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

Chapter 7: Liquefaction and Related Building Damage

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7. Liquefaction and Related Building Damage

The December 29, 2020, Petrinja earthquake caused widespread liquefaction with extensive surface manifestations. Most of the surface manifestations of liquefaction were observed in the predominantly flat valleys surrounding the Kupa and Sava rivers and their tributaries. These locations were close to the epicenters of the main shock and aftershocks (**Figure 7.1**). Both the Kupa and Sava rivers have been meandering, producing alluvial deposits (**Figure 7.1**) with up to 50-m depths, primarily layers of soft clay, silt, and sand. Liquefaction effects were identified in many streets in Petrinja, Glina, Stari Brod, some villages and surrounding fields. Liquefaction was also present along several stretches of levees, as discussed in Chapter 8.

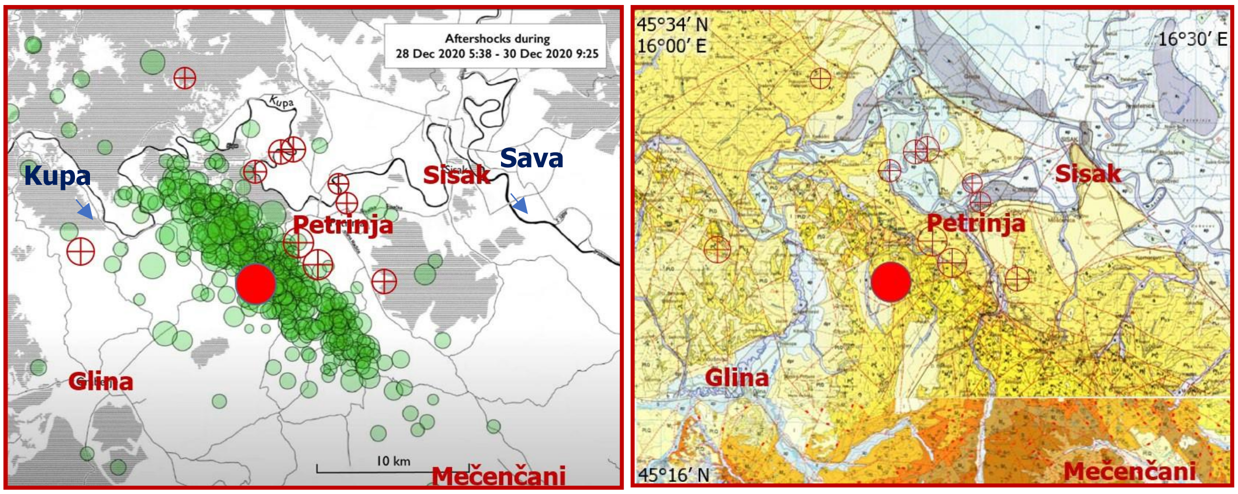

Figure 7.1 Full red circle shows the location of the main shock M_w 6.4, green circles indicate earthquakes from December 29, 2020, to December 30, 2020, at 9:25 a.m. (Croatian Seismologic Survey 2020), and red circles show aftershocks with magnitudes above 2.5 (USGS Earthquake Catalog). On the right is the appropriate section of the geologic maps Sisak (Pikija 1987) and Bosanski Novi (Šikić 2014). The locations of the most damaged cities and villages mentioned in the text are shown on both figures.

The city of Sisak developed mainly after the 2nd World War as a modern industrial city with rich cultural life, while the town of Petrinja, due to its administrative role, has a distinctive old city center, with most of the residents living in family houses. Most of the family houses in the broader area affected by the earthquake are founded on shallow foundations and have no basements. This is due to the groundwater table being very high in the area. Many of the houses 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 had an extra story added by their owners. Consequently, there had been no extensive geotechnical investigations even though liquefaction occurred in the area a century ago (discussed in Section 7.2). Pre-earthquake geotechnical investigations were performed for the Sisak Refinery, Sisak Thermal Power Plant, and a series of buildings in areas where no liquefaction occurred due to this earthquake.

7.1. Geological Information

The region where liquefaction was observed is underlain by Quaternary alluvial deposits (**Figure 7.2**). The primary geologic units in the affected areas are Holocene floodplain (ap) and terrace deposits (a_1) near the active river channels along with deluvium-proluvium (dpr). Only few locations with liquefaction effects were identified in the Pleistocene and Pliocene deposits ($Pl_{2,3}$ and Pl_Q); however, all of them were located near the contact with the Holocene deposits near Glina and Petrinja. Given the scale and date of the geologic map, the locations of these contacts are approximate; hence, and it is likely that these observations occurred within the Holocene sediments.

