor injuries.

Figure 4.90 Church of St. Nikola and Vida in the village of Žažina after the earthquake exhibited severe collapse of the bell tower and extensive cracking of load bearing walls (source: Total Croatia News 2021).

Figure 4.91. Aerial view of the Church of St. Nikola and Vid in the village of Žažina (source: Instagram account visitlekenik).

Figure 4.92. Church of St. Nikola and Vid in the village of Žažina after it suffered the collapse of a campanile and roof structure (source: Instagram account visitlekenik).

Figure 4.93. Interior of the Church of St. Nikola and Vid in the village of Žažina after the earthquake (source: Facebook Page - Sisačka biskupija).

4.8.4 Church of St. Mary Magdalene in Sela (Crkva Sv. Marije Magdalene)

The unique example of a Church with an oval nave in this region is located in the village Sela. The construction of the Church lasted from 1759 -1765. Its ellipsoidal nave is concluded by a rectangular sanctuary. The length from the entrance to the conclusion of the sanctuary is 31.42 m, and the width of the nave in the transverse axis is 13.40 m. The large dome, which was not common for a provincial Church, was 16.5 m long and made of bricks. It was damaged in the earthquake in 1909, and repaired in 1912, when the cement and sand-based plaster was applied all over the Church. Around the bell tower, a concrete base was made, while an old stone base remained around the Church. The ribs were placed on the Dome. After the recent earthquake, the dome showed extensive cracking and plaster detachment. However, Figure 4.94 shows that it remained standing, but it is out of function.

Figure 4.94. Interior of the Church of St. Marije Magdalene in Sela. Extensive cracking visible in the dome, as well as plaster detachment (source: Facebook Page Sisačka biskupija).

4.8.5 Church of Our Lady of the Mountain (Uznesenja Blazene Djevice Marije)

The parish Church in Gora is a reconstructed early Gothic Templar structure with some architectural forms taken from its Baroque period. After devastation during the war in the 1900s, the Church was rebuilt. The finalization of works and consecration of the Church took place in 2015. The Church was made of properly carved stone blocks, smaller in the façade and larger in the bell tower. The roof is covered with larch shingles. In 2016, one year after completion of the reconstruction, it was noted that the stone is not sufficiently weather resistant since some stone blocks showed horizontal cracks. Furthermore, some stones of the base on the north façade of the central buttress were missing, as well as the stones of the cornice. This pre-existing issue with stone and inadequate design possibly had influence on the poor behavior of the top of the facade, where the lack of connections and support led to out-of-plane failure, as presented in Figure 4.95.

Figure 4.95. Church of Our Lady of the Mountain in the village Gora after its triangular gable suffered out-of-plane failure and the part of the bell tower collapsed (source: Facebook Page - Sisačka biskupija).

4.8.6 Church of St. Catherine in Zagreb (Crkva Sv. Katarine)

In Zagreb, around 60 km from Petrinja, the earthquake on December 29, 2020 increased the damage already present due to the earthquake in March 2020, which had an epicenter close to Zagreb. Church of St Catharine is a Baroque single-nave Church with six side chapels and an apse, situated in Gornji Grad, Zagreb. A detailed renovation of the Church took place after the earthquake of 1880, and the project was designed by Hermann Bolle.

(a) (b)

Figure 4.96. (a) Vault of the Church before the earthquake (source: Lice grada 2021) and (b) The collapse of the vault (source: Zagrebacka nadbiskupija).

4.8.7 Church of the Exaltation of the Holy Cross in Kravarsko (Crkva Uzvišenja Sv. Križa)

The Church of the Exaltation of the Holy Cross is located on the main route Zagreb-Pokupsko-Glina. The first church built in this area was in Gothic style. Demolished and rebuilt in 1847 on the site of the older one, the new church was severely damaged by German bombing during World War II and then rebuilt in 1969 as it is nowadays (Župa uzvišenja Svetoga Križa Kravarsko 2021). The recent earthquake has significantly damaged the structure. Part of the bell tower and the roof of the church have collapsed, and major damage appears also on the side walls (Figure 4.97). The church is out of function (Figure 4.98a).

Figure 4.97. Aerial view of the Church of the Exaltation of the Holy Cross (Crkva Uzvišenja Sv. Križa) in Kravarsko (source: Youtube 2021).

Figure 4.98. (a) Devastated interior of the Church in Kravarsko (source: Brnada 2021) and (b) Expulsion of the wall corner (source: Brnada 2021).

4.8.8 Church of the Resurrection of the Lord (Hram Vaskrsenja Gospodnjeg)

A small village of Majske Poljane, located near Glina, was a home to one of the two Orthodox timber churches in this area. The original church was built in 1820. This church survived the wars in the past century but exhibited a complete collapse under the earthquake on December 29, 2020 (Figure 4.99).

(a) (b)

Figure 4.99. (a) Church in Majske Poljane (Hram Vaskrsenja Gospodnjeg) before the earthquake (source: Eparhija Gornjokarlovacka) and (b) Complete collapse of the Church (source: Eparhija Gornjokarlovacka).

4.8.9 Other Damaged Religious Buildings

Many other churches throughout Croatia experienced light to heavy damage during the earthquake. Images showing the damage to just a few of them are included below. Figure 4.100 shows the damage reported to the masonry structure of the St. Nicholas Chapel in Petrinja and its cemetery. The bell tower collapsed causing heavy damage also to the roof and tombstones and crosses were damaged in the nearby cemetery. Another church suffered damage to the bell tower in the village of Hotnja: the cross windows on the bell tower and part of its structure fell down during the seismic event (Figure 4.101). The church in Mracaj, near the village Majur (Figures 4.102 and 4.103) suffered an almost complete collapse of the timber roof structure and cover. the severely cracked bell tower represents a danger, and it will have to be removed.

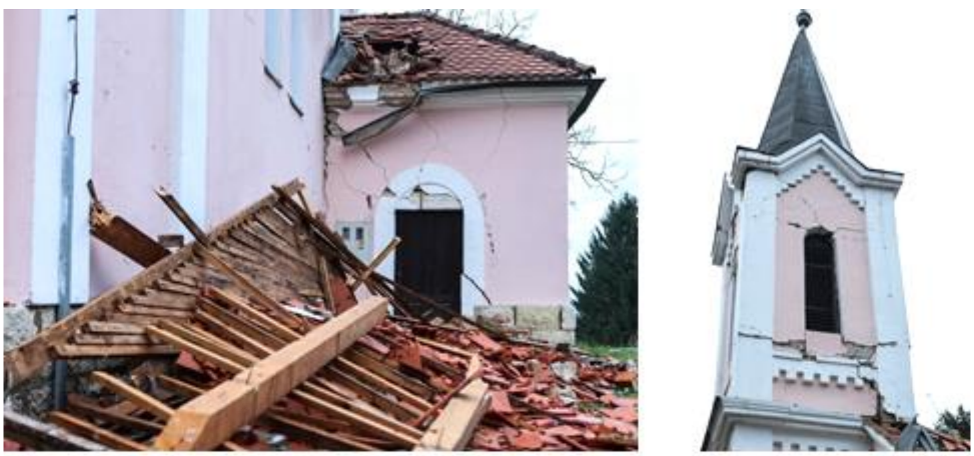
(a) (b)

Figure 4.100. (a) Overturned cross at the cemetery in Petrinja and (b) St. Nicholas Chapel in Petrinja after severe damage due to the earthquake (source: Service of the Serbian Orthodox Church 2021).

(a) (b)

Figure 4.101. (a) Church St. Vid in Hotnja before the seismic event (source: Google); (b) Collapsed windows on the bell tower of the church (source: Facebook Page - Sisačka biskupija).

Figure 4.102. Church in Mračaj, near village Majur. Collapse of the timber roof structure and cover and severe cracking of the bell tower (source: Marko Pripic/PIXSELL).



(a) (b)

Figure 4.103. Church in Mračaj, near village Majur: (a) heavy cracking in the interface between adjacent shorter unit and the main nave (source: Marko Pripic/PIXSELL) and (b) severe cracking of the bell tower (source: Marko Pripic/PIXSELL).

After the earthquake in Petrinja, historical buildings made of URM once again were confirmed to be prone to damage during earthquake shaking. It is worth highlighting that the top section of the façade, the bell towers and the vaults were often a place for damage concentration. The common local out-of-plane failure, overturning of the gables, was observed in a few churches, due to insufficient lateral support and inadequate construction details. In most of the cases, it seems that timber roof structures were simply supported by the load bearing masonry walls. Numerous churches collapsed fully or partially, and are inappropriate for further use. Displacements of the roof tiles and failures of chimneys were commonly detected. Furthermore, damage to the artistic assets is significant. Cracks in the plaster in the interior were noticed in almost all the churches. Statues, religious decoration, and chandeliers were broken. In order to attain a satisfactory level of seismic resistance, various strengthening techniques can be applied. Furthermore, in case of historical structures and protected monuments, specific treatment needs to be performed, ensuring that the solution is removable, compatible, durable, non-invasive, while providing stability and sufficient load and displacement capacity.

4.9 Industrial facilities

While the building stock mostly comprises unreinforced masonry structures, a few steel industrial facilities are situated in the general area. Figure 4.104 illustrates a timber production industrial building, which used to be a brick production plant in the past.

Figure 4.104. Timber production industrial building in Sisačka ul. 116, 44250 Petrinja (source: Google Earth https://maps.app.goo.gl/m2joQ6FJzUVymvJ78).

The industrial facility complex consists of several buildings. Referring to Figure 4.105, the primary structural systems deploy either steel or non-ductile precast moment resisting frames in one direction (see Figures 4.105a and 4.105b, respectively). These are constructed for reasons of economy and speed of construction and have been used in several places in Europe (e.g., Sezen and Whittaker 2006, Belleri et al. 2015). The connections in those systems are mostly designed as pinned to resist gravity loads. The lateral loads are resisted through cantilever action of the columns.

(a) (b) (c) (d)

Figure 4.105. Primary structural systems within the industrial facility in Sisačka ul. 116, 44250, Petrinja (source: Marko Bartolac).

In the perpendicular loading direction, the structural system is usually a multitiered steel braced frame with two tiers having split low-ductility cross-braced configuration (see Figure 4.105c). The steel moment resisting frames are designed with cantilever step columns for crane operations. These columns feature deep cross sections (i.e., at least 500mm) up to about 5m to 6m height. The steel column is usually 200mm deep and acts as a support of an inclined heavy truss beam (see Figures 4.105a and 4.105d). Horizontal bracing is provided at the roof. These structures are usually designed with a strength reduction factor q=1.5 without any particular seismic design and/or detailing requirements. In general storage areas (see Figure 4.106a and b), horizontal bracings feature either cables or struts because of the lightweight nature of the overall structure.

While the primary lateral load resisting systems in the main facilities and storage areas did not experience any visible structural damage after preliminary inspection, in some of the adjacent structures, within the same industrial complex, where lateral resistance was provided with tension-only bracings (see Figure 4.107) a number of connection fractures were observed. Figure 4.107a shows one of the braces that was bent and stayed in place after fracture of its top left bracing connection. Moreover, Figure 4.107b illustrates another bay of the same structure where one of the two braces completely fell to the ground whereas the one standing exhibited flexural buckling during the earthquake. Failures of the same nature were observed in low ductility steel industrial facilities in prior earthquakes (e.g., Cruz and Valdivia 2011; Okazaki et al. 2013). Moreover, considering the fairly poor performance of precast low-ductility industrial buildings in past earthquakes in Europe (e.g., Sezen and Whittaker 2006, Belleri et al. 2015), special attention should be paid to other industrial facilities of similar nature in this and other seismically prone regions.

(a) (b)

Figure 4.106. Storage areas within the industrial facility in Sisačka ul. 116, 44250, Petrinja (source: Marko Bartolac).

(a) (b)

Figure 4.107. Fracture of tension-only steel bracings in an industrial facility in Sisačka ul. 116, 44250, Petrinja (source: Marko Bartolac).

Finally, the primary industrial facility shown in Figure 4.108 experienced complete collapse of its exterior cladding. Some of the reinforced concrete columns inside the older part of the building also experienced cracking during the earthquake.

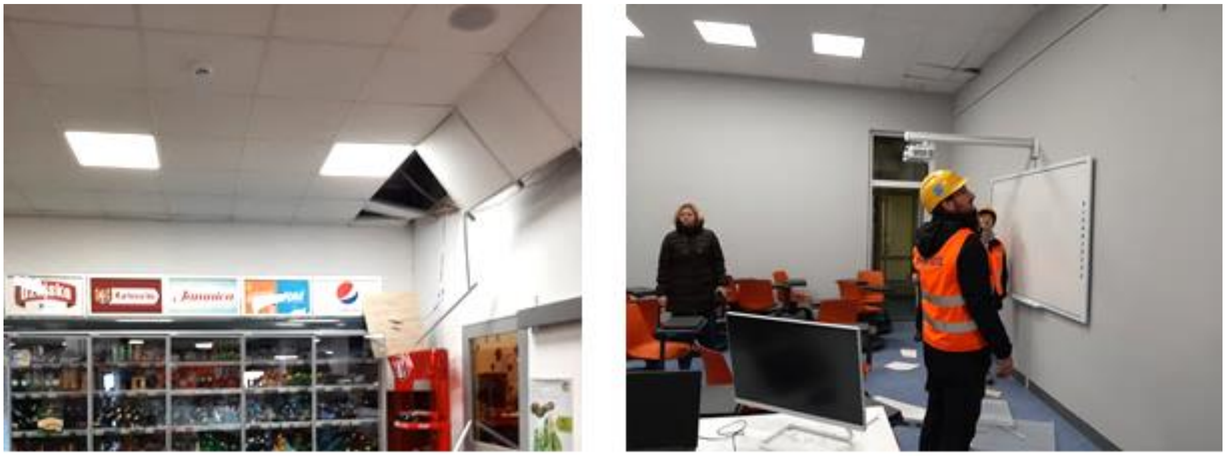
(a) (b)

Figure 4.108. Damage to exterior cladding and concrete columns in an industrial facility in Sisačka ul. 116, 44250, Petrinja (source: Marko Bartolac).

