Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake, and Associated Seismic Sequence

Chapter 1: Introduction

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1.0 Introduction

The December 2020 sequence of earthquakes in Croatia started on 28 December 2020 at 6:28 local time, with a magnitude M5.0 with epicenter near Petrinja. It was followed with a M4.7 at 7:49 and a M4.1 at 7:51, with a series of weaker aftershocks. On 29 December 2020 at 12:19, a M6.2 struck, which was felt in all parts of Croatia and neighboring countries. The sequence as shown in **Figure 1.1** continued for 36 days (Croatian Seismological Survey 2021) . The main shock was felt throughout Croatia and the neighboring countries Estimated accelerations are shown in **Figure 1.2** (USGS 2020).

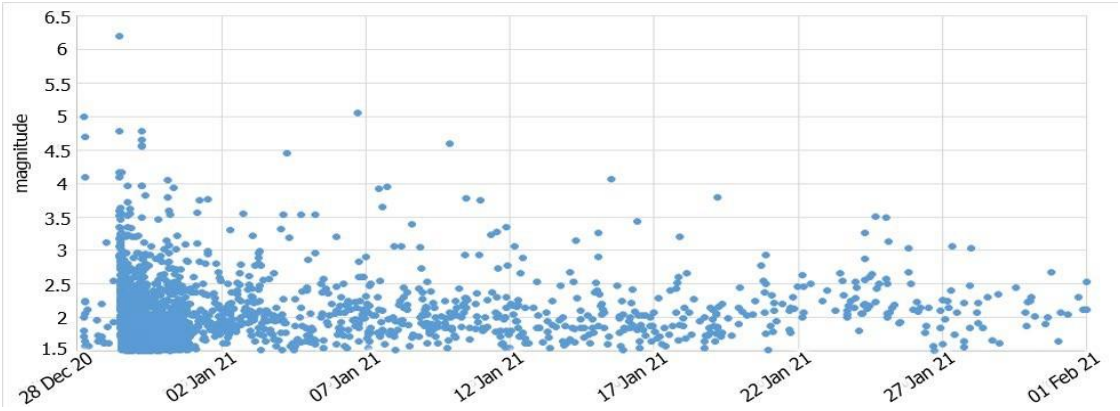

Figure 1.1 Magnitudes of the earthquakes in the Petrinja area from 28 December 2020 to 01 February 2021. (Croatian Seismological Survey 2021).