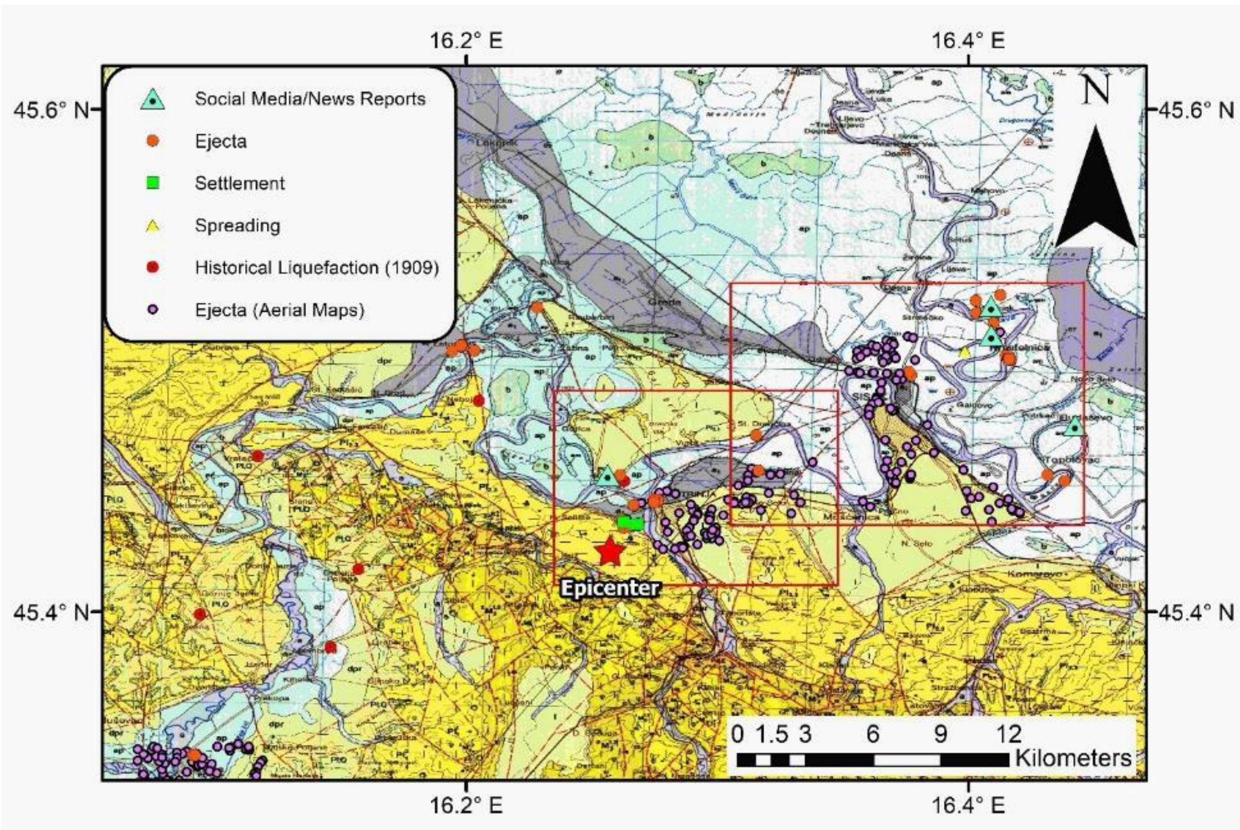

Figure 7.2. Geologic map of the study area showing locations of liquefaction observations. The red boxes indicate the extent of the focused maps of Petrinja and Sisak. Historical observations from the 1909 earthquake were mapped based on the LIQUEFACT GIS database (Lai et al. 2018). The translated legend of the geologic map from Pikija (1987) is shown in **Figure 7.3**.

Figure 7.3. Legend for geologic maps from Pikija (1987). Translated from Croatian.

Moreover, Figure 7.4 shows the geologic units in the Petrinja region along with the liquefaction observations and historical reports of liquefaction (discussed in a subsequent section). The epicenter of the earthquake was located approximately 2 km west of Petrinja (**Figure 7.4**). Many of the locations where ejecta were observed occurred along with the contact between the terrace sediments (a_1) and the flood sediments (ap) or within the area mapped as diluvium-proluvium (dpr).

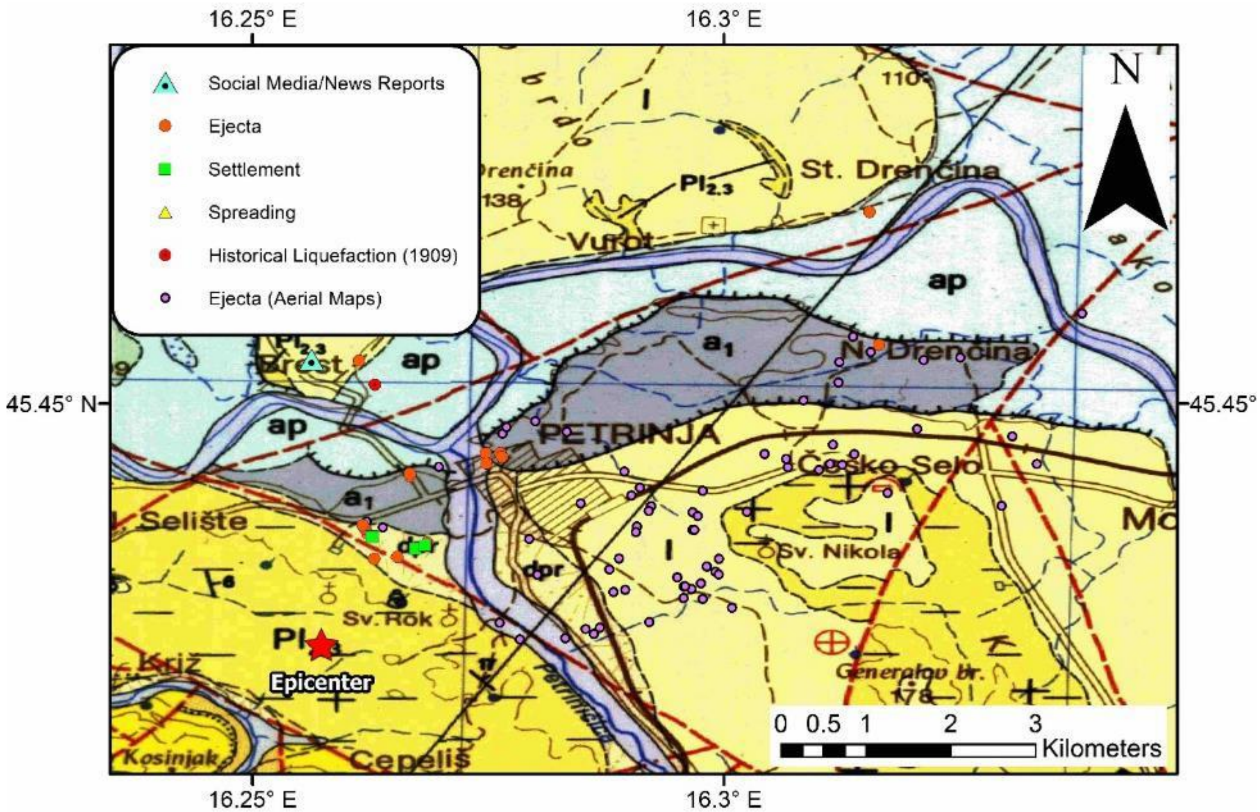

Figure 7.4. Geologic map of the Petrinja region showing locations of liquefaction observations. A single observation from the 1909 earthquake was in this region (Lai et al. 2018). The translated legend of the geologic map from Pikija (1987) is shown in **Figure 7.3**.

Finally, **Figure 7.5** shows the geologic units in the Sisak region along with the liquefaction observations and historical reports of liquefaction (discussed in subsequent sections). All of the locations where ejecta were observed occurred within the flood sediments (ap). All of the observations were relatively close to the active river channels.