4.10 Nonstructural components and building content

4.10.1 Performance of ceiling systems

While damage of fallen ceiling tiles / panels was not as extensive as in prior earthquakes (e.g., Miranda et al. 2012), this was related to the fact that the damage was mostly observed in low-rise commercial buildings (i.e., single story) (Figure 4.109a). The elementary school in Ul. Mirka Antolića 18, 44250, Petrinja, which was a mixed wood-steel-reinforced concrete concrete structure also experienced damage of the same nature (Figure 4.109b). Preliminary evaluation of the ceiling systems did not seem to comply with seismic requirements of EN13964 (EN 2014) neither for moderate nor high seismic hazard ceiling systems. Figure 4.109 indicates that damage was mostly initiated in the perimeter and around columns due to ceiling supports slipping of the clips over the perimeter trim. It appears that this occurred due to lack of suspension wire in the initial span. While failure of ceiling systems was not extensive in this case, it still caused partial functionality disruption in the commercial store.



(a) (b)

Figure 4.109. Damage to: (a) ceiling systems in a single-story commercial store and (b) Elementary School Mate Lovraka in Ul. Mirka Antolića 18, 44250, Petrinja (source: Sonja Belovarac Radenović (a), Marko Bartolac (b)).

Figure 4.110a depicts the collapse of the entire ceiling in the lecture hall at a university building (Učiteljski fakultet), which was originally built in 1962. The ceiling, which consisted of simply supported wooden girders, was a attached to the slab with post-installed anchors (see Figure 4.110b). Because of large vertical acceleration, most of the anchors pulled out of the slab. The entire ceiling collapsed in one piece as shown in Figure 4.110b. In prior earthquakes, such as the 2011 Great East Japan Earthquake, the collapse of entire ceiling systems at cultural halls caused the death of a number of people. This was attributed to inadequate design of the ceiling for the vertical high-frequency motion(e.g., Motosaka and Mitsuji 2012).

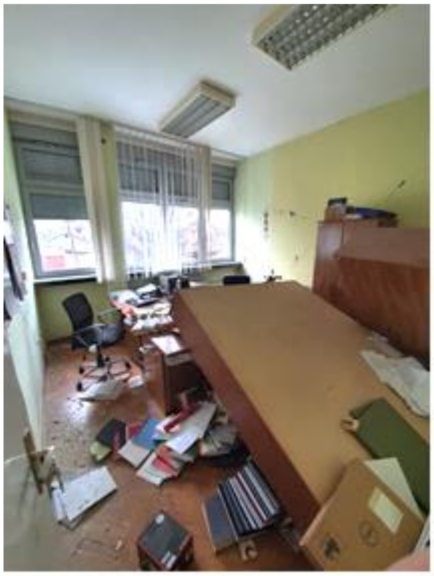
(a) (b)

Figure 4.110. Ceiling collapse in 1962 university building (Učiteljski fakultet) (source: Marko Bartolac).

4.10.2 Anchorage of building contents

In many cases, the falling of building contents was due to lack of, or inadequate, anchorage. In general, contents such as bookcases shown in Figure 4.111 were fairly slender. Therefore, the seismic excitation resulted in a rocking-dominated response that eventually caused overturning, as shown in Figure 4.111a. On the other hand, fully loaded bookcases which were properly anchored to walls and/or partitions remained standing (see Figure 4.111b). The above observations corroborate prior work on the rocking response of unanchored building contents (e.g., Filiatrault et al. 2004).

Overturning of unanchored slender contents often caused blocking of emergency exits in commercial stores, university buildings as well as residential houses as depicted in Figures 4.112. During the inspection of the building of the Faculty of Education (Učiteljski fakultet) in one classroom a detachment and collapse of the school board was observed (Figure 4.113).

(a) (b)

Figure 4.111. Comparisons of (a) inadequate and (b) sufficient (b) anchorage of building content in 1962 university building (Učiteljski fakultet) (source: Marko Bartolac).

(a) (b)

Figure 4.112. Examples of unanchored slender contents blocking emergency exits and doors in commercial stores and residential houses (Otona Kučere 90, Petrinja) (source: Nenad Bijelić (a) and Damir Lazarević (b)).

(a) (b)

Figure 4.113. Detachment and collapse of the school board in one classroom (Faculty of Education - Učiteljski fakultet) (source: Marko Bartolac).

Building contents that are particularly sensitive to seismic excitations are computer server rooms. Although damage may not occur, the functionality of computer equipment is often jeopardized. This event also caused significant shaking of the server equipment as shown after 54 seconds in the video available at https://www.youtube.com/watch?v=u7cEL40eBEM&feature=youtu.be.

4.10.3 Piping

Nonstructural damage included partial damage to water piping due to shearing with either walls or concrete floors in some university buildings and hospitals as shown in Figure 4.114. This caused some water leakage. Fire sprinkler piping generally seemed to perform well in commercial buildings, hospitals and educational facilities.

Figure 4.114. Examples of failures in piping systems in university building constructed in 1962 (Uciteljski fakultet) (source: Nenad Bijelić and Damir Lazarević).

4.10.4 Elevators

In a few buildings equipped with elevators, such as the retirement home in Petrinja, elevators experienced seismic damage that caused the elevator to stop operating. At this stage, it is not clear if damage is associated with cabin derailment, the fall of counterweight blocks, bending of guide rails, or rope system damage, because in most cases elevator shafts were not accessible at the time of building inspection. In hospitals, such as the one in Sisak, elevators stopped operating due to power shut down, a few days after the December 29 2020 mainshock they were operational after electricity was restored. However, it appears that there is neither an established protocol for elevator inspection in the aftermath of earthquakes nor seismic switches for safe shutdown during an earthquake. Moreover, it is not clear at this stage whether the inspected elevators were designed with seismic considerations in mind according to ISO/TR 25741:2008 or other seismic requirements for elevators and escalators (e.g., ASME 2007).

4.10.5 Façades, parapets and balconies

Several incidents of façade and parapet collapses were reported similar to those shown in Figure 4.115.

Figure 4.115. Fallen façades and parapets (source: 24sata.hr).

Moreover, in the area close to the Faculty of Education, a complete collapse of a URM balcony guardrail was observed (Figure 4.116). The heavy masonry wall probably fell due to lack of adequate reinforcement and connection to the slab. The guardrail on a residential balcony was damaged due to collapse of a gable end wall (Figure 4.117)

Figure 4.116. Collapsed unreinforced masonry balcony guardrail (source: Nenad Bijelić and Damir Lazarević).

Figure 4.117. Damaged balcony guardrail in a family house in Sisak due to collapse of the gable end wall above (source: Instagram account on_a_binge_art).

4.10.6 Chimneys

During the site visits frequent failure of chimneys was observed. Falling of the chimneys to the street as well as through the roof can endanger people in and adjacent to the buildings. Figures 4.118 to 4.121 present some examples of collapsed and damaged chimneys.

(a) (b)

Figure 4.118. Damaged chimneys (source: (a) Getty and (b) Twitter 2021).

Figure 4.119. Fallen chimneys and gable end wall in hospital Dr. Ivo Pedrišić in Sisak (source: Nenad Bijelić and Marko Bartolac).

(a) (b)

Figure 4.120. (a) Damaged chimney, (b) chimney fallen on the street (source: Nenad Bijelić and Damir Lazarević).

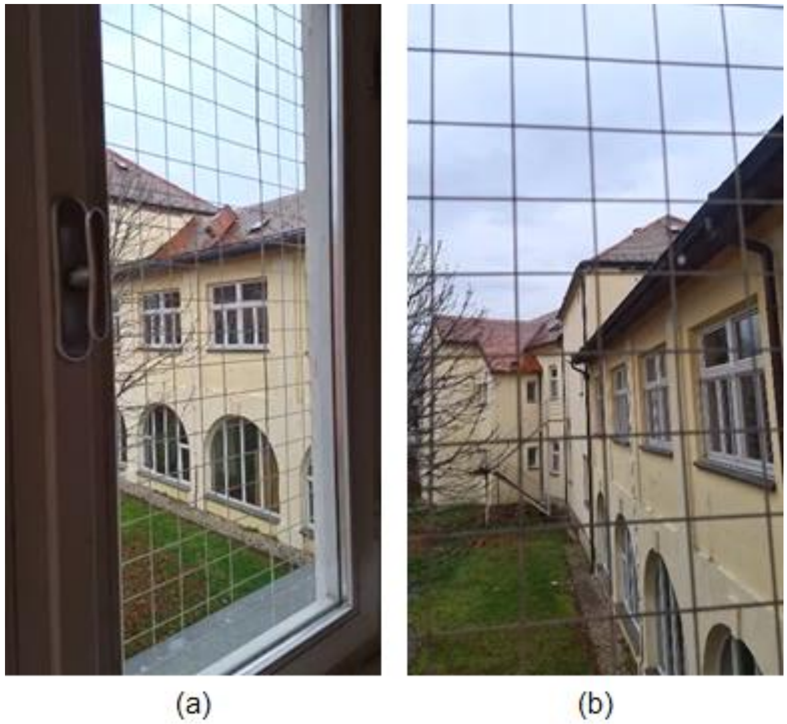


Figure 4.121. Collapsed chimneys (source: Nenad Bijelić and Damir Lazarević).

4.10.7 Roof tiles

A significant number of roofs were damaged during this earthquake event. Besides failure of the roof construction, roof tiles often fell on the street and around the perimeter of the structures. Figures 4.122 and 4.123 show some examples seen during the site visits.

Figure 4.122. Damaged roof tiles (source: rtvslo.si).

Figure 4.123. Damaged roof tiles on St. Lawrence church (crkva Sv. Lovre) in Petrinja (source: Nenad Bijelić).

5.0 Damage to Infrastructure

This chapter presents the observed damage to the electric power and transportation infrastructure. Electric power disruptions, described in more detail in Chapter 7, are primarily caused by the damage of the power distribution system, as reported in Section 5.1. The airport and railway infrastructure damage are presented in Section 5.2. Next, the observed damage of the Brest and Galdovo bridges, located at approximately 3 and 12 km from the epicenter, respectively, is reported in Section 5.3. Most of the damage to the bridges was caused by the relative lateral displacement between the abutments and the ground. Section 5.4 discusses the damage experienced by the road infrastructure, primarily due to lateral ground displacement. The damage to the road infrastructure caused by liquefaction is presented in Section 6.4.

5.1 Electric Power Infrastructure

Electricity generation, transmission, and distribution in Croatia were to a certain extent affected by the earthquake. Electric power infrastructure is owned and managed by Hrvatska elektroprivreda (HEP), a state-owned corporation. The installed generation capacity of Croatia in 2016 was approximately 4.8 GW, with hydroelectric power accounting for 46%, thermal power 44%, and wind and solar 10% (World Bank, 2018).

The earthquake caused shutdowns in some power plants. The Krško Nuclear Power Plant in Slovenia (Figure 5.1), located approximately 100 km from the epicenter of the earthquake and jointly owned by Croatia and Slovenia, was automatically shut down as a precautionary measure (Reuters 2020). The plant (696 MW capacity), was inspected and restored its functionality to 50% capacity a day after the earthquake and to 100% capacity the subsequent day (Index.hr 2020b, Dolsek 2021). The Sisak Thermal Power Plant was not in operation at the time of the earthquake but experienced damage (Index.hr 2020a). The repair started shortly after the earthquake and it was expected to restore its functionality within seven to ten days after the earthquake (Jutarnji list 2020). A power plant in Zagreb malfunctioned immediately after the earthquake but its operation was restored on the same day (Jutarnji list 2020). Despite interruption in the operations of the Krško and Sisak power plants, HEP stated that enough electricity was available in the Croatian electric system to supply consumers (Jutarnji list 2020).

Figure 5.1. Krško Nuclear Power Plant (source: Stubelj 2018).

Damage to transmission and distribution infrastructure was also reported in the epicentral area, including Petrinja, Glina, and Sisak. Approximately 130 substations suffered damage, of which 10 were completely destroyed (Figure 5.2). In Petrinja and the neighboring villages 3 transmission lines and 79 substations went out of operation (Index.hr 2020b), among which 35 substations were reported as heavily damaged. The damaged equipment from the substations is planned to be fully replaced (Štajdohar Mladen, 2021). HEP noted that it continued to receive reports of individual breakdowns of the low-voltage distribution network in the areas of Sisak, Petrinja, and Glina. As a result the number of users without power supply varied on an hourly basis (Jutarnji list 2020).