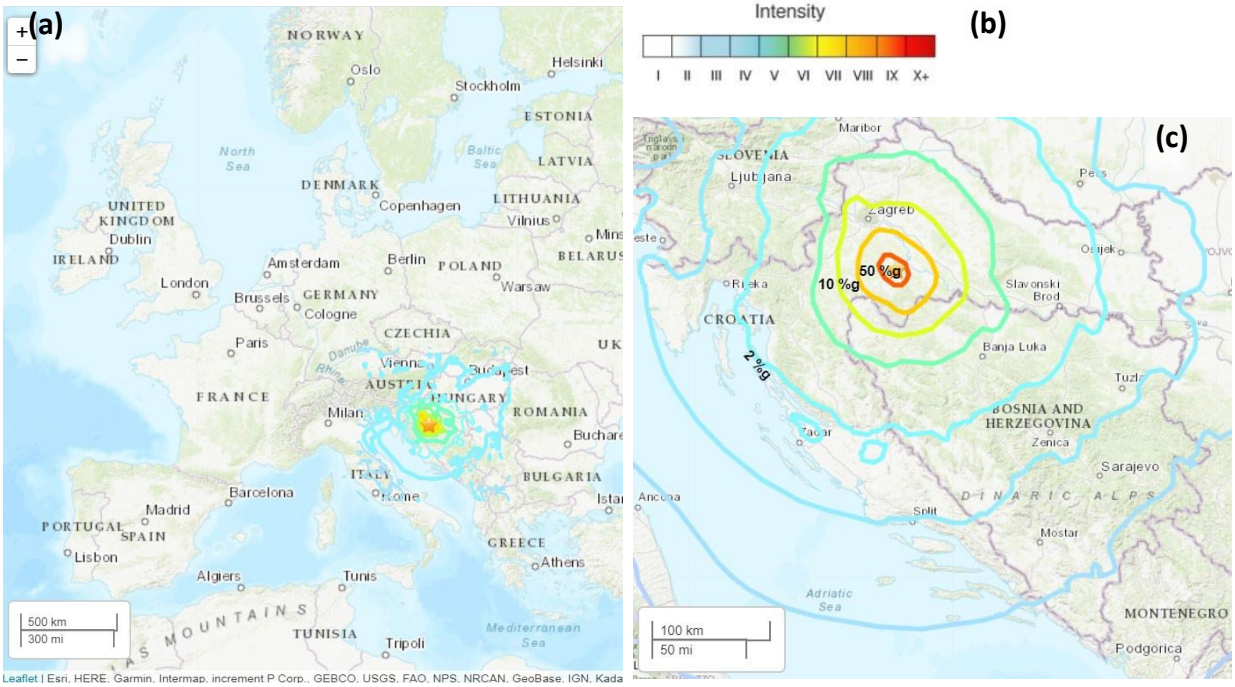

Figure 1.2 (a) Shake map: epicenter and MMI contours. (b) Legend. (c) Estimated accelerations (USGS 2020).

Already the earthquakes in the morning of 28 December 2020 caused damages of some old houses in the area. Therefore, civil engineers, volunteers organized by the Croatian Center for Earthquake Engineering, started inspecting the buildings. This is how some of the engineers got hurt when the M6.2 struck next day. Luckily, weakened houses were already mostly abandoned. Additionally, this happened in the period between Christmas and New Year when schools were closed, with the partial lockdown due to the COVID-19 pandemic. However, seven citizens lost their lives. Immediately after the earthquake, volunteers from all over the country started bringing water, food, clothes, toys etc., taking down the damaged chimneys, repairing roofs and helping in all necessary ways. Organized support intensified, both from the civilians and from civil engineers. Many campers were brought, and many mobile houses and prefabricated houses. The epicenters of the earthquake sequence are shown in **Figure 1.3** with a section of the geologic map covering the area most affected by the earthquake. Some of the most important locations are indicated in the map. Sisak, which has been developingsince Roman times (Siscia), is city of the headquarters of the Sisak-Moslavina County. Petrinja was administrative center for a long time, famous for its meat industry. Glina has an important wood industry. However, in most of the area affected by the earthquake citizens live from agriculture. The area, although very beautiful and pleasant, is one of the least developed areas of Croatia.