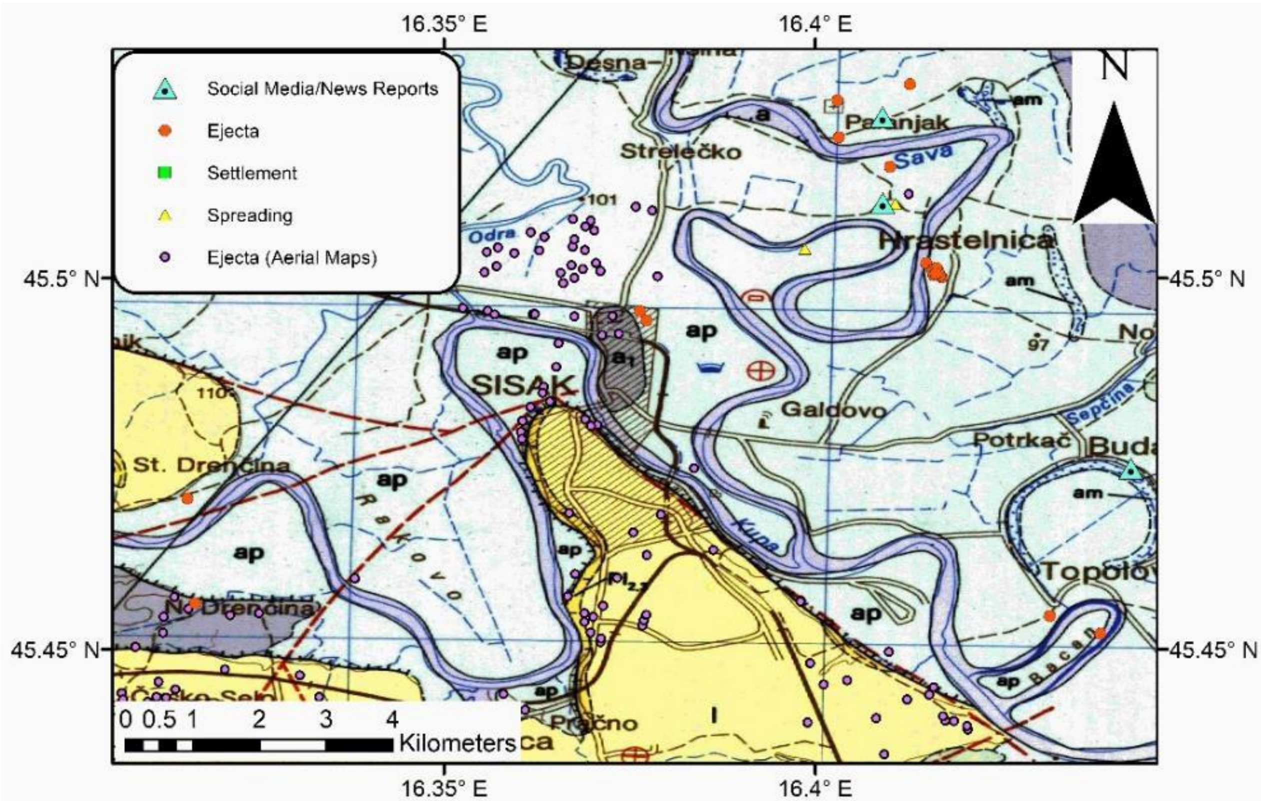

Figure 7.5. Geologic map of the Sisak region showing locations of liquefaction observations. No observations from the 1909 earthquake were mapped in this region. The translated legend of the geologic map from Pikija (1987) is shown in **Figure 7.3**.

7.2 Historical Observations

Croatia is a country with rather high seismic activity and several occurrences of liquefaction during earthquakes have been documented over the years, e.g., Dubrovnik 1667, Virovitica 1757, Zagreb 1880, and during the Dubrovnik and Montenegro earthquake of 1979 (Veinović 2007). The historical evidence also confirms that liquefaction is not a new hazard for the areas surrounding the Kupa and Sava rivers. In 1880, six cases of water gushing from the earth alongside the formation of sand boils were during the November 9 Zagreb earthquake (Torbar, 1882, after Veinović et al. 2007). The 1909 Kupa valley earthquake also produced cases of liquefaction. 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 and Herak 2010). Brežice also lies by the Sava River northwest of Zagreb. **Figure 7.6** 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) 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 the 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. (2007) clearly indicates that some areas around rivers in Croatia have a high liquefaction potential.

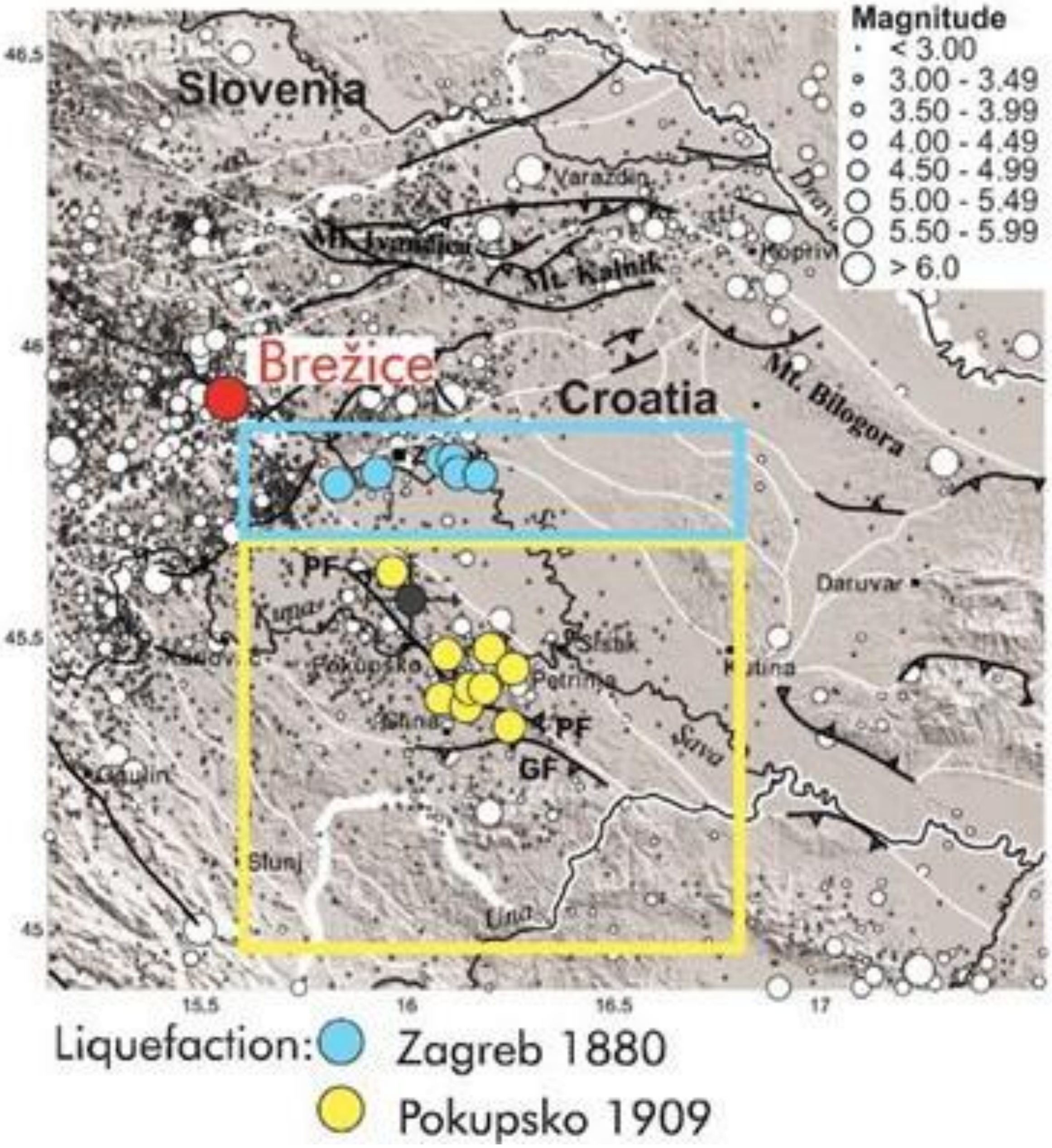

Figure 7.6 Epicenters of earthquakes at the Krško-Brežice field and in its close surroundings from 567 to 2007 AD, alongside with the locations where liquefaction-related effects were observed during the Zagreb (blue dots) and Kupa Valley (yellow dots) earthquakes (Veinović et al. 2007, Herak and Herak 2010) (after Smolar et al. 2019).