(a) (b)

Figure 5.2. Severely damaged (a) and collapsed (b) substations in the Petrinja area. The size of substation structure on the left is 2.5 m square in plan and 8 m high (source: Mladen Štajdohar).

5.2 Airport and Railway Infrastructure

Zagreb International Airport (Figure 5.3) is located south of Zagreb and approximately 40 km northwest of the epicenter. According to the Croatian Air Navigation Services, the control tower suffered minor damage due to the earthquake, which led to an interruption of air traffic for a few hours (Dubrovnik Times 2020).

The Sisak Railway Station experienced severe damage during the event (Figure 5.4) but railway tracks were not damaged and railway transportation was not disrupted (CroatiaWeek 2020).

Figure 5.3. Control tower at the Zagreb International Airport experienced minor damage (source: DubrovnikTimes).

Figure 5.4. Significant damage of the Sisak Railway Station building (source: CroatiaWeek).

5.3 Bridges

Several bridges were affected by the earthquake; however, the team was only able to collect data related to two bridges located close to the epicenter. One of them is the Brest Bridge (Figure 5.5) located 3 km from the epicenter, which crosses the Kupa river and connects Petrinja and Zagreb. The bridge superstructure was rebuilt in 1998 using the piers and abutments of the original bridge which was destroyed in the war in 1991. The bridge structure is a continuous structural system with two spans. The main structure consists of steel with a concrete deck. The bridge has two spans and its overall length is 123 m. Although it was damaged in the earthquake, the bridge remained in use but with a reduced speed limit of 30 km/h (Civil Protection Agency 2020).

Figure 5.5. Satellite view of the Brest Bridge (coordinates 45.4486, 16.2604).

Based on the visual inspection, it was determined that the concrete bearing pads forming both vertical and lateral supports were severely damaged. Figure 5.6 shows deep cracks in the base bearing pad and lateral shifting of the lateral pad at the upstream side of the river bed.

Figure 5.6. Damaged bearing supports of the Brest Bridge (source: Mate Baričević).

The "asphalt wedge" constructed between the bridge structure and the transition slab must be refilled to make the transition to the bridge as smooth as possible. Currently, the vehicles approaching the bridge impose large dynamic loads on the bridge structure (Figure 5.5 right-hand side and Figure 5.7). A transverse crack in the transition slab was also observed at the left-hand side of the bridge, but no denivelation was observed as on the opposite abutment (Figure 5.7).

(a) (b)

Figure 5.7. Asphalt at right-hand side abutment (a) and asphalt at left-hand side of abutment (b) of the Brest Bridge (source: Mate Baričević).

Wide ground fissures (up to 10 cm wide) were observed on the embankments leading to the bridge (Figure 5.8a). The asphalt curtain partially collapsed at the intersection with the access road to the center of Petrinja, as shown in Figure 5.8b.

(a) (b)

Figures 5.8. (a) Wide cracks at the bridge embankment and (b) collapsed portion of the asphalt curtain at the intersection with the access road to the center of Petrinja (source: Mate Baričević).

(a) (b)

Figure 5.9. (a) A wide transverse crack at the Brest Bridge approach road (source: Mate Baričević) and (b) a wide fissure in the road close to Brest Bridge (source: Index.hr 2020d).

Galdovo Bridge across the Sava River (east of Sisak), located 12 km from the epicenter, is shown in Figure 5.10. The bridge was originally constructed about 30 years ago, but was rehabilitated in May 2020. It is a continuous structure with 4 spans and the overall length is 170 m. The superstructure consists of steel girders and concrete deck.

Figure 5.10. Satellite view of Galdovo Bridge (coordinates 45.4791, 16.3848).

Based on a visual inspection, it was determined that there was a horizontal displacement of the ground relative to the abutments which caused failure of the bearing supports at the abutment (Figures 5.11). However, the bridge girders maintained gravity load capacity.

Figure 5.11. Rubber bearings at the abutments failed due to relative displacement demands between the support and the superstructure exceeding the capacity of the bearings, Galdovo Bridge (source: Mate Baričević).

Due to the abutment displacements, damage was observed on the transition device above the abutment, pedestrian guardrail on the bridge, access ramps, and the utility lines attached to the bridge (Figure 5.12). Other parts of the bridge structure were also inspected but there were no signs of earthquake damage.

Figure 5.12. Damage due to lateral displacement of the bridge relative to the slab approach, Galdovo Bridge (source: Mate Baričević).

Figure 5.13. The displacement of the platform is visible on the ground, Galdovo Bridge (source: Mate Baričević).

5.4 Roadways

Due to the proximity to the epicenter, the roads close to Brest Bridge experienced differential settlements, which caused a decrease of the ground bearing capacity and resulted in ground and pavement failure. Iron railings were also damaged. These damages to roadways are shown in Figures 5.14 through 5.19.

Figure 5.14. A major fissure in the road in Sisak was observed after the December 29, 2020 earthquake (source: Marin Tironi/Pixsell via Xinhua).

Figure 5.15. Damage to roads in Brest, north of Petrinja (source: Nenad Bijelić).

Figure 5.16. Ground failure of the road close to the Brest Bridge (source: Index.hr 2020d).

Figure 5.17. Ground failure of a road close to Brest Bridge (source: Nenad Bijelić).

Figure 5.18. Partial ground slide due to reduced ground bearing capacity in the road close to Brest Bridge (source: Nenad Bijelić).

Figure 5.19. Partial lateral ground slide close to Brest Bridge (source: Nenad Bijelić).

6.0 Observed Geotechnical Failures

This section provides an overview of geotechnical damages as evidenced mostly in the free field and in the extended levee system along the Kupa river. It provides a combination of images taken by our field reconnaissance team as well as third-party photos (with appropriate source acknowledgement).

6.1 Geological Setting

The affected area is characterized by two major rivers, Sava and Kupa, which have formed alluvial deposits with depths up to 50 m. The deposits are interchanging layers of loose sands, loose gravels underlain by 1 - 5 m of thick clay with up to 26% of organic content. Below the alluvial deposits are layers of medium to stiff clay, with interchanging low to high plasticity. The soil layers are generally soft, and heavy industrial buildings situated in the area are founded on floating drilled shafts of large diameters in a pile-raft foundation system, while 1 - 2 story commercial and residential buildings typically rest on shallow foundations. Groundwater levels in the city of Sisak are typically 4 - 5 m deep, vary seasonally, depending on the river's water level but can reach the ground level.

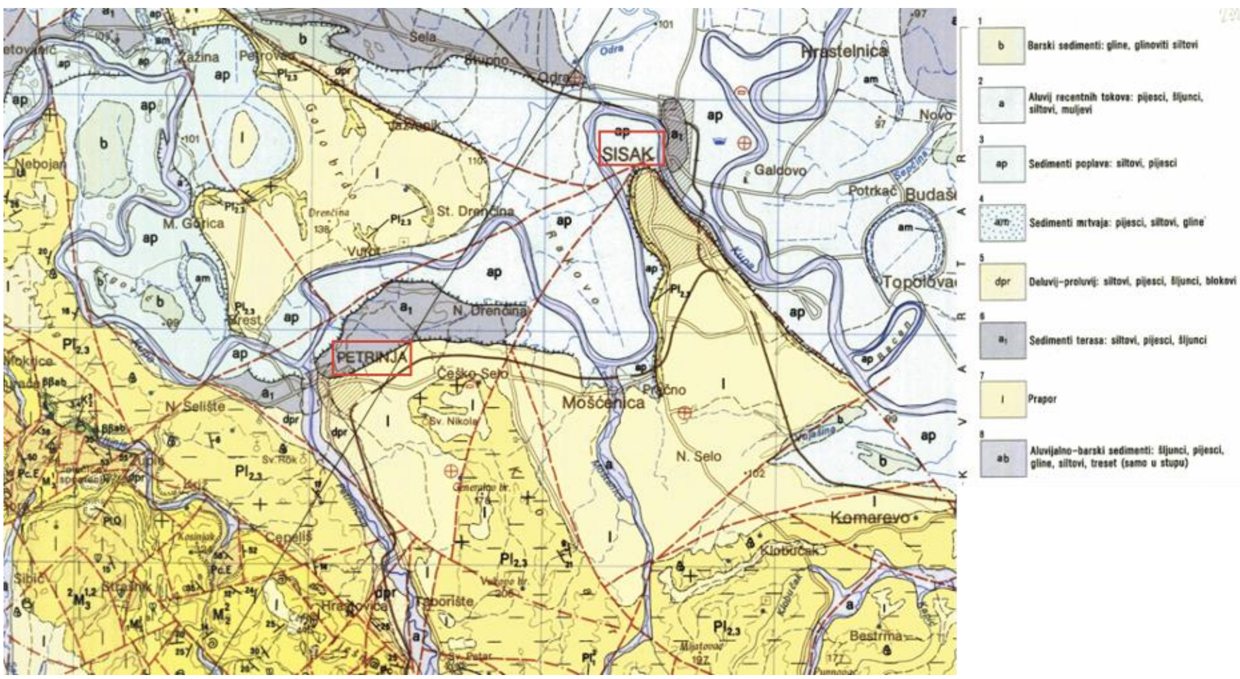


Figure 6.1. Geological map of the area around Petrinja and Sisak (after Pikija 1987). The light blue sediments are all shown to be fresh alluvial deposits consistent with what one would expect in this dense meandering river system. The darker zone north of Petrinja is characterized as Terasa sediments consisting of silts, sands, and gravels. The light-yellow area south of both locations is indicated as loess.

Soil properties in the wider area of Sisak can be illustrated with soil investigations for the thermo-electric power plant in Sisak. Soil characterization, laboratory and in-situ tests were performed on six 30m deep boreholes, in addition to others that were previously performed. The soil water level varies from 5.5 to 6.5 m below ground surface, and strongly depends on the river Sava water level. Six borehole logs indicate strong soil layers heterogeneity that is typical for alluvial deposits. A surficial **(I) fill** layer is up to 3 m thick and is composed of fine sand and gravel; and below is a 0.5 - 2.6 m thick brown **(II) clay (CL-CH)** layer, with soft consistency, very silty (w_0 = 26.3 - 28.6 %; w_L = 16.2 - 63.2 %; w_P = 12.4 - 26.0 %; I_P = 9.5 - 44.4 %; γ = 18.6 - 19.5 kN/m^3; γ_d = 14.6 - 15.4 kN/m^3; q_u = 18 - 195 kPa; c' = 20 - 50 kPa; eff. fric.angle= 24 - 28°). Below the clay layer is **(III) sand (SFs, SFc, SP, SU)** 3.5 - 13 m thick, with various classifications: SFs, SFc, SP, SU, typically as fine sands, light-brown color. The SPT results are N=5 - 16, indicating loose to medium compacted sands. Granulometry curves show spans of particle sizes: sand 59 - 99 %, silt 6 - 38 %, clay 1 - 6 %. The next detected layer is also **(IV) sand (SFs, SP)**, 2.1 - 14.5 m thick, fine, poorly graded, with clay and silt, sometimes with gravel, loose to medium dense, with SPT=5 - 16. Below is a layer of **(V) gravel (GW, GP, GFs)** 1.8 - 11.0 m thick. However, at the same depths some boreholes demonstrated thinner or thicker layers of sand (SP), sometimes even 7.0 m thick. Gravel granulometry curves show spans of particle sizes: gravels 19 - 88%, sands 12 - 81%, silt 0 - 2%. The bottom layer is **(VI) clay (CL-CH)**, with varied plasticity in different boreholes, stiff to very stiff, of blue-grey color. Clay strata are detected at depths 22.5 - 28.0 from the surface, while some 30 m boreholes did not display the bottom clay layer, but only sand. Clay properties are as follows: w_0 = 18.2 - 30.7 %; w_L = 21.8 - 63.5 %; w_P = 17.1 - 23.5 %; I_P = 0.1 - 40.9 %; γ = 15.6 - 20.4 kN/m^3; γ_d = 15.2 - 17.4 kN/m^3; q_u = 81 - 366 kPa; c' = 6 - 64 kPa; eff. Fric.angle = 13 - 31°. The average SPT blow counts, collected from numerous deep boreholes (6 in 2005, and 25 others earlier), are as follows: N=12 (5 - 10 m), N=13 (10 - 15 m) N=15 (15 - 20 m) N=10 (20 - 31.5 m). One of the six borehole cores is shown as an example in Figure 6.2.