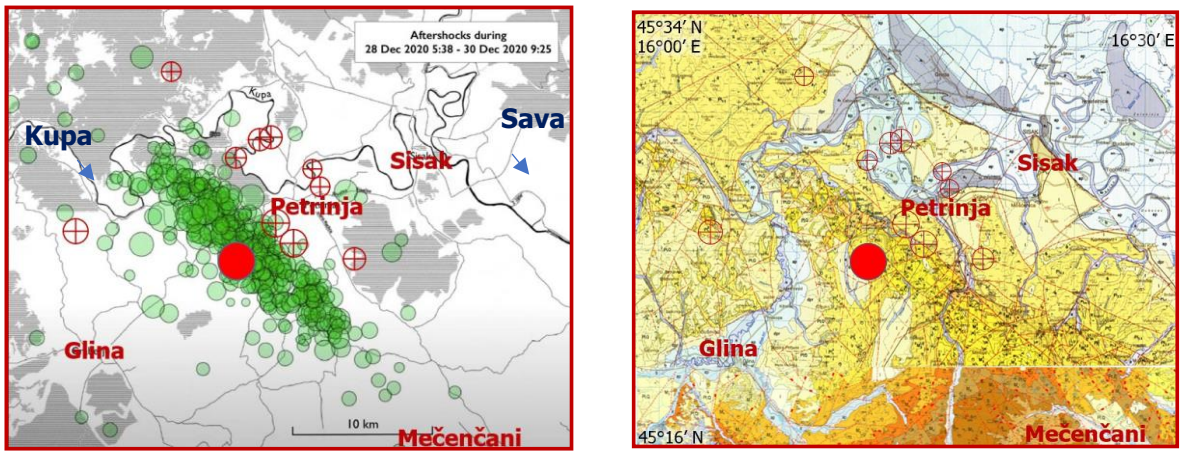

Figure 1.3 (left) The full red circle shows the epicenter of the main shock; the green circles show the epicenters of the earthquakes in the area from 28 December 2020 at 5:38 to 30 December 2020 at 9:25. (Croatian Seismological Survey). Red circles show the epicenters for earthquakes with magnitudes above M2.5 from 28 December 2020 to the end of April 2021 (USGS). **(right)** Corresponding sections of the geologic maps (Pikija 1987, Šikić 2014). Names of some of the main locations discussed in the report are indicated.

Geology of the area is presented in more details in Chapter 3. The area affected by the earthquake is the mostly flat valley of the meandering rivers Kupa and Sava with their tributaries,with mostly soft layers and a high ground water table. The underlaying limestone is visible in rare locations. The levees erected to protect the cities, villages and the fields from the high waters of the Sava and Kupa rivers, were inspected by the geotechnical engineers who later joined the GEER team. Mostly built in or since the 1950s from the local clays, in several stretches, the levees got longitudinal cracks. In some cases, cracks crossed the levee crest, in some cases connection of two levees failed. Measured depth of the cracks is up to 2 m.

Along the toes of the levees sandy ejecta, were often found. Croatian Waters, the institution in charge of flood protection in Croatia, immediately repaired some of the damages, and built secondary levees where necessary. Descriptions of levee damages are presented in Chapter 8. Although liquefaction was observed in the past in Croatia, the sand boiling was a surprise (**Figures 1.4-1.6**). Sand ejecta were found in a series of yards and around family houses in Petrinja, Glina, some villages and in many fields (**Figure 1.7**).

Figure 1.4 Levee south from Stara Drenčina, along the Kupa river. Sand ejecta are visible in front, levee on the left, settlement of the levee in the distance, and secondary levee (white box barrier) on the right side of the photograph (45.4609N, 16.3362E).

Figure 1.5 Sand boiling observed during the main shock in Sisak – a snapshot from the video recorded by Daniel Pavlić (45.4735N, 16.3926E) at the distance of 15km from the epicenter and under the levee along the Sava river.

Figure 1.6 A crack in Brest Pokupski which opened through several yards and houses, ejecting water and sandy soil in time of the main shock (**left** 45.4553N, 16.2628E; **right** 45.4539N, 16.2611E; photos by Igor Gukov).

Figure 1.7 A 15 m long crack with sand ejecta at the football playground in Letovanić (45.5057N,16.1979E).

An overview of the liquefaction damage is given in Chapter 7: air photos were used to recognize some of the locations in Petrinja and Sisak. Some illustrative examples (Petrinja, Glina, Stari Brod) are shown in more details. The Croatian volunteers, geologists and geotechnical engineers, detected sand boils at 85 locations, lateral spreading at 8 and subsidence at 6 (Pollaket al. 2021).

The most prominent, surprising, and relatively rare geotechnical earthquake effect includes the collapse of numerous sinkholes in the time frame of three months after the main shock. Ninety-one new sinkholes collapsed within a 4km^2 area surrounding Borojevići and Mečenčani villages between Petrinja and Hrvatska Kostajnica. Sinkhole diameters vary from 1 m to 25 m, with a maximum depth of 11.7 m. Cover-collapse sinkholes occurred in the past but very sparsely and were considered rare events. Residents refer to historical sinkhole events through jokes, such as saying, “I wish your field turned into a pond”. The GEER team registered 136 sinkholes, 91 which opened after the 29 December, and 45 old ones, as well as three potential sinkholes, as shown in Chapter 6, together with an overview of the geological and hydrogeological characteristics of the area, and details of the most interesting sinkholes. The geotechnical and geophysical investigations consisted of 61 nanometrics ambient noise readings, four geotechnical boreholes, two Multichannel Analysis of Surface Waves (MASW) profiles, and one compound electrical resistivity tomography (ERT) profile performed by the joint effort of the US and local GEER teams in the period between March 15 and March 26. The comprehensive database of lidar images of around 60 sinkholes is available as open-source in DesignSafe Data Depot. The most interesting sinkholes are presented in detail in Chapter 6, with the results of geotechnical and geophysical investigation. Chapter 10 describes details of the extent of complementary investigation works. **Figures 1.8 - 1.10** show some characteristic examples. Although not included as part of this GEER report, the Croatian company Terra Compacta in cooperation with the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, performed geophysical investigations in the area, in order to find a safe location for the temporary container settlement for the villagers of Mečenčani and Borojevići,