7.3 Liquefaction Observations following the December 29 2020 Petrinja Earthquake

Liquefaction observations were documented using reports from residents, observations from field visits, social media reports, and mapping using aerial and satellite images of affected regions. Post-earthquake digital orthophotographs for Drenčina, Glina, Mošćenica, Petrinja, and Sisak were developed by the Faculty of Geodesy at the University of Zagreb, while the corresponding aerial photographs were acquired by the Croatian Mountain Rescue Service (HGSS) (© OpenStreetMap contributors). High-resolution satellite imagery was available in Google Earth for regions around Petrinja and Sisak. The orthophotographs were visually inspected for traces of liquefaction ejecta. Evidence of ejecta was mapped manually with points recorded (shown as purple circles in **Figures 7.2**, **7.4**, **7.5**, **7.7**, **7.8**, and **7.9**). An example of one of the sites where ejecta was mapped is shown in **Figure 7.10**. The mapped locations near Petrinja and Sisak are shown in Figures **7.7** and **7.8**, respectively. Locations with liquefaction observations near Glina are shown in **Figure 7.9**. Importantly, the absence of ejecta away from Drenčina, Glina, Mošćenica, Petrinja, and Sisak and near the Kupa, Sava, and Odra rivers is not necessarily due toany mitigating effects but due to the limited coverage of aerial photographs. The locations of ejecta marked by triangles colored in cyan in **Figures 7.2**, **7.4**, **7.5**, **7.7**, and **7.8**, are approximate as they are based on news and social media reports (Buljan 2021, Jakubin 2020, Kovač 2021, Milotić and Uremović 2021, Šarčević 2021).

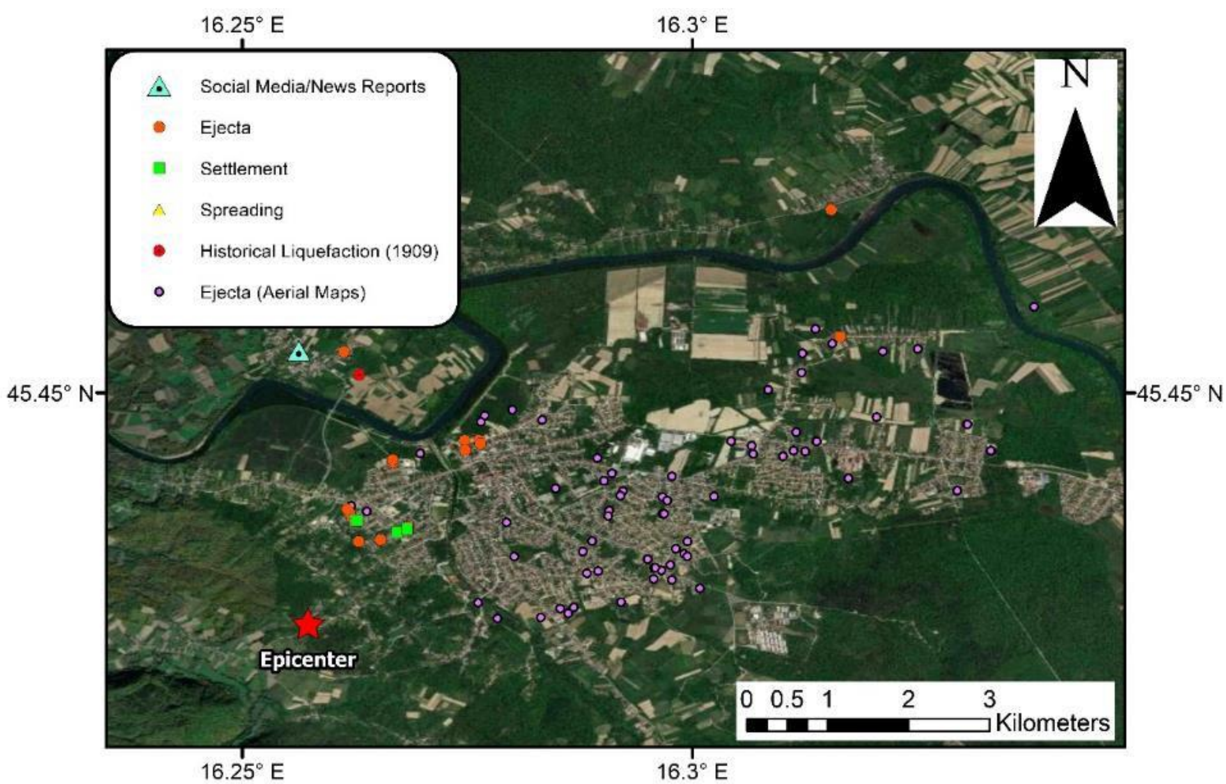

Figure 7.7 Satellite map of the Petrinja region showing locations of liquefaction observations.

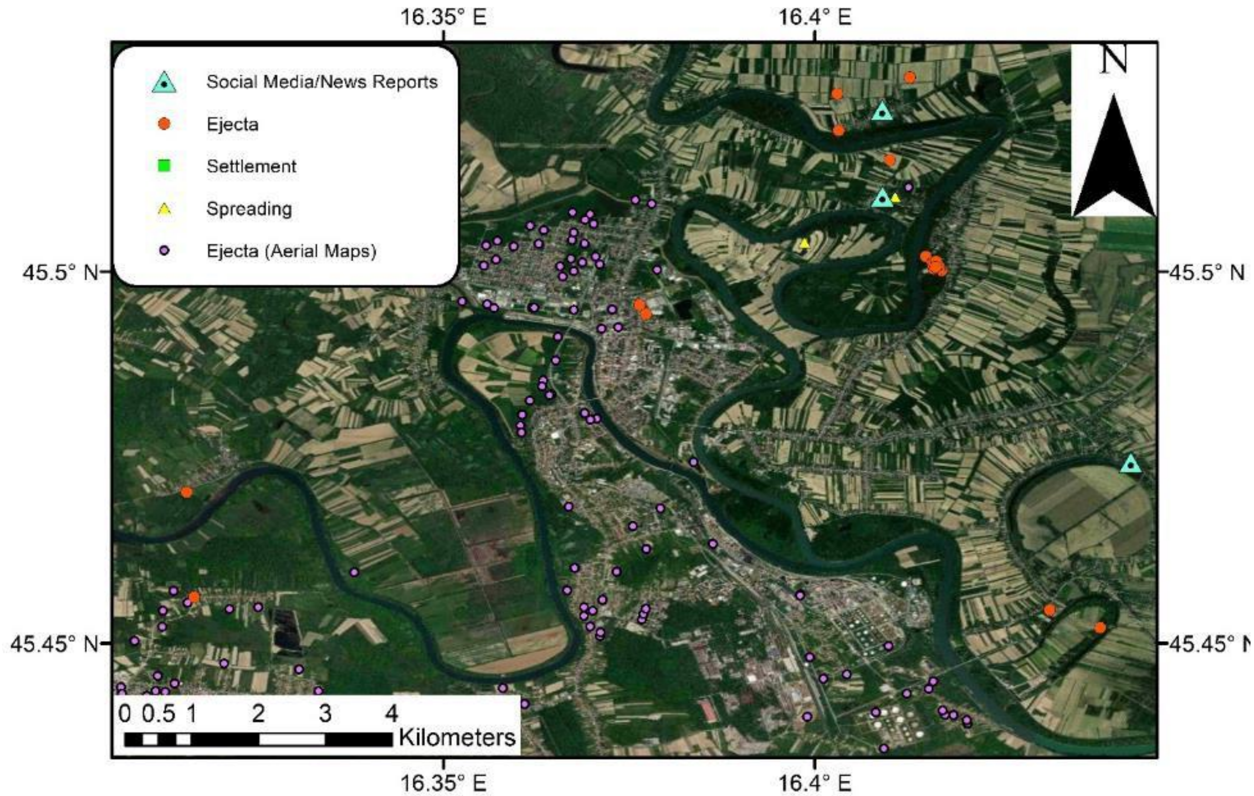

Figure 7.8 Satellite map of the Sisak region showing locations of liquefaction observations.