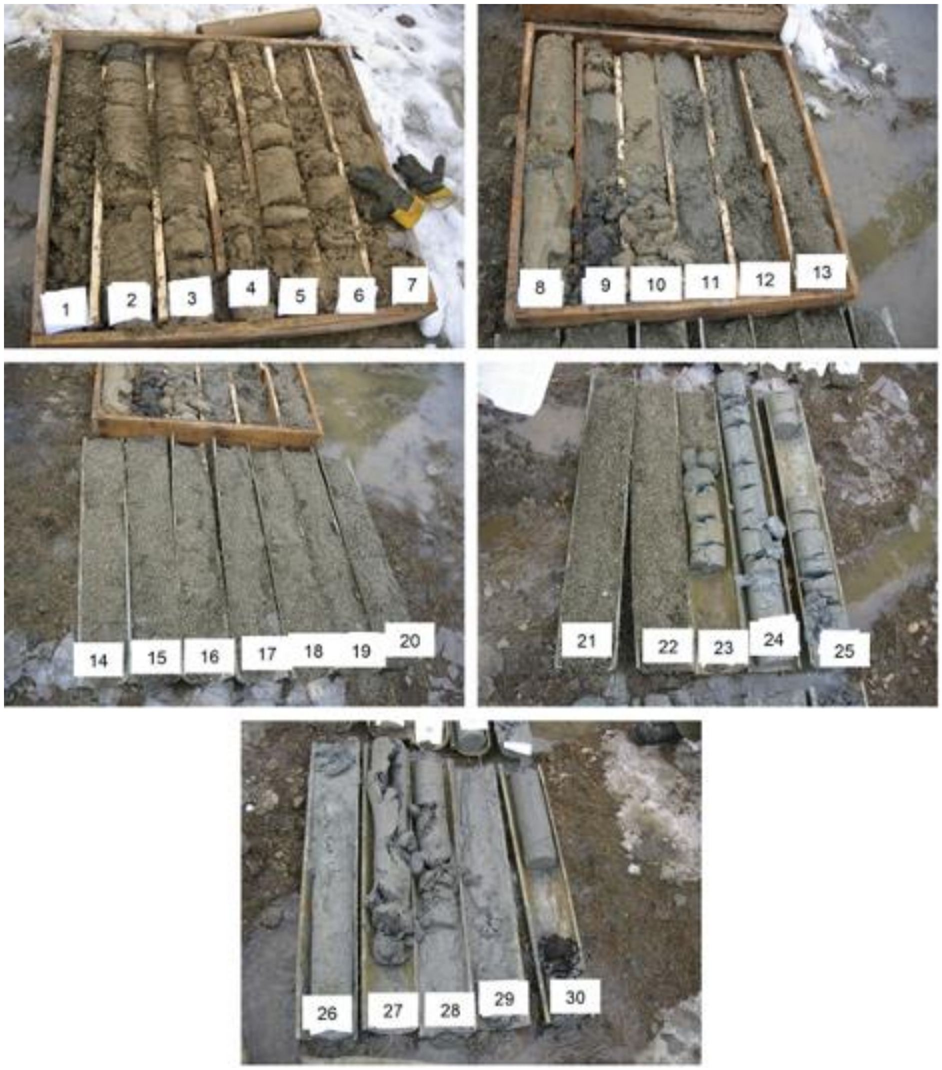


Figure 6.2. Soil properties in the area of the thermal electric power plant in Sisak, Čret (45.4538, 16.4145) (source: Conex, Zagreb).

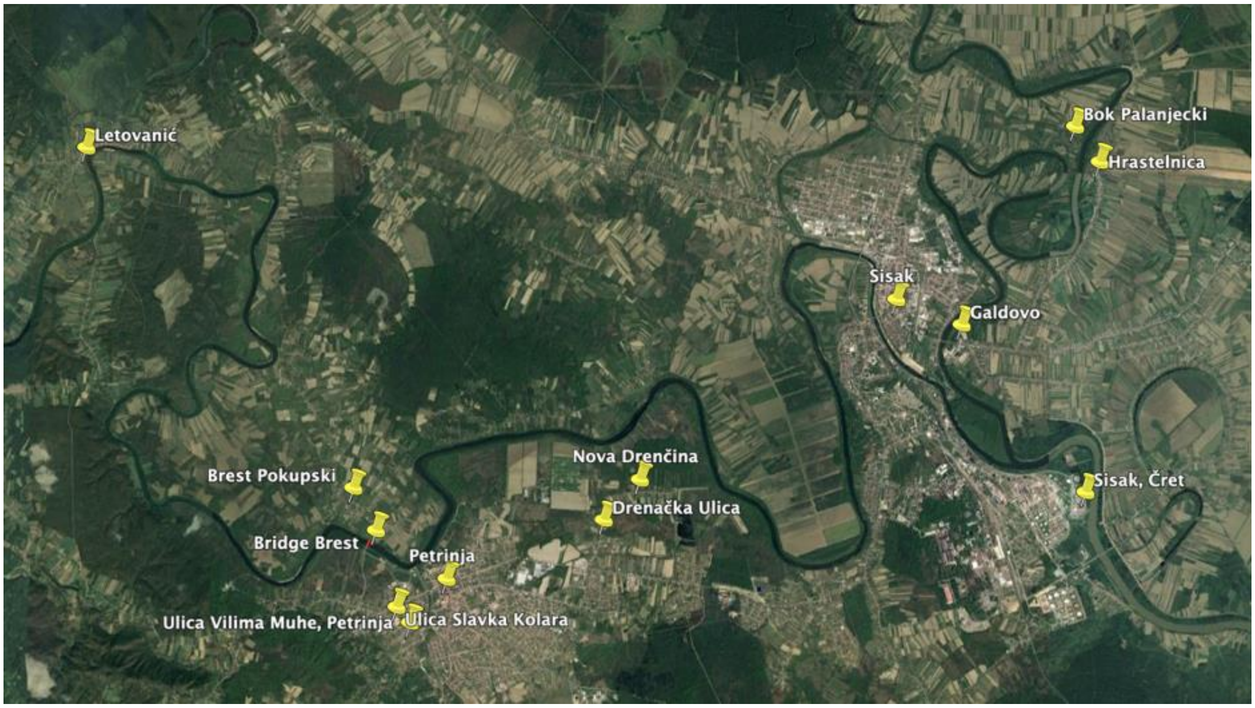


Figure 6.3. Google Earth imagery of the broader area with pins at locations with ground failures (referred to later in the corresponding subsections).

6.2 Free-field Liquefaction

The December 29, 2020 earthquake caused widespread liquefaction with surface manifestations in many locations close to the Kupa and Sava rivers. Liquefaction is rare but not a new phenomenon in the broader area. Six cases of water gushing from the earth alongside with the formation of sand boils have been reported as early as 1880 during the November 9 Zagreb earthquake (Torbar 1880, after Veinovic et al. 2010). The 1909 Kupa valley earthquake also produced cases of liquefaction. The Kupa and Sava rivers along with their common geological processes and materials, allow us to form useful connections between these historical events and the most recent one. The areas where such phenomena have been observed are close to the Krško-Brežice field in Slovenia and in the valley of the Sava River (Veinović et al. 2007, Herak et al., 2009; Herak & Herak, 2010). Brežice also lies by the Sava River north-west of Zagreb. Figure 6.4 illustrates the epicenters of earthquakes at the Krško-Brežice field and in its close surroundings from 567 to 2007 AD, as well as the locations where liquefaction-related effects were observed during the Zagreb (blue dots) and Kupa Valley (yellow dots) earthquakes (Smolar et al. 2019). Smolar et al. (2019) in particular performed a liquefaction assessment study in the Brežice Hydroelectric Power Plant (Slovenia), close to the Sava River, and found a stratigraphy similar to the ones in the areas affected by the Petrinja earthquake: a top layer up to 5 m thick, consisting of recent deposit of very loose silts and sands

(ML, SM, SP), likely liquefiable, overlying a medium dense to dense Quaternary gravel, beneath which there are over-consolidated, uncemented Miocene silts and marls.

The Liquefact project (Lai et al. 2018) further indicates that 13 liquefaction cases have been observed in Croatia during three earthquakes while the microzonation and liquefaction hazard mapping of Veinović et al. (2010) clearly indicates that some areas around rivers in Croatia have a high liquefaction potential.

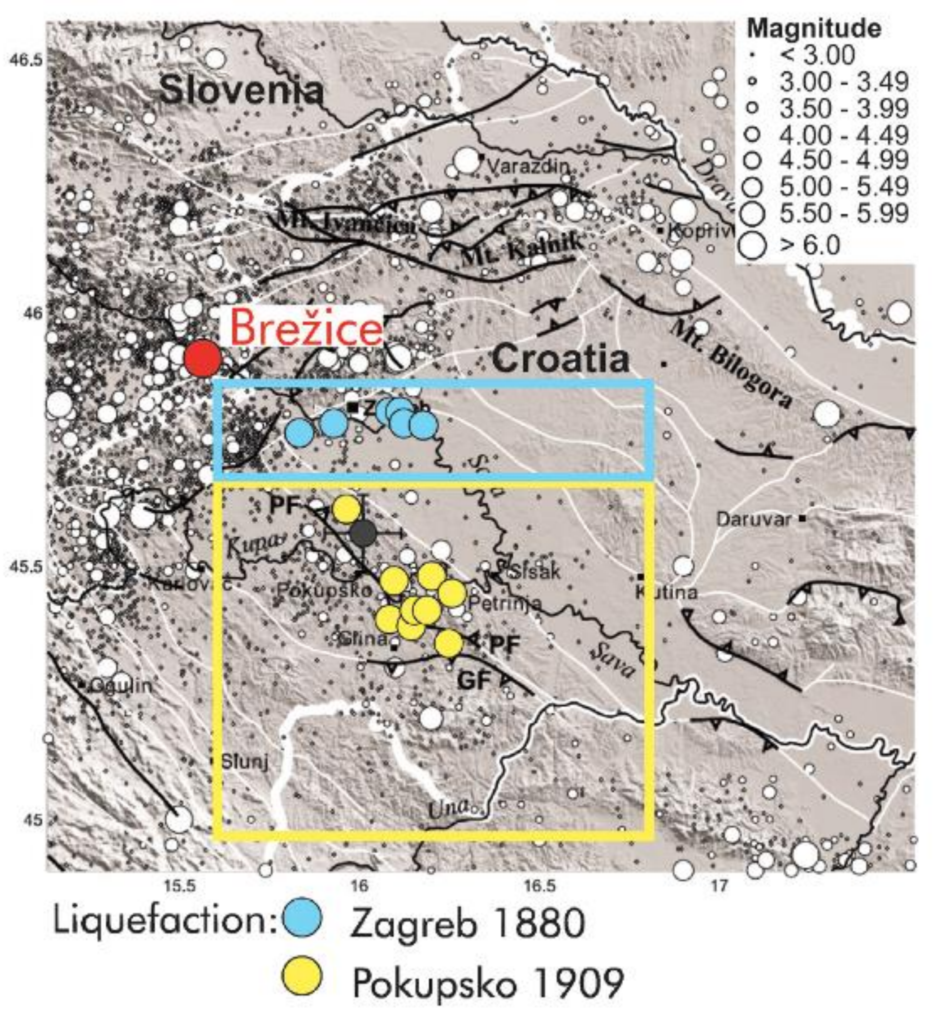


Figure 6.4. Epicenters of earthquakes at the Krško-Brežice field and in its close surroundings from 567 to 2007 AD, and the locations where liquefaction-related effects were observed during the Zagreb (blue dots) and Kupa Valley (yellow dots) earthquakes (Veinović et al. 2007, Herak et al. 2009, Herak & Herak 2010) (after Smolar et al. 2019).

Figure 6.5 illustrates all locations where liquefaction surface manifestation was located by the field reconnaissance teams (Jagodnik, Arbanas, and Mihalic Arbanas), and other images retrieved by Croatian Waters and other individual field team members (Zlatovic, Bartolac, Jagodnik).

Figure 6.5. Locations of verified liquefaction manifestation (source: Vedran Jagodnik).

Pervasive liquefaction took place in the fields surrounding the rivers in the area. Liquefaction was manifested in the form of sand boils and extensive ejecta, identified through their greyish and brownish color. Videos that were circulated in the web showed ejecta/ muddy water flowing out of the soil deposit for a while after the main shock ceased. Unsurprisingly, the basin was characterized with high probability of liquefaction and verified by the USGS liquefaction potential map in Figure 6.6. Fields along river Sava, particularly near Hrastelnica, showed multiple locations of sand boils on the surface (Figures 6.7 - 6.12). Vienevic et al. (2010) published a liquefaction hazard map for Zagreb indicating high probability of liquefaction around Sava River and the same is to be expected for the Sisak/Petrinja area south along Sava. This was extensively confirmed by the December 29, 2020 earthquake.

Faculty from the Department of Civil Engineering of the University of Rijeka and the Faculty of Mining, Geology and Petroleum Engineering from the University of Zagreb confirmed and mapped the occurrence of liquefaction at a total of 18 locations in Sisak and Petrinja as well as surrounding settlements caused by the earthquake. The liquefaction probability map issued by USGS after the earthquake on the basis of shaking intensity and geological information (Figure 6.6) agrees well with the identified field locations. The greatest damage resulting from liquefaction was identified through the observed settlements of Brest Pokupski and Bok Palanjački and on the embankments along the Kupa and Sava rivers (see later subsections).

The extensive liquefaction and surface manifestation led to structural infrastructure damage as well as multiple levee and road embankment damage, documented in later subsections.