and to inspect the roads. The Croatian companies Karst and Geotehnički studio performed borings in order to inspect safety of some houses, however, still uncertainty remains.

Figure 1.8 The largest (diameter of 26m) of the sinkholes which opened a week after the main earthquake in Mečenčani (45.2833N, 16.4259E; 26 February 2021).

Figure 1.9 (a) One of the previously known sinkholes with pond containing spring (45.286953N, 16.426297E). (b, c) a sinkhole which opened under an unoccupied house two days afterthe main earthquake (45.283, 16.4295) photographed on 4 January and 15 February 2021.

Figure 1.10 Deformed ground surface in the previously flat field as a potential sinkhole near Borojevići (45.2963N,16.4140E) on 19 March 2021.

Some landslides were affected or initiated in the area. **Figure 1.11** shows sliding in Hađer, at the distance of around 8km from the epicenter. The Croatian volunteers, geotechnical engineers and geologists, detected 36 slides and 4 rockfalls Pollak et al. (2021). The data will be presented on the pages of the Croatian Geologic Survey (www.hgi-cgs.hr).

Figure 1.11 Sliding in Hađer on the top of a hill, (a) in three directions (45.3795N, 16.1200E; Bačić & Terzić 2021). Ground is recognized by the farmer as exceptionally soft (b) consequent gap opening (45.3793N,16.12016E). (c) An existing landslide situation worsened in the earthquake (45.3798N,16.1198E).

Damages on infrastructure - several bridges and roads are presented in Chapter 9. **Figure 1.12** shows Brest bridge near Petrinja after the earthquake. **Figure 1.13** shows building damage.

Figure 1.12 Bridge Brest after the earthquake (45.4481N,16.2600 E).

The tectonic setting of the area is given in Chapter 2, and an overview of geology and soil characteristics is given in Chapter 3. Additional perishable data are given in following chapters. This was the largest earthquake to occur in Croatia since the advent of modern seismic instrumentation, and the important earthquake which happened in the area in the year 1909 in Pokupsko, or Pokuplje, in the river Kupa valley. Andrija Mohorovičić, the Croatian meteorologist and seismologist on this occasion corresponded with many prominent seismologists, compared data from 36 seismic stations and proved the existence of the crust- mantle boundary later named Mohorovičić discontinuity, or Moho (Herak & Herak 2010). Some recorded ground motions are presented in Chapter 4. Interferometric Synthetic Aperture Radar (InSAR) was used to analyze the ground surface deformations induced by the 29 December 2020 earthquake, as shown in Chapter 5. Croatian State Geodetic Administration (Državna geodetska uprava) published precise geodetic measurements of the fixed points of geodetic basis at their web pages (State Geodetic Administration 2021). Chapter 10 gives complementary geotechnical and geophysical investigation works.

(a) **(b)**

Figure 1.13 Photos of the damaged buildings after an earthquake rocked (a) Sisak, and (b) Petrinja, Croatia (Source: Miranda et al., 2021), Coordinates of the photo (a) 45.476794, 16.368347, and (b) 45.441082, 16.277061).