Direct observations of liquefaction effects were made at more than 70 sites along the Kupa, Glina, and Sava rivers (**Figure 7.2**). These locations were mapped based on direct observations during reconnaissance trips by field team members and local collaborators and reports from residents. Many of the liquefaction observations occurred in open fields, such as agricultural fields (e.g., **Figure 7.11**) or sports fields (e.g., **Figure 7.12),** located near rivers. Damage to levees is discussed in Chapter 8. The field team noted that the groundwater table was near the ground surface in many of these locations. Many of the sites had multiple locations where ejecta were observed, indicating extensive liquefaction of the loose alluvial sediments underlying these locations (**Figure 7.11**). Differential settlements were observed at some residential structures in Petrinja (**Figure 7.7**), while lateral displacements were observed at two locations, Bok Palanječki (northeast of Sisak, **Figure 7.8**) and Stari Brod (northwest of Petrinja, **Figure 7.2),** as discussed in Section 7.5.1. Additional lateral spreading and cracking of levees is discussed in Chapter 8.

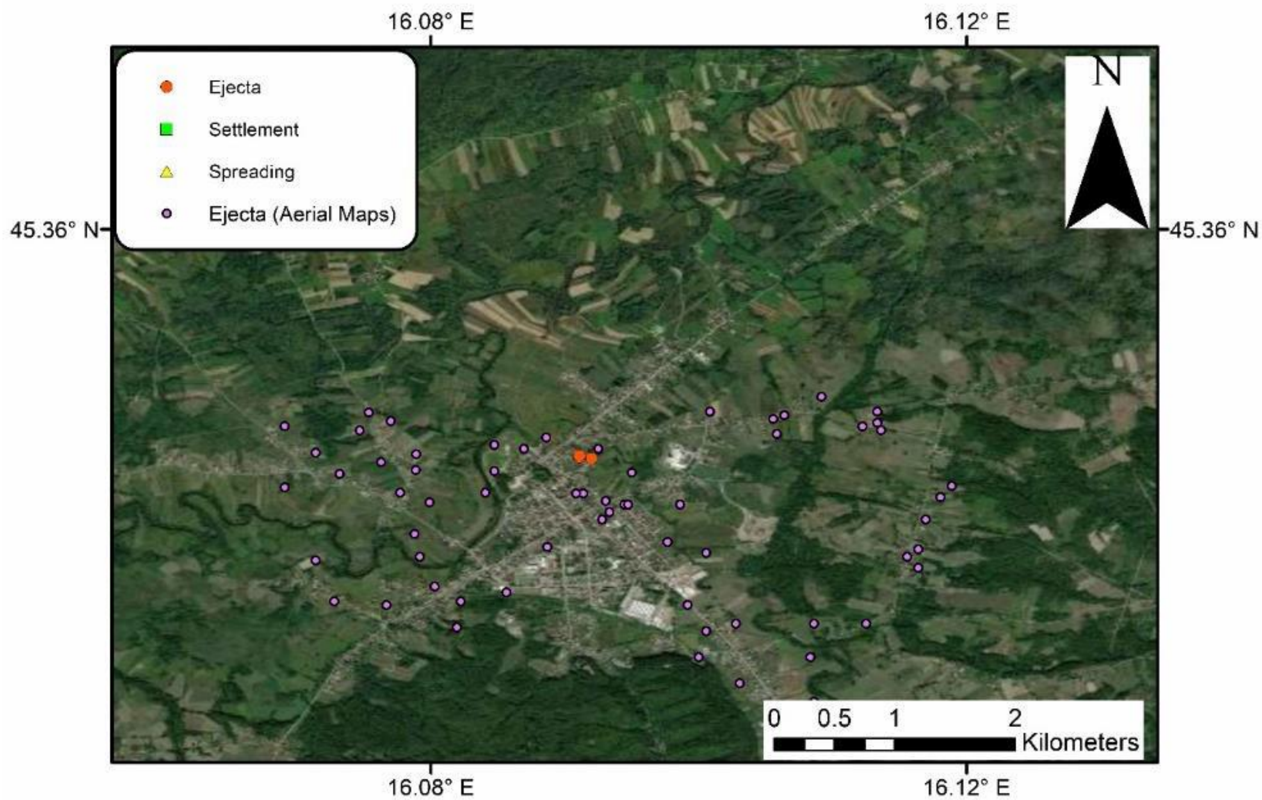

Figure 7.9 Satellite map of the Glina region showing locations of liquefaction observations mapped from aerial imagery and by the field team.

Figure 7.10 Linear pattern of sand boils at a field north of Glina (45.343889N, 16.084722E).

Figure 7.11 Ejecta in an agricultural field near Hrastelnica (45.5009N, 16.4166E).

Figure 7.12 Ejecta in a football field near Letovanić (45.506095N, 16.198165E).

One common observation in both the aerial and field images was the linear pattern of sand boils emerging from surface cracks (e.g., **Figures 7.10 - 7.13**). For the locations shown in **Figures 7.10-7.13**, no ejecta were observed without cracks. Ejecta were also commonly observed within water wells in residential areas that penetrate through the overlying non-liquefiable soil layers to the sandy liquefiable soils below. **Figure 7.14** shows a nearby water well that was partially filled with sand following the earthquake, as well as the road settlement in Drenačka Street, Petrinja, without the presence of ejecta. This non-liquefiable crust found in this region may partially explain the lack of significant damage associated with liquefaction.

Figure 7.13 Linear patterns of ejecta located along cracks in Petrinja (left; 45.444714N, 16.274728E) and Hrastelnica (45.500594N, 16.416287E).

Figure 7.14 Liquefaction under the Drenačka Street in Petrinja (45.4560936N,16.3173009E) and sand in the well nearby (45.4562236N, 16.3164433E).

7.5 Selected Case Histories of Liquefaction Effects

Liquefaction occurred in many locations across the Kupa and Sava river valleys and tributaries, as previously discussed. This section presents some additional details on selected illustrative locations where damage was observed (lateral spreading or settlement) and locations where in-situ data (dynamic penetrometer soundings) were collected. Additional spreading and cracking of levees is discussed in Chapter 8.

7.5.1 Lateral Spreading

Lateral spreading is shown for two locations in Figure 7.2. Additional spreading and cracking of levees is discussed in Chapter 8. In Bok Palanječki, cracking and lateral offsets were observed on both sides of the river (**Figure 7.15**). Vertical offsets of approximately 30 cm and lateral offsets of approximately 10 cm were observed for the driveway of one of the residences in Bok Palanječki (**Figure 7.16**). Cracks were observed in the fields too, but no damage to the structures in this area was noted.