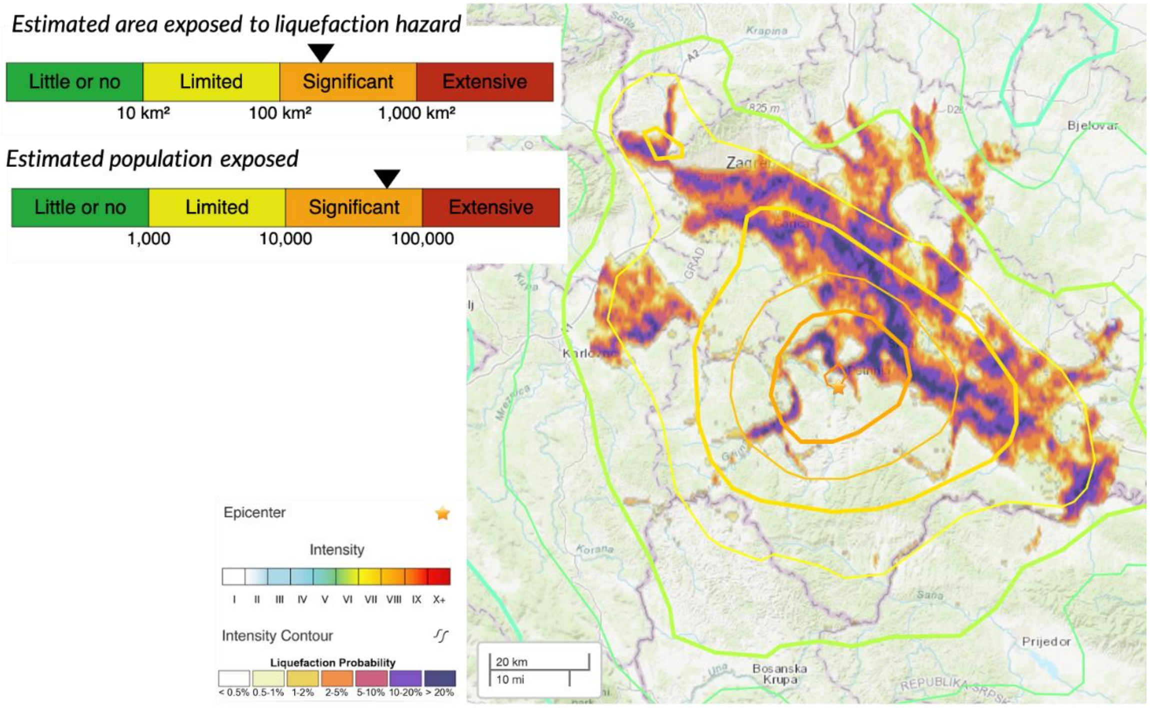


Figure 6.6. Liquefaction hazard map based on spatial extent and population exposure level (source USGS).

Figure 6.7. Aerial image of liquefaction ejecta at (45°30'41.988"N,16°24'37.632"E, source: Vedran Damjanović).

Figure 6.8. Liquefaction near Hrastelnica and Sisak. The proximity of these liquefaction surface manifestations to levees indicates that liquefaction was a definite mechanism contributing to the levee failures (see later subsection). The bottom right image is a close-up of the bottom left (source: Croatian Waters Archive).

Figure 6.9. Liquefaction in Hrastelnica, Sisak (source: Vedran Jagodnik 45°30'2.538"N,16°24'58.842"E).

Figure 6.10. Liquefaction ejecta in Petrinja (Location: 45° 26' 38.6694"N, 16° 16' 33.5238"E, photo: Marko Bartolac).

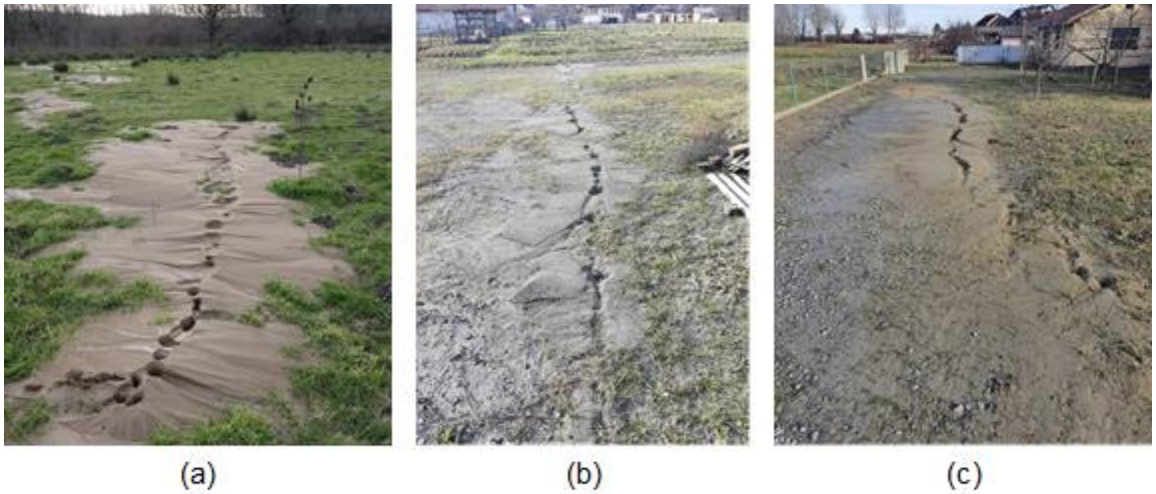


Figure 6.11. Liquefaction ejecta in Petrinja ((b) and (c): 45° 26' 39.447"N, 16° 16' 31.188"E, photo: Marko Bartolac, (a) photo: unknown location, Željko Arbanas).

Figure 6.12. Liquefaction surface manifestation and floatation of manholes in Petrinja (left: 45° 29' 5.25"N, 16° 9' 52.306"E; right: 45° 31' 10.986"N, 16° 24' 16.416"E; source: Željko Arbanas).

6.3 Levee damage

Rivers Sava and Kupa flow through highly populated areas, thus over the years a system of embankments was built for flood protection. Embankments are built, but also retrofitted in stages and their quality varies. Embankments on the left riverbank of Sava ruptured perpendicularly (Figure 6.13). Ruptures parallel to the longitudinal axis of the embankment, in the soil left and right from the embankment core in near Hrastelnica and in Galdovo depict another failure mechanism, which is probably a deep and gradual slope stability failure or lateral spreading. This is characterized by parallel long fractures on the surface (Figs. 6.13, 6.14). Given the extensive liquefaction in the same areas and the proximity of the levees, this is very plausible. Local faculty indicated that this type of failure has not been observed before in Croatia (Professor Arbanas).

Figure 6.13. Rupture of the left riverbank of Sava (source: Croatian Waters Archive).

Figure 6.14. Embankment / levee failure by river Sava in Galdovo (source: Croatian Waters Archive).

Figure 6.15. Embankment failure of river Sava near Hrastelnica (source: Croatian Waters Archive).

6.4 Building, Foundation, and Pavement Damage due to Liquefaction

Buildings and foundations were affected by liquefaction and sinkholes (see later subsection). These were identified by faculty from the University of Zagreb and Zagreb University of Applied Sciences after observing the extensive surface manifestation of liquefaction. Figures 6.16 - 6.22 illustrate some indicative examples.

Figure 6.16. Liquefaction occurred under and around the residential building in the photograph. Sand appeared just next to the house, along the fence, and the area covered with bricks moved up. Cracks opened as the house sank. Petrinja, Ulica Vilima Muhe (45.43514, 16.2684, source: Sonja Zlatović).

Figure 6.17. Building settlement due to lateral spreading, Bok Palanječki (photo: Vedran Jagodnik, 45°30'36.21''N,16°24'38.892''E).

Figure 6.18. Crack between two houses due to liquefaction (45.4540, 16.2611). The line of liquefaction spreads through several yards and under houses, Brest Pokupski (source: Tomislav Ivšić, Sonja Zlatović, Igor Gukov).

Figure 6.19. Liquefaction under a residential building with sandy soil ejected next to the structure and filling the underground space, Petrinja, Ulica Slavka Kolara (45.4349,16.2683, source Sonja Zlatović).

Figure 6.20. Settlement of the road along which the sewage system was renovated recently. It is possible that the material around the pipes was not compacted properly during construction, but liquefaction might have been the main reason for the settlements as a nearby well (45.4562, 16.3164) was filled with sandy material. Nova Drenčina, Drenačka ulica. (source Sonja Zlatović).

Figure 6.21. Settlement of the area between the embankment and the road between Petrinja and the bridge for Brest Pokupski (source Sonja Zlatović). The likely cause for the damage depicted in the left and middle photos, which is compatible with the extensive liquefaction that occurred in the broader area. The right photo shows a longitudinal subvertical crack of the embankment due to subsidence.

Figure 6.22. Bridge Brest, from Petrinja for Brest Pokupski (45.4461, 16.2628, source Sonja Zlatović).

Figure 6.23. Road pavement cracking (45°29'45.108"N,16°22'36.888"E, source Zeljko Arbanas).

6.5 Sinkholes

In the area of the village Mečenčani, on Friday December 31st a dozen sinkholes appeared, as shown in Figures 6.24 to 6.27. The location is approximately 30 km southeast of Petrinja, and it can be seen on the map that the village is located very close to or directly on the fault.

Similar sinkholes were known to appear occasionally in this area after individual communications with the local community. Many of the sinkholes appeared in the aftermath of the earthquake. Part of these sinkholes may be connected with abandoned mines. However, some of them are probably karst phenomena. It seems that new sinkholes continued appearing. Additionally, as seen in the photos, the slopes of the soil are quite steep, so widening of these holes may be expected with new rains, earthquakes etc.

Figure 6.24. Sinkholes (source: Index.hr news portal).

Figure 6.25. Sinkhole under a house with quite weak foundations (photos: left: Sonja Zlatović, right: Joško Krolo).

Figure 6.26. Sinkhole in Mečenčani (45.2829,16.4298, source Sonja Zlatović).

Figure 6.27. One of sinkholes in Mečenčani (45.2829,16.4299, source: Marijan Car; Mario Bačić and Josip Terzić, 2021).

6.6. Landslides

A series of landslides were analyzed before the earthquake. Various colors of the asphalt on the roads in the hilly area suggest that many small landslides happened often. Figure 6.28 illustrates the Sentinel1 interferogram in distances as far as 30 km from the earthquake rupture, showing that a number of large landslides were triggered (with a few cm of displacement) by the M_w 6.4 Petrinja earthquake (S. Valkaniotis 2021).

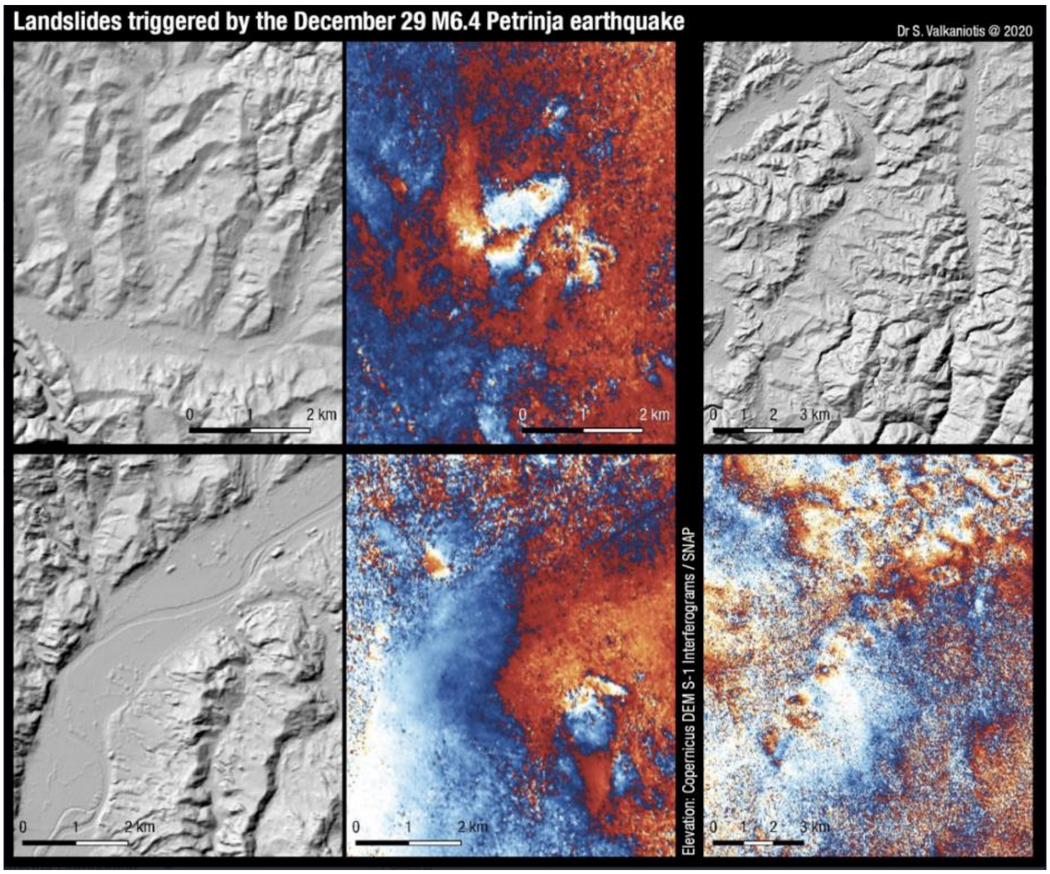


Figure 6.28. Sentinel1 interferogram showing the landslides triggered by the M_w 6.4 Petrinja earthquake. Color images show the phase difference (displacement) for a pair of radar images. Each color fringe from blue to red represents 2.8 cm of ground displacement (relative to satellite position). Gray-scale images show topography (image source and explanation by Dr. Sotiris Valkaniotis 2020).

Figures 6.29 and 6.30 show additional effects of liquefaction and slope stability issues resulting from the earthquake.