Socio-economic and COVID-19 pandemic impacts

The 6.4 magnitude Petrinja, Croatia earthquake occurred on December 29, 2020. The importance of this time is multifold: The quake happened right between Christmas andNew Year's Eve, while children were out of school due to the winter break and families were gathered at home. In addition, the nationwide lockdown, mitigation measures, and travel restrictions due to the COVID-19 pandemic were in place at the time of the earthquake, which made the emergency response even more challenging than usual. Lastly, the 6.4 Petrinja, Croatia earthquake occurred only nine months after the devastating March22, 2020 earthquake of magnitude 5.3 Mw, which hit Croatia's capital Zagreb 50 km northwest of the Petrinja earthquake epicenter. Thus, the event had a severe psychological impact on people due to overlapping extreme events. The city of Sisak mainly developed afterthe 2nd World War as a modern industrial city with rich cultural life. In contrast, the town of Petrinja, due to its administrative role, has a distinctive old city center, with most of the residents living in family houses. Many of the homes in the area were built by their owners.After the war in the 1990s, the damaged houses were repaired or rebuilt by the state. Some single-story residences were later added with an extra floor by their owners. Consequently, there has been no extensive geotechnical investigation even though liquefaction occurred in the area a century ago.

A series of Croatian structural engineers who were inspecting the buildings contributed to the report. The structural engineers together with architects and other civil engineers, as volunteers, were invited and organized by the Croatian Center for Earthquake Engineering, HCPI. The citizens were invited to report on the damages, and the group of volunteers performed the preliminary inspection of the buildings. Total number of reported damages and an overview of the estimates is given in **Figure 1.14** for the 8 January and **Figure 1.15** for the 21 May 2021.

Figure 1.14 Results of the damage estimates on buildings after the earthquake near Petrinja in the year 2020 on the 8 January 2021, 11 days after the main shock (HCPI, 2021).

Figure 1.15 Results of the damage estimates on buildings after the earthquake near Petrinja in the year 2020 on the 20 May 2021 (HCPI, 2021).

Scope of USA-Croatia GEER Reconnaissance

A starting point to the present report was the preliminary hybrid reconnaissance reportjointly prepared by Earthquake Engineering Research Institute (EERI) - Learning From Earthquakes (LFE) Program and the Structural Extreme Events Reconnaissance (StEER) Network, where several members of the Geotechnical Extreme Events Reconnaissance Association (GEER) team also participated. A preliminary list of locations with liquefaction, landslide, lateral spreading, sinkholes, and damage to levees was prepared as part of the joint EERI's LFE and StEER reconnaissance report, which was then subsequently expanded as part of this investigation (Miranda et al., 2021).

List of Figures taken from the EERI'S LFE and StEER report:

- Figure 6.2. Soil properties in the area from the thermal electric power plant in Sisak, Čret (45.4538, 16.4145) (source: Conex, Zagreb).
- 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 4.6. Collapsed URM buildings in downtown Petrinja (a) before the earthquake (Source: Google Earth) and (b) after the earthquake (source: Nenad Bijelić).
- Figure 4.42. Building #2: (a) front view and (b) back view (source: Croatia Week 2021, Jan 5).

Immediately after the December 29 earthquake, a joint GEER team formed between the Croatian scientists and engineers (local team) and the GEER sponsored by the U.S. National Science Foundation (NSF). The local reconnaissance team, media, volunteers, and Croatian state-owned companies Croatian Waters – Hrvatske Vode Ltd. Croatian Roads – Hrvatske Ceste Ltd. conducted field observations and collected liquefaction and infrastructure damage data right after the main event. The second GEER team consisted of one US-based researcher and local team members who visited the affected region between March 15 and 26, 2021, to perform additional geotechnical investigations. The GEER team organized geotechnical investigation works mainly around Mečenčani and Borojevići. A substantial number of sinkholes appeared in the two months following the mainshock, from January until mid- March 2021.

Survey Regions and Methods

The local and the U.S. GEER teams performed ground-level surveys and detailed inspections throughout the affected region (Petrinja, Siska, Glina). During the U.S. GEER team visit in March 2021, the field investigations followed: four geotechnical boreholes, in-situ soil classification, and index tests, two Multichannel Analysis of Surface Waves (MASW) profiles in Mečenčani and Borojevići, and two in Petrinja on-field liquefaction site and 65 Horizontal-to- vertical Spectral Ratio seismic method (HVSR) measurements, 61 HVSR in Mečenčani and Borojevići and four HVSR in Petrinja near MASW's. In addition, the GEER team analyzed the ground surface deformations induced by the main event with the Interferometric Synthetic Aperture Radar (InSAR).

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