Figure 7.15 Post-earthquake satellite imagery (01/27/2021) near Bok Palanječki (45.510N, 16.409E). The yellow triangles indicate locations where cracking was observed.

Figure 7.16 Cracks in the driveway of one of the residences in Bok Palanječki (45.510058N, 16.410803E).

In the village of Stari Brod (approximately 10 km from the epicenter of the main shock), liquefaction and lateral spreading were identified around a series of houses along the Kupa River. The residents noticed water with sand and mud coming out from the ground around houses, in their yards, and the fields. Like other locations in the region, many water wells were filled with liquefied sand and became unusable. Liquefaction was noted at 83, 97, 98, 99, 99B, 110, and 110A Ižišće Street (Bostjančić, 2021), and their positions are shown in **Figure 7.17**.

Figure 7.17 Location of the liquefaction ejecta by the Kupa River in the Ižišća Street in Stari Brod. (45.480N, 16.182E; Google Maps). Numbers show street numbers where liquefaction was observed. Cracks and sliding due to lateral spreading is shown in the area bordered by the white rectangle and enlarged in **Figure 7.24**.

Figure 7.18a shows a crack in the yard of the house at 97 Ižišća Street that propagated through the neighboring yards, on the western side, while **Figure 7.18b** shows a crack on the eastern, river side. Both cracks are parallel with the riverbank. The property also had sand ejecta (**Figure 7.18c**). The house is slightly inclined towards the river suggesting the land is sliding towards the river. The house itself was not severely damaged, although some damages are to be repaired and further settlement due to liquefaction could be expected. **Figure 7.18d** shows the crack between the terrace and the house.

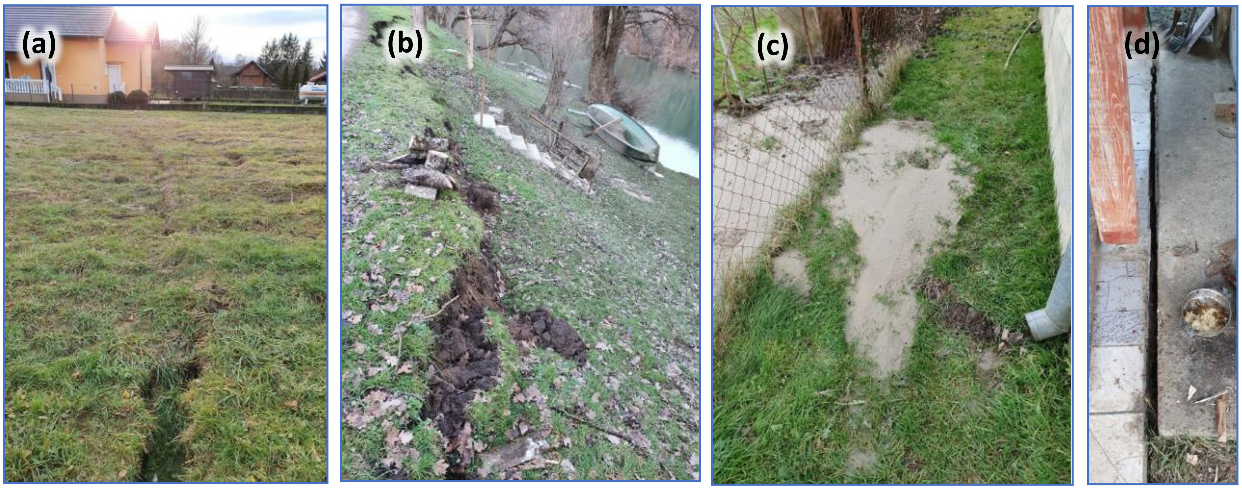

Figure 7.18 (a) Crack in the yard west from the house, (b) crack along the riverbank, (c) sand ejecta around the house, and (d) crack due to settlement of the terrace, at 97 Ižišća Street, Stari Brod (45.4801N, 16.1841E) (Taus 2021e). The cracks are parallel with the riverbank.

The 98 Ižišća Street property contained the same ground crack observed in the western yard of the house at 97 Ižišća Street (further referred to as the "western" crack). The house at 98 Ižišća Street was damaged and in danger due to differential settlement and possible sliding. The crack in the yard and the crack along the riverbank that progressed from 97 Ižišća Street– both parallel with the riverbank – as well as sand ejecta are shown in **Figure 7.19**. Therefore, it may be concluded that the sliding was caused or contributed to by liquefaction of underlying sandy layers.

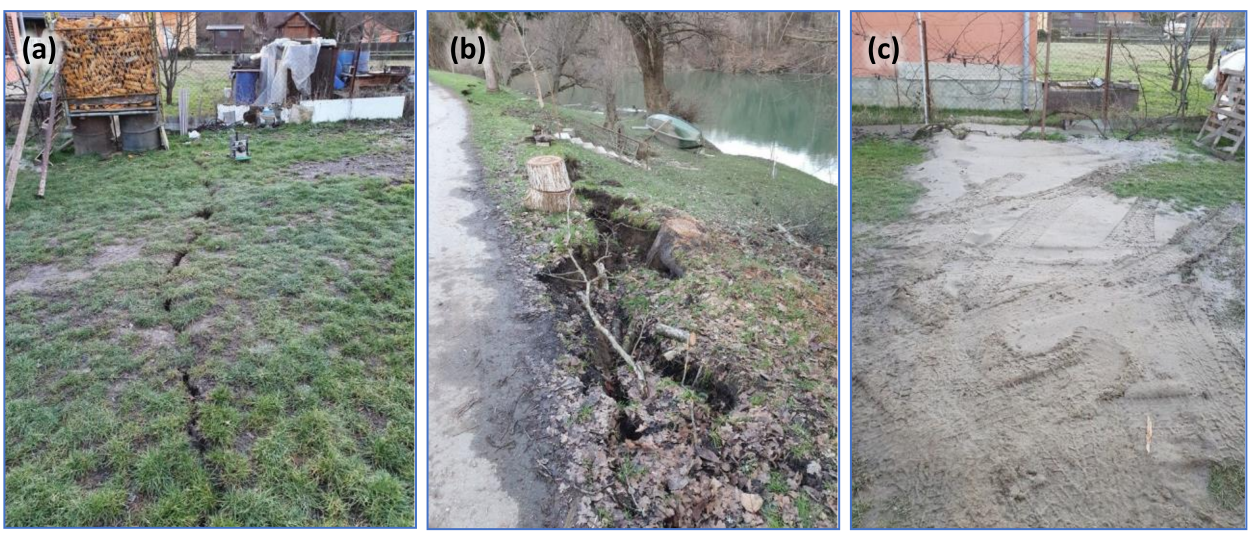

Figure 7.19 (a) Crack in the yard west from the house, (b) crack along the bank, and (c) sand ejecta around the house at 98 Ižišća Street, Stari Brod (45.480158N, 16.184210E) (Taus 2021f). The cracks are parallel with the riverbank.