Figure 6.29. Neighboring the previously known landslide in Hadžar, is a small farm where various houses started moving down the slope, in different directions. The figure on the left shows a gap opening after the earthquake. The grass covered slope, usually firm even in rainy days, as rain would quickly run off, suddenly became wet and soft - maybe due to liquefaction in the shallow layer, which released water to the upper surface layer (45.3795,16.1199, source Sonja Zlatović).

Figure 6.30. Landslide on the coast of the river Kupa, Letovanić (45.5082,16.2118, source Sonja Zlatović).

7.0 Current Conditions and Access

7.1 Power Outages

The earthquake generated significant power outages throughout the region. Most of Zagreb lost electricity following the earthquake, causing considerable congestion in the road network (Index.hr 2020a). The next morning, the power was returned to all remaining users who reported a power outage in Zagreb, and the supply in the entire city was functioning normally (Jutarnji list 2020).

In the Sisak-Moslavina county, where the earthquake epicenter was located, 150,000 users were left without electricity (Index.hr 2020b). Several towns within this county experienced significant outages. The town of Petrinja and its hospital lost electricity (CNN 2020). A hospital in the town of Sisak lost power immediately after the earthquake but switched to emergency power generators without issues. By 10 pm on the day of the earthquake, the electricity supply was restored for 85% of the network users in the Sisak-Moslavina county (Index.hr 2020c). However, due to damage to the transmission and distribution networks, most of Petrinja and parts of the nearby town of Sisak were still without electricity, with approximately 2,000 and 7,000 users without power, respectively (Index.hr 2020a). By the early morning of the day after the earthquake, large parts of Petrinja and Sisak were still without electricity (BBC 2020). Later that day, HEP, the state electricity provider, reported that there was still no electricity for about 1,300 users from Petrinja and its surroundings and 200 users in Glina and Sisak (Index.hr 2020b). By the evening of the same day, approximately 850 users were left without electricity, 700 in Petrinja and 150 in Glina (Index.hr 2020b).

On December 31st, two days after the earthquake, 150 electricians were still working on fixing the power distribution system (Večernji list 2020). Moreover, by that same day, 30 mobile power generators and five mobile transformers had been delivered to the affected region; however, it was reported that they were still not connected to the power grid (Večernji list 2020).

Power outages also occurred in Glina, Topusko, Dvor, Gvozd, Hrvatska Kostajnica, Sunja, and Velika Gorica, but the power supply was reestablished during the same day of the earthquake (Index.hr 2020a).

Future outages are also expected for safety reasons. HEP announced that they would disconnect severely damaged buildings from the power grid to protect their residents and workers fixing the power grid (Večernji list 2020). Lack of electric power was also reported in the housing containers that were being used as temporary shelter by the displaced population (Index.hr 2021).

7.2 Water Disruption

The town of Petrinja lost running water supply (SFGATE 2020), and there was reported damage to the water supply system in about a hundred places (Index.hr 2020c). A disruption in water supply was also reported in Sisak, Glina, and several nearby villages. Bottled potable water was quickly supplied to the affected region (N1 2020e). Water supply to Sisak and nearby municipalities of Sunja and Martinska Ves was restored the day after the earthquake, and water was declared safe to drink (Sisački Vodovod 2020). Water supply in Glina was restored by January 1, 2021 (Al Jazeera Balkans 2021). The potable water supply in all parts of Petrinja was expected to be restored by January 4, 2021 (N1 2021).

7.3 Cellular Outage

Disruptions in telecommunication services were reported immediately after the earthquake due to an increased number of calls. In most parts, the disruptions lasted less than two hours. However, in Petrinja, Sisak, and Glina, the disruptions lasted longer, and the Croatian Telecom Operator employees were sent to check on the state of the network (Jutarnji List 2020b). Mobile base stations (Figure 7.1) were sent to Petrinja and Glina, increasing the network capacity by 30% and 100%, respectively (novac.hr 2020).

Figure 7.1. Mobile base station sent to the affected region (source: novac.hr 2020).

7.4 Post-earthquake Safety Structural Evaluations

This section is based on the description of the post-building safety evaluations conducted by the Croatian Center for Earthquake Engineering (Hrvatski Centar za Potresno Inženjerstvo, HCPI by its initials in Croatian) after the March 22, 2020 earthquake contained in Šavor Novak et al. (2020) and updated with the similar evaluation being conducted after December 29, 2020.

A few hours after the March 22, 2020 earthquake, experts with prior training to conduct post-earthquake inspections started the evaluation process. They inspected hospitals in the northern central (old) region of Zagreb, which suffered moderate to severe damage. Given the crucial significance for the city's proper functioning, inspections were independently organized to check on the structural integrity of bridges over the Sava river, which crosses the city in the East-West direction. Most of them were built more than fifty years ago. As the number of calls by citizens reporting damage increased with every passing hour, additional professionals with experience in the post-earthquake inspection of buildings and post-war reconstruction activities and experts having the necessary expertise of traditional masonry structures were also incorporated into the safety structural evaluations. Shortly afterward, in cooperation with the Civil Protection Directorate of the Ministry of the Interior, a proposal was made to mobilize civil engineers, structural engineers in particular, through collaboration with the Croatian Chamber of Civil Engineers. Within the first day after the quake, more than 150 engineers started the rapid assessment of building damage, and all of them were provided with conventional protective equipment (hardhats, vests, etc.) as well as health protection to conduct the inspections during the quarantine (e.g., masks, gloves, and hand sanitizers). After a week, the number of volunteers (Figure 7.2) rose to over 500 engineers.

Figure 7.2. A group of engineers volunteered to conduct post-earthquake safety evaluations shown in Zagreb after the March 22, 2020 earthquake (source: Šavor Novak et al., 2020).

The basis for the evaluation form was a template used in a Study on Seismic Risk Mitigation conducted by the Faculty of Civil Engineering of the University of Zagreb in cooperation with the Zagreb's Emergency Management Office. The form was adapted for conditions specific to Croatia from a field manual for post-earthquake inspection developed in Italy at the Joint Research Centre of the European Commission (Baggio et al. 2007). The printed form was used during the first two days (Figure 7.3), but soon after was turned into a digital form using an application based on the ArcGIS Online geo-information platform. The application Collector for ArcGIS was adjusted for collecting on-site information (Figure 7.4) by interactively changing the parts of the form as the evaluators were filling them. The Collector for ArcGIS software was installed both on personal computers and mobile phones. It proved to be very useful during post-earthquake rapid assessments conducted after the Zagreb March 22, 2020, and the Petrinja December 29, 2020 earthquakes. Another application used for on-line reporting of building damage was based on the ArcGIS Survey poll, which enabled map-based direct reporting of damage that also accelerated communication with experts performing the inspections. In addition, the application enabled geospatial monitoring of teams of volunteers in real-time, which facilitated coordination, e.g., sending crews to critical areas. The data were stored in the Esri Geospatial cloud, and searches and analyses of data were conducted daily, with particular importance given to on-site photographs that provided better insight into the condition of buildings.

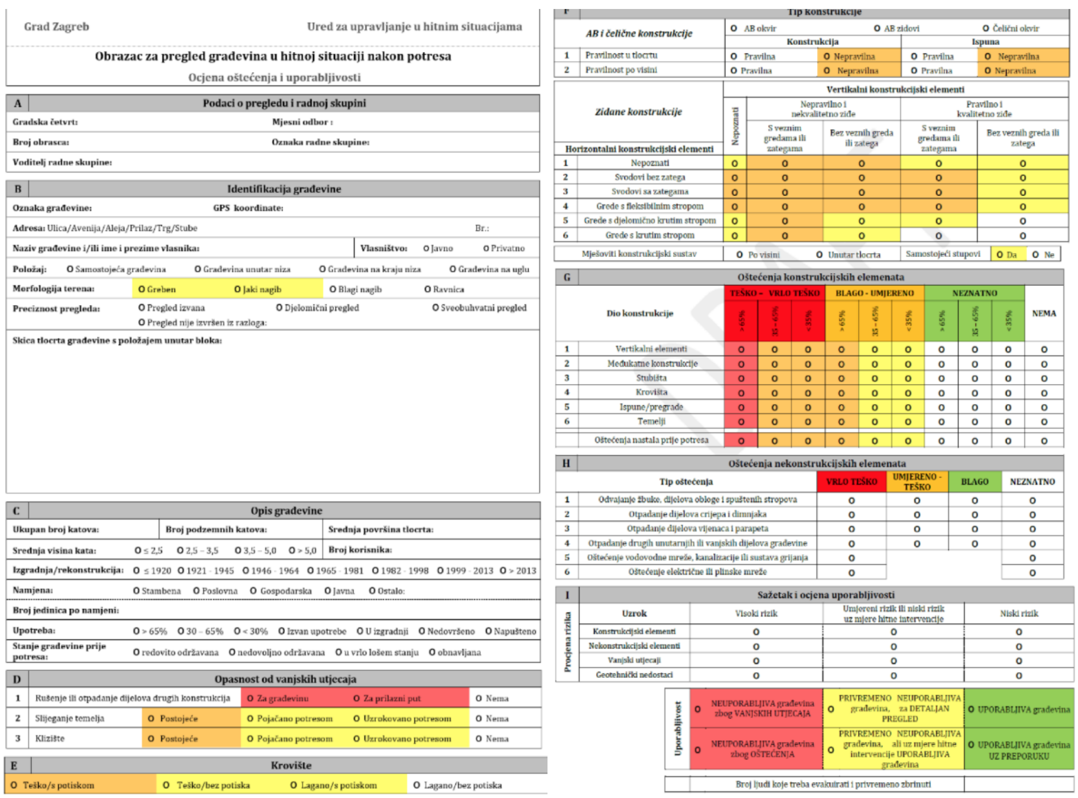


Figure 7.3. Post-earthquake building inspection form used during safety evaluations after the March 22, 2020 earthquake (source: Šavor Novak et al. 2020).

After the on-site assessment of damage, inspected buildings were marked as follows: green (can be used without limitations – U1, or can be used with the recommendation for short-term countermeasure – U2), yellow (temporarily unusable, detailed inspection needed – PN1 or building can become usable after performing urgent interventions – PN2) and red (unusable due to external risks – N1, or unusable due to damage – N2). Fire brigades and municipal services had direct insight into building inspection data, which enabled them to take urgent actions such as removing debris, removing damaged and collapsed chimneys, removing hanging parts of facades, and eliminating other items if considered potentially hazardous to human life. In addition to fire brigades, the insight into the number of damage reports and usable buildings was also provided, depending on the level of authorization, to various municipal services and ministries, which enabled transparency and proper exchange of data at the required level. Special attention was paid to buildings belonging to critical infrastructure, and decisions on their usability were made in consultations with the headquarters and management of these buildings.

Inspections were ended three months after the March 22, 2020 earthquake. As many as 25,528 inspections were performed, with some buildings inspected several times. On 30 June 2020, there were 19,188 buildings evaluated with a green tag (U1 = 10,309 and U2 = 8,879) corresponding to approximately 75 % of the total buildings inspected, 4,998 evaluated with a yellow tag (PN1 = 2,585 and PN2 = 2,413) corresponding to approximately 20 % of the total buildings inspected, and 1,342 of buildings were evaluated as a red tag (N1 = 178 and N2 = 1,164) corresponding to approximately 5 % of the total buildings inspected. An image of a visualization of the HCPI database is shown in figure 7.5.

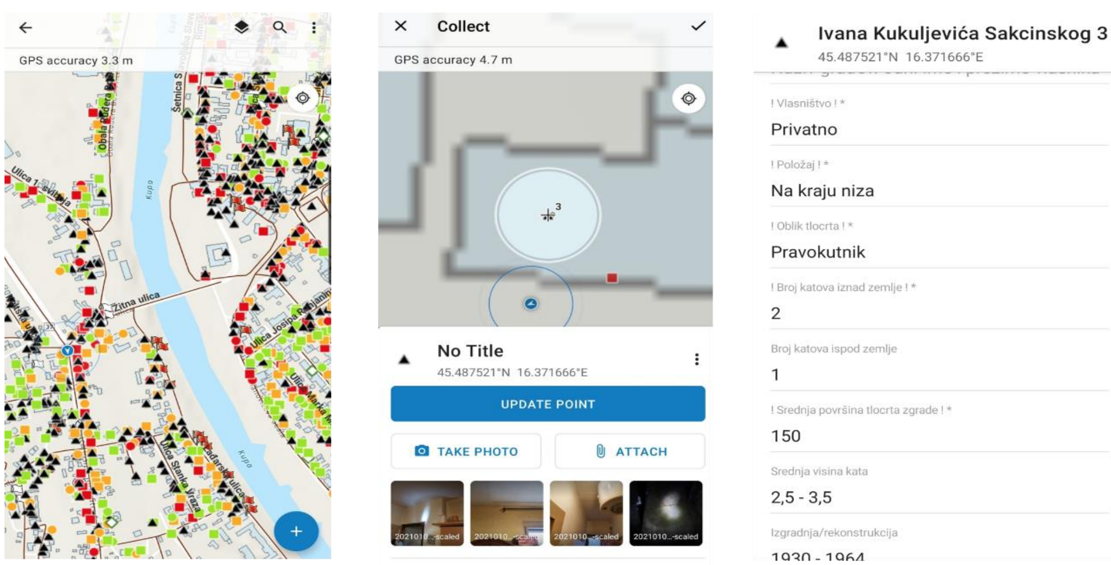


Figure 7.4. Screenshots of Collector for ArcGIS mobile app: (left) map indicating inspected locations where tags are color-coded as well as remaining locations indicated by black triangles, (middle) zoom in on a specific area and associated photos, (right) evaluation fields to be filled out by engineer on site (source: Marko Bartolac).

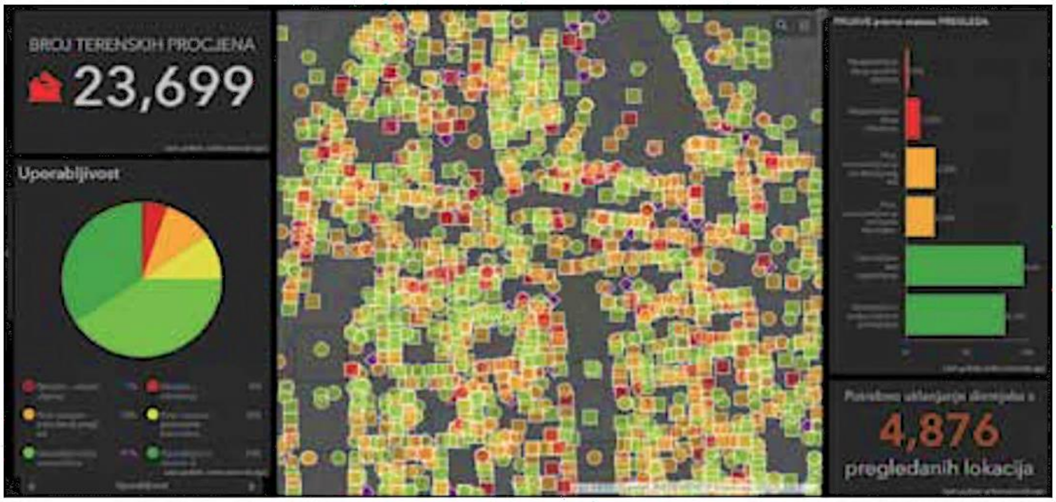


Figure 7.5. Example of the visualization of tagged buildings as of June 8, 2020, in the HCPI database (source: HCPI).

Immediately after December 29, 2020, HCPI started contacting and mobilizing their volunteers to reinitiate some safety evaluation inspections, in the greater Zagreb area but primarily to initiate safety building evaluations in the epicentral region in the Sisak-Moslavina county with emphasis on cities of Petrinja, Sisak and Glina. An example of a red tag form placed on a severely damaged structure is shown in Figure 7.6. The inspection form was adjusted to specific conditions on the field, and a tag U0 (usable - without damage) was added to the usability assessment.

Figure 7.6. Example of red tags used by HCPI during their post-earthquake safety evaluations (Source: Damir Lazerevic).

8.0 Summary and Recommendations

Croatia has a long history of earthquakes. The largest earthquakes in Croatia have typically occurred in the Dinaric Alps region in the southwestern coastal part of the country near the Adriatic Sea. The strongest earthquake in historic times is the Great 1667 Dubrovnik earthquake in which more than 3,000 people lost their lives and most of the buildings in the city were destroyed by the earthquake and the subsequent fire. The December 29, 2020 Petrinja M_w 6.4 earthquake is the largest earthquake to hit the northern central part of the country since the great Zagreb earthquake of 1880 (largest earthquake in the region in 140 years) and the largest earthquake to occur in Croatia since the advent of modern seismic instruments. This earthquake has many similarities to the November 8th, 1909 Pokupsko earthquake, a magnitude 6.0 earthquake that occurred soon after Andrija Mohorovičić had installed a seismograph in Zagreb which led him to collect evidence of the existence of the boundary between the Earth's crust and the mantle that we now know as the Mohorovičić discontinuity, usually referred to as the Moho, in honor of this Croatian seismologist. The 2020 Petrinja M_w 6.4 earthquake was preceded by another strong earthquake that occurred on March 22, 2020 with a magnitude M_w 5.3 which occurred approximately 7 km north of downtown Zagreb. The March 22 earthquake caused one fatality, 26 injuries, and produced some level of damage to up to 26,000 buildings with approximately 1,900 of them being uninhabitable after the event.

The December 29, 2020 Petrinja earthquake struck at 12:20pm local time in the Vukomeric Hills (Vukomeričke gorice in Croatian) and Kupa valley in the Sisak-Moslavina County of Croatia with an epicenter approximately 3 km southwest of Petrinja,12 km southwest of Sisak and about 50 km south of Zagreb, with a hypocenter depth of 11 km. The earthquake was approximately 12 times larger and released about 45 times more energy than the March 22, event that occurred earlier in the year. The Petrinja earthquake caused 7 fatalities and resulted in extensive damage in the cities of Petrinja, Glina, and Sisak as well as in numerous neighboring small towns and small settlements in the region.

According to data of HCPI, who is conducting all of the safety building evaluations, as of January 8, 2021, 12,886 buildings have been inspected out of approximately 30,000 buildings, that their owners or occupants have reported as experiencing some level of damage. Of those that have been inspected 15% were red tagged and judged as not suitable for occupation and 24% were yellow tagged, which rendered them temporarily not suitable for occupation until a more detailed inspection and evaluation was performed. Five schools in the Sisak-Moslavina County will need to be rebuilt and nine others were severely damaged. News agencies covering the earthquake also reported about 825 damaged commercial buildings, 700 damaged buildings with commercial shops, and 13 non-occupiable high-school buildings. More than 250 patients were transported to other hospitals as most buildings in the Sisak hospital had to be evacuated as a result of the earthquake.

In order to put this earthquake into perspective, it is interesting to compare it to some recent earthquakes having similar magnitudes that have occurred in other countries with similar population sizes. One of those earthquakes is the 2011 Christchurch M6.2 earthquake that struck New Zealand, a country which has practically the same population size as Croatia. Even though the 2020 Petrinja earthquake was approximately 60% stronger, had an energy release about twice that of the Christchurch earthquake, and affected a building stock that, in general, is much older than that of New Zealand, the impact of the Petrinja earthquake was much smaller. This is primarily because the earthquake in New Zealand occurred essentially within the metropolitan region of the second largest city of New Zealand with a population of almost 400,000 people while the population within 20 km of the epicenter of the Petrinja earthquake was less than 100,000 people. Furthermore, the capital of Croatia, Zagreb and its metropolitan area with a population of approximately 800,000 inhabitants is located approximately 50 km northwest of the epicenter and, for an earthquake of this size, the intensity of seismic waves attenuated approximately 75% prior to their arrival at the capital. Despite the much larger number of fatalities in the Christchurch earthquake (181 vs. 7 deaths) and the much larger economic loss ($40 billion vs. what will probably be less than $3 billion), the long-term impact in Croatia is very likely going to be much larger than that suffered in New Zealand. This is primarily because Croatia has a GDP of only about one fourth of the one of New Zealand and does not have strong risk transfer mechanisms in place as those in New Zealand where there is a strong market penetration of earthquake insurance that subsequently transfers most of the insured losses to other countries through reinsurance contracts. However, the occurrence of the 2011 Christchurch earthquake within a large urban area highlights the large seismic risk of Zagreb, and also of Split/Kastela which is the second largest metropolitan area in the country or of Dubrovnik both located in the region of highest seismic hazard, where a similar or larger magnitude earthquake could occur in their close vicinity.

It is also interesting to put in perspective the Petrinja 2020 earthquake by comparing it to the January 2020 sequence of earthquakes that occurred at the beginning of the same year in southwestern Puerto Rico, whose main shock also had a M_w6.4 magnitude. Puerto Rico is a former colony of Spain and of the United States of America (USA) which is now an unincorporated territory (free associated state) of the USA with a population similar to Croatia (3.8M in Puerto Rico vs. 4.0M in Croatia). The number of fatalities in both earthquakes was very similar (4 in Puerto Rico vs. 7 in Croatia). It is very likely that in both situations, the occurrence of strong foreshocks the previous day (M5.8 in Puerto Rico and M5.2 in Petrinja) played a major role in reducing fatalities by producing significant damage and therefore providing warning about many hazardous buildings. With the Petrinja earthquake happening in winter with mean temperatures in the order of 0ºC (32ºF), and during the COVID-19 nationwide lockdown, this very likely led to a less people walking on sidewalks at 12:20pm in the cities and small towns located near the epicenter. The economic impact of the earthquake is likely to be similar for both earthquakes (in the order of $3 billion) but Puerto Rico is a significantly wealthier territory with a GDP and GDP per capita approximately twice of those of Croatia. Furthermore, being an associated state of the USA and inhabitants of Puerto Rico being US citizens, they had access to aid and funds from the U.S. Federal Emergency Management Agency (FEMA) which is a large federal agency prepared to deal with large natural or man-made disasters. On the other hand, some aspects of the response were better handled in Croatia than in Puerto Rico. For example, despite the access to assistance from a large emergency agency such as FEMA, only a very small number of safety building evaluations had been performed in Puerto Rico six days after the main shock, while in the case of Croatia, the occurrence of the March 22, 2020 Zagreb earthquake had led to the creation of HCPI (within a few hours after the earthquake) which swiftly reconvened their trained volunteers to immediately start doing safety evaluations after the December 28 foreshock of the December 29 Petrinja earthquake with a well-organized day-to-day updated GIS database leading to nearly 13,000 inspected buildings only nine days after the earthquake.

With the Austro-Hungarian Empire having created the first national seismic service in 1897 by E. von Mojsisovicz and with Volosko being the birthplace of the famous seismologist Andrija Mohorovičić who is considered by many as the founder of modern seismology, there is no doubt that Croatia has many excellent seismologists and earthquake engineers that are well aware of the seismic hazard and seismic risk in their country. However, that seismic risk awareness in the scientific and engineering communities has not fully permeated into government officials to be translated into an adequate seismic risk mitigation program and the occurrence of large earthquakes painfully highlights such deficiencies leading to larger impacts on the Croatian society.

Based on observations of our team over 10 days after the occurrence of the earthquake, we provide a few recommendations expressed briefly in the following paragraphs.

1. **Seismic Evaluation and Upgrading of Existing Buildings**. Similarly to what has been observed in many previous earthquakes, loss of life, collapses and severe structural damage was primarily concentrated in old construction built prior to the advent of earthquake-resistant design provisions, particularly in unreinforced masonry buildings. Like other countries, including many countries in the Mediterranean region, Croatia was slow in creating mandatory earthquake-resistant design codes. The first seismic code was introduced in former Yugoslavia in 1964 following the 1963 Skopje earthquake. Therefore, many, perhaps most, buildings in Croatia were built without taking into consideration seismic loading. In contrast, in Japan seismic design started in 1924 when the *Urban Building Law* was updated soon after the great Kanto earthquake of 1923. These structural provisions which included a seismic coefficient of 0.1, were then replaced after World War II by the *Building Standard Law* which included improved provisions which were used in the reconstruction of many buildings after WWII.

   There is no doubt that improving earthquake resistant design provisions and construction of new buildings and other types of structures built according to these provisions will mitigate potential losses from future earthquakes. In particular, the use of Eurocode 8 which is mandatory in Croatia for all buildings since 2017 and which started to be used on a volunteer basis in many projects at least ten years earlier will result in significantly smaller seismic risk to these buildings. However, new construction typically adds less than two percent to the total building stock each year, and probably much less in a country like Croatia whose population has remained nearly the same for the last 60 years, therefore it would take many years before the inventory of existing buildings reflects even the current knowledge of earthquake engineering. Therefore, one of the most effective ways of mitigating potential losses in future earthquakes is to conduct reliable assessment of the seismic vulnerability of existing structures and to develop and implement effective and cost-effective ways to seismically upgrade those identified as hazardous, particularly where loss of life could occur (Miranda, 1991). It is important to emphasize that achieving this goal not only requires adequate engineering solutions but, equally important, a well-thought set of public policies. In recent years the European Union has given special attention to retrofitting existing buildings to improve their energy efficiency but has given significantly less attention to seismic retrofits. Several of the buildings visited as part of this reconnaissance effort had been recently retrofitted to improve their energy efficiency with significant economic investments with little or no attention to seismic retrofit. A notable exception are the joint efforts by the Catholic church and the Croatian Ministry of Culture which initiated the repair and reconstructions of many churches in the Sisak-Moslavina County after the war of independence and many of these projects included an earthquake resistant design. An example of this is the St. Lawrence (Crkva Svetog Lovre) church in downtown Petrinja which, in general, had a very good seismic performance in this event.

We recommend that Croatia accelerates its ongoing efforts (e.g., through collaboration with GEM) on seismic risk assessment and creates technical documents and national standards for the evaluation and seismic upgrade of existing structures with special emphasis on unreinforced masonry (URM), non-ductile reinforced concrete buildings and critical infrastructure such as hospitals and bridges, which could be added specifically as the Croatian National Annex to the Eurocode 8. However, development of the methodologies, technical guidelines and national standards is not enough, it must be accompanied by the development of carefully thought public policies to incentivize and, if necessary, mandate its application together with an adequate timeframe for its implementation. The development of these policies, gaining advocacy for them and achieving their issuance and implementation is very challenging, even in large wealthy countries.