Furthermore, the neighboring 99 Ižišća Street property had the same "western" crack that now passed through the house causing severe damage and the same crack on the bank side that originated at 97 Ižišća Street. **Figure 7.20** gives a southeastern view of the house and the water well at the property. During the earthquake, sand was ejected upward through the well and onto the surrounding ground, as visible in **Figure 7.20a**. The well remained filled with sand up to the 6-m depth below the ground surface level (**Figure 7.20b**).

The cracks passing through the house floor at 99 Ižišća Street (**Figure 7.21** and **Figure 7.22**) were aligned with the crack in the neighboring yards at 97 and 98 Ižišće Street. Ejecta at this property were also observed, as shown in Figure 7.23. The cracks were mapped across the different homes (**Figure 7.24**) and indicated this portion of the bank was moving towards the free face of the river.

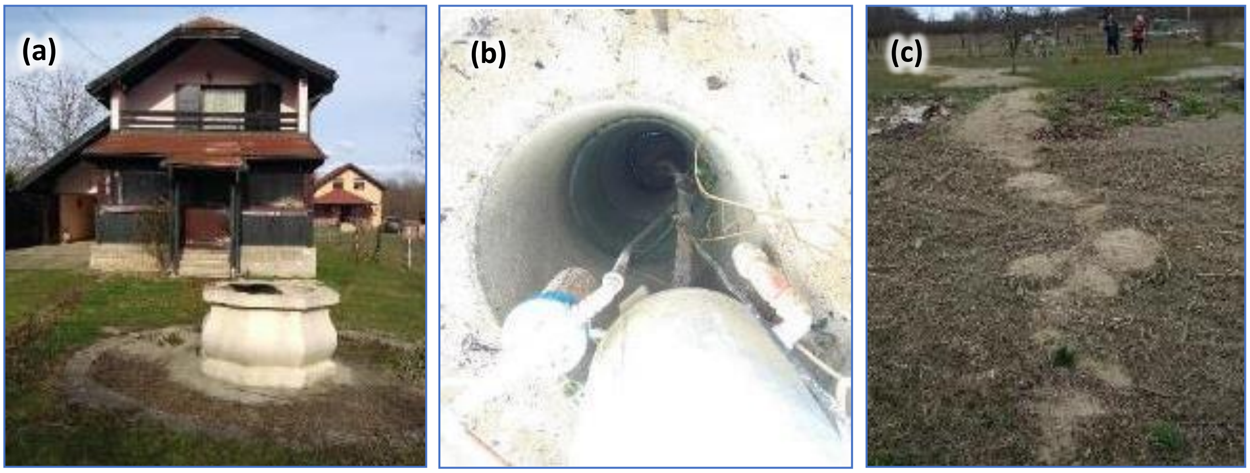

Figure 7.20 (a) The southeastern view of the house at 99 Ižišće Street (45.480248N, 16.184285E) with the water well and sand ejected through the well and onto the ground during the Mw 6.4 earthquake and (b) the water well filled with sand to a depth of 6 m below the ground surface level. (c) Sand ejecta.

Figure 7.21 (a) Northwestern side of the house at 99 Ižišća Street (45.480248N, 16.184285E) in Stari Brod, (b, c) the propagation of the crack through the western yards of the houses at 97 and 98 Ižišća Street marked (1) in Figure 7.23. Crack is deeper than 1m, with opening of around 10 cm and a vertical offset of 8cm.

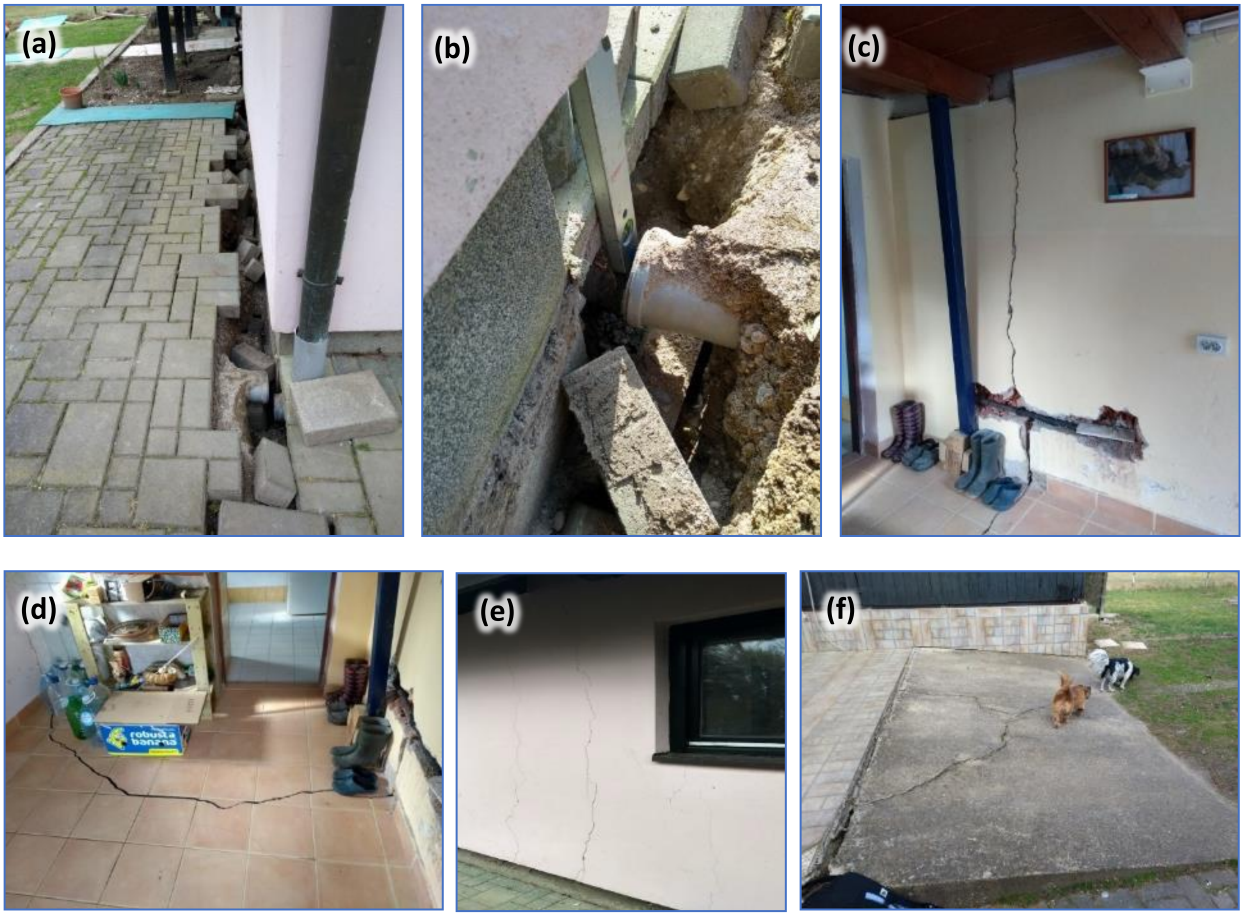

Figure 7.22 (a, b) Western corner of the house at 99 Ižišća Street (45.480248N, 16.184285E) in Stari Brod with pavement heave of 8 cm and rupture of the roof drainage pipe, marked (2) in Figure 7.23. (c, d) Water pipe rupture caused by vertical crack in the wall and crack on the garage floor between the terrace and house foundation on the line marked (3) in Figure 7.23 and (e) corresponding crack on the outside. (f) Cracks on the pavement at the garage entrance marked (4) in Figure 7.23.