There are many legal and political barriers in addition to technical and economic challenges. For example, in the United States efforts to identify and seismically retrofit existing buildings were initiated as early as 1933 in a document known as the Field Act which was passed in response to the 1933 Long Beach earthquake. The Act ensures compliance with stringent design regulations through rigorous plan review and enhanced field inspection and testing for all new public-school buildings for grades kindergarten through 14th grade (K-14) in the state of California. The 1939 Garrison Act subsequently required that all pre-Field Act public K-14 school buildings receive a seismic evaluation and be retrofitted to meet the requirements of the Field Act. In 1971 the city of Long Beach passed the first ordinance in the United States for mandatory comprehensive strengthening of buildings. The ordinance applied to all non-wood frame pre-1934 buildings, including buildings with non-load bearing unreinforced masonry walls and concrete buildings. Similar ordinances were passed in the city of Los Angeles not until 1981 and not until 1992 in the city of San Francisco.

While carrying out a comprehensive seismic retrofit of old URM buildings is the best solution, particular for critical and historical buildings, it can be quite costly and therefore onerous to building owners. A complementary approach which can be achieved in a shorter timeframe and with smaller expenditures is the issuance of public policies aimed at reducing the seismic risk in URM buildings by addressing only specific components typically present in this type of buildings. For example, the city of Los Angeles was the first local government in the United States to pass a retroactive URM seismic ordinance in 1949 for parapet correction. Essentially all buildings were in compliance by the 1960s. Similarly, in 1959 the city of Long Beach issued local amendments to the building code that gave the building official authority to abate parapets and other appendages that posed falling hazards and most parapets in the city were reportedly abated again by the 1960s. More recently, in 1976, the city and county of San Francisco enacted its Parapet Safety Program, which required owners to retain a structural engineer to provide a seismic assessment of parapets, which applied to all pre-1949 URM buildings posing falling hazards to public sidewalks or occupied spaces. For various document describing the development of successful risk mitigation programs to URM buildings the reader is referred to (California Legislature,1986; EERI, 2004; EN 1998–3, 2005; FEMA 2005, 2009; CSSC 2006, 2020; NZSEE 2006; MiBAC, 2010; Ingham et al. 2011; Paxto et al. 2013, 2015a, 2015b; D'Ayala and Paganoni, 2014; Amore, 2016; Brower, 2017).

We recommend that, as a first step with a shorter timeframe for its implementation, Croatia develops public policies aimed at reducing risk to lives posed by specific components commonly present in older URM buildings not only for Zagreb but for the whole country. In particular, we recommend that these public policies include the following three aspects: (1) tying floor diaphragms to URM walls by means of steel rods, steel anchors or other structural components aimed at reducing the possibility of experiencing an out-of-plane failure of the URM walls; (2) laterally bracing URM parapets and gable roofs; and (3) strengthening, bracing or even replacing older URM chimneys. The costs of these interventions are relatively small relative to the replacement cost of these constructions and can significantly reduce the risk posed to occupants and people in the vicinity of these buildings and to adjacent buildings. We recommend that previous efforts in other countries such as those previously mentioned in California, but particularly those in other European countries, be carefully studied as a starting point for the development of technical documents and public policies specific to Croatia. Croatian colleagues should be commended for developing guidelines for emergency repairs shortly after the March 22, 2020 earthquake (UPPO 2020) and we recommend that this material be improved and also recommended for seismic upgrading of structures in other seismic regions of the country even if they have not been damaged.

2. **Seismic Instrumentation.** Croatia has a long history of seismic instrumentation as well as of making significant contributions to modern seismology from measurements made in those early seismographic stations. However, political and economic hardship created

by WWII, and in particular by the war of independence in the 90s, have led to a relatively small seismic network that lags those in many other seismic regions of similar size and level of seismicity. Currently the Croatian Seismological Service Network operates the permanent Croatian State Seismological Network run by the Croatian Seismological Survey consisting of 17 broadband, mainly Güralp instruments with the exception of two Lennartz and two STS-2 seismographs. Additionally, the City of Zagreb operates the Zagreb-Net subnetwork (Ivancic et al., 2017). Other networks are the Seismicity of Croatia, the Velebit and the AlpArray CASE temporary networks for specific research projects. In total there are only 23 permanent stations currently operating in Croatia. The National Network of Reference Stations operates the CROPOS system with 33 Global Navigation Satellite System (GNSS) stations distributed throughout the country. These stations are part of the European Permanent Network (EPN) and are aimed at collecting satellite measurements and calculating correction parameters and are primarily used for accurate geodetic positioning for navigation, surveying and related activities but can also be used for geoscience research to determine relative plate motions. It is not clear if these Croatian GNSS stations have sampling rates that allow the recording of waveforms useful to engineering purposes.

Without seismic records it is not possible to determine the ground motion intensities that led to the collapse or severe damage of various types of structures in the epicentral region. Similarly, it is not possible to determine the ground motion intensities that many other structures were able to sustain without damage. Being able to compare and analyze recorded ground motion intensities with observed performance is key to the development of fragility and vulnerability functions and to reducing the variability in them, key to improving ground motion prediction models to estimate ground motion intensities in future earthquakes, key to improve design spectra and in general of utmost importance to improve earthquake-resistant design. The learning potential from this earthquake is, unfortunately, *severely hampered* by the lack of seismic instrumentation in the epicentral region and we have to rely on field observations and very rough estimates of ground motion intensity near the source which, unfortunately, is not much different to what A. Mohorovičić did more than 100 years ago after the 1909 Pokupsko earthquake.

We recommend that seismic instrumentation be significantly expanded in Croatia. In particular, we concur with the Department of Geophysics of the University of Zagreb that there is a need to expand the accelerograph network in the wider Zagreb area which is one of the most active areas in Croatia and concentrates approximately one fifth of the country's population. Similarly, we recommend that local accelerograph networks be installed with at least ten stations in the cities of Split/Kastela and Dubrovnik which are located in the region of highest seismic hazard in the country and a smaller network of at least five accelerographic stations in the city of Rijeka, the third largest city in the country with a moderate seismic hazard. It is recommended that these accelerographic stations in urban regions be planned and coordinated by seismologists jointly with geotechnical and structural engineers as seismological and engineering networks often have different goals and a collaborative approach between seismologists and engineers can maximize *the benefits for mitigation of seismic risks. This is the approach that is used, for example, in Puerto Rico where two separate, but well-coordinated networks exist. We additionally recommend studying the possibility of installing at least one downhole array in the Sisak/Kupa valleys and at the Krško- Brežice deposits where soil deposits have liquefied in at least 3 different earthquakes and the risk of liquefaction is very high. Such instrumentation array could provide valuable information to improve our understanding of liquefaction and, in particular, of liquefaction-induced deformations. The array at the Krško-Brežice could perhaps be installed as a cooperative project between Croatia and Slovenia as part of the seismic monitoring of the jointly-operated nuclear power plant near the border. Significant underground earthquake-triggered activity in areas with limestone and karst underlying alluvial deposits led to appearance of more than 30 sinkholes in the area south of Petrinja towards Hrvatska Kostajnica. We recommend to periodically monitoring this activity by areal imaging and documenting spatio-temporal changes in terrain morphology. This is specifically important for future urbanistic developments and plans in this presently rural area.*

We recommend that Croatia also seismically instruments a small number of modern multistory buildings and at least one historic structure (e.g., the cathedral of St. Lawrence at Trogir and/or the cathedral at Zagreb) even if it is done with only a small number of channels. Seismic motions recorded on instrumented buildings allow us to improve our modeling of these structures and in particular to improve our current understanding of soil-foundation-structure interaction effects and energy dissipation mechanism in buildings.

3. **Post-earthquake safety evaluations.** Post-earthquake safety evaluations play a key role in the aftermath of any strong earthquake, but this is particularly important when earthquakes with magnitude larger than 5.0 occur at or near urban areas. These evaluations allow the prompt identification of hazardous buildings that should not be occupied given the damage they have sustained as a result of the earthquake and, equally important, also allow occupants to reoccupy their buildings if they are safe to do so therefore reducing the demands on post-emergency temporary shelters. The creation of the Croatian Center for Earthquake Engineering (Hrvatski Centar za Potresno Inženjerstvo, HCPI by its initials in Croatian) after the March 22, 2020 earthquake which is a joint initiative of the Faculty of Civil Engineering of the University of Zagreb in cooperation with the Emergency Management Office of the city of Zagreb, the Civil Protection Directorate of the Ministry of the Interior and the Croatian Chamber of Civil Engineers is a commendable effort that gathered, organized and trained many volunteers who provided a valuable service after the March 22, 2020 earthquake primarily in the wider Zagreb area and now again providing it after the December 29, 2020 earthquake.

   We recommend that the cooperation with Italian and other European research centers such as Eucentre's MATILDA (MultinATIonaL module on Damage Assessment and countermeasures) Project be continued and expanded based on experiences gained from these two earthquakes. Post-earthquake safety evaluations of buildings are *challenging even for experienced structural engineers with good training due to limited prior experience in conducting these evaluations. These evaluations require not only a good understanding of local construction methods, but also a thorough understanding of load paths in the structure both under gravity loading and when subjected to lateral loading. In particular, engineers conducting these post-earthquake evaluations need to identify damage that may jeopardize the vertical-load-carrying capacity of various elements of the structure as well as seismic damage that may have compromised the lateral-load-resisting capacity of the main elements responsible for transmitting the inertia loads to the foundation. This is not an easy task, especially when it must be carried out in a short period of time. Therefore, it is not surprising that some mis-classification errors are produced during this process, either by false positive (e.g., a structure that is incorrectly red tagged) or false negative (e.g., a structure that should have been red tagged but it is not).*

We recommend that HCPI conducts an evaluation of their safety evaluation program and procedures to access the approximate percentage of misclassification. Moreover, we recommend that in a few months HCPI conducts an evaluation of the data-capturing software and GIS-based database to not only document the aspects that worked well or very well, but also those where some problems were encountered to subsequently improve the post-earthquake safety evaluation process in preparation for future earthquakes.

We recommend that the training that has been created by HCPI be expanded and improved and be offered on a regular basis to engineers in various Croatian cities. Furthermore, we recommend that available videos made during evaluations after these earthquakes be expanded with new videos, then carefully select and edit a reduce number of them to improve current training material. Other recommendations entail exploring the possible incorporation of immersive virtual reality experiences by using simple and affordable viewers (e.g., $10 USD Google Cardboard) that would allow engineers to use their smartphones to immerse themselves as much as possible in the post-earthquake safety evaluation experience of various types of structures which experience different levels of damage in this earthquake. This could even also lend itself to the creation of evaluation modules to then test the learning of the engineers by immersing them into other buildings that were not presented as part of the course that they need to placed tags on.

4. **Earthquake engineering education.** Earthquake engineering is a specialized field that gathers knowledge from several disciplines such as geology, seismology, dynamics, soil mechanics, structural mechanics, probability and statistics, modeling and analysis, etc. A significant part of this material is not part of conventional Civil Engineering curricula, particularly after the Bologna process for standardization of higher education in Europe. Although a few excellent Master's degree programs in Earthquake Engineering exist in Europe (e.g., Rose School in Pavia, Italy or Institute of Earthquake Engineering and Engineering Seismology, IZIIS in Skopje, North Macedonia) and the European Erasmus

program facilitates the mobility of graduate students, *we recommend that a well-planned Earthquake Engineering Master's degree program be developed and taught in Croatia to increase the number of professionals with such a background. Ideally, this should be at least an 18-month program which could be perhaps compressed into a 12-month program.*

5. **Earthquake preparedness and awareness raising campaigns for general public.** The two earthquakes that struck Croatia in 2020 confirmed the need for an ongoing earthquake awareness and earthquake preparedness for the general population. *We recommend the development of earthquake awareness and preparedness campaigns, such as those that have been successfully done in other countries such as in the USA (e.g., USGS, 2005, 2006), in Italy (DPC, 2017; Piangiamore, 2017), in Greece (e.g., EPPO, 2015) and in Portugal (e.g., Oliverira et al. 2018, Ferreira et al. 2018) as well as of the need to seismically retrofit existing building.*

In the last 100 years, Croatia (formerly part of the Austro-Hungarian Empire and Yugoslavia) has suffered two World Wars and more recently the cruel war of independence (1991-1995) which was followed by a period of reconstruction and of and mine removal. The COVID-19 pandemic is having a major economic impact in Croatia due to the nationwide lockdowns that have significantly reduced economic activity in the country and drastically reduced tourism which is a significant source of revenue for the country, consequently increasing unemployment. Preliminary World Bank estimates indicate that the pandemic and the March 22, 2020 Zagreb earthquake may reduce Croatia's GDP by 9% in 2020 with most of the recession being produced by the pandemic and not the earthquake (RNDA, 2020). There is no doubt that the still ongoing COVID-19 pandemic and the December 29, 2020 Petrinja earthquake will continue to have a major economic impact on the country for many months to come.

The year 2020 will undoubtedly also be remembered as another period of hardship for Croatia with a combination of the COVID-19 pandemic and two destructive earthquakes. But there is no doubt that Croatians have proven to be resilient and they will recover again from this earthquake. We hope that these two important seismic events will lead not only to a rapid reconstruction of collapsed structures, but that will also mark a turning point to the initiation of a strong seismic risk mitigation program in Croatia.

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