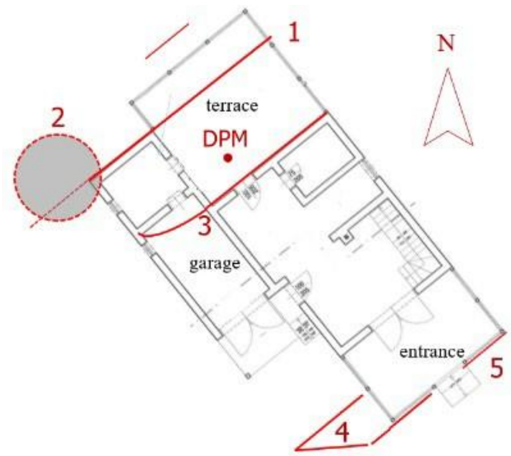

Figure 7.23 Plan of house at 99 Ižišće Street (45.480248N, 16.184285E) in Stari Brod and cracks shown in red. Numbers indicate features of interest: (1) Crack shown in Figure 7.21; (2) Pavement deformation shown in Figure 7.22a-b; (3) Water pipe rupture caused shown in Figure 7.22c-d; (4) Cracks in the pavement as in Figure 7.22f; (5) Cracks along the south east wall, probably widening. Steps are moving away from the terrace. Red dot: DPM location.

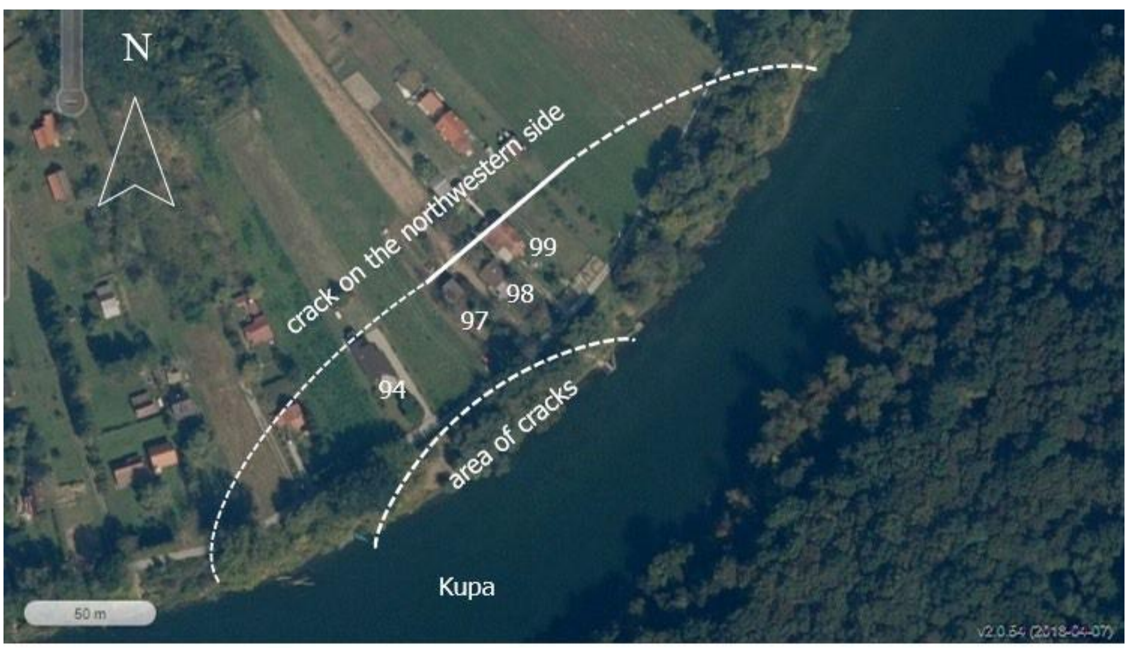

Figure 7.24 Position of the cracks mapped at 97, 98, 99, 99 Ižišće Street in Stari Brod due to lateral spreading along the Kupa River (45.480N, 16.183E; Geoportal, https://geoportal.dgu.hr/).

Dynamic penetrometer (DPM 30) testing was performed near the foundations of the three aforementioned houses (97, 98, and 99 Ižišća Street). The test results are shown in **Figure 7.25.** The DPM 30 uses rods with a 20-mm diameter and the crown bottom that is 35.6 mm in diameter (i.e., its cross-sectional area is 10.00 cm^2). A hammer with the mass of 30.0 kg is dropped from the height of 20 cm and the number of blows required to drive the crown 10 cm into the soil is counted. The counted values are then converted into dynamic cone resistance. The test results indicate low penetration resistance in the upper 6 meters of the soil profiles.

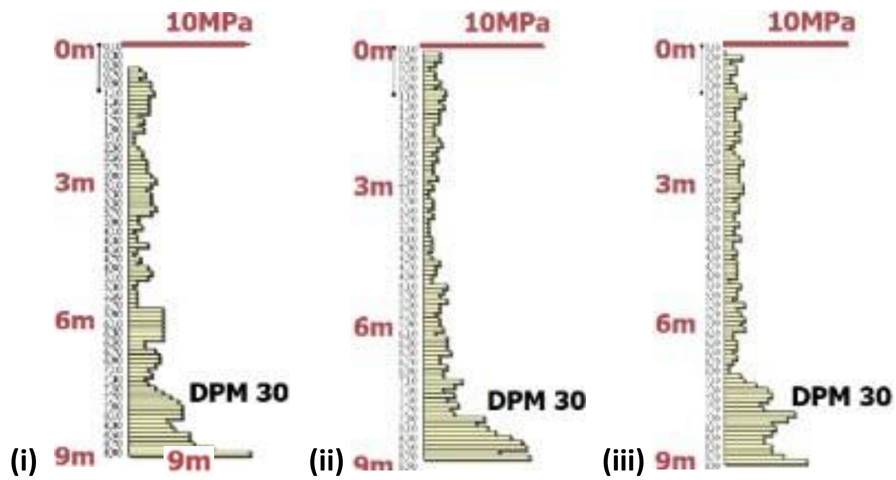

Figure 7.25 The DMP 30 test results obtained at (i) 97 Ižišća St (45.480060N, 16.184103E), (ii) 98 Ižišća St (45.480158N, 16.184210E), and (iii) 99 Ižišća St (45.480229N, 16.18433E7) (Taus 2021e-g).

7.5.2 Effects of Liquefaction on Residential Structures

Many residential properties in Petrinja had sand ejecta in yards or around house foundations. **Figure 7.26** illustrates thin cracks above the foundation of a house in Petrinja. At the property across the street from this house, the sand ejecta were visible in the yard and along the fence foundation, and part of the yard heaved, all contributing to the formation of thin cracks in the house wall around the balcony near the single column, as shown in **Figure 7.27.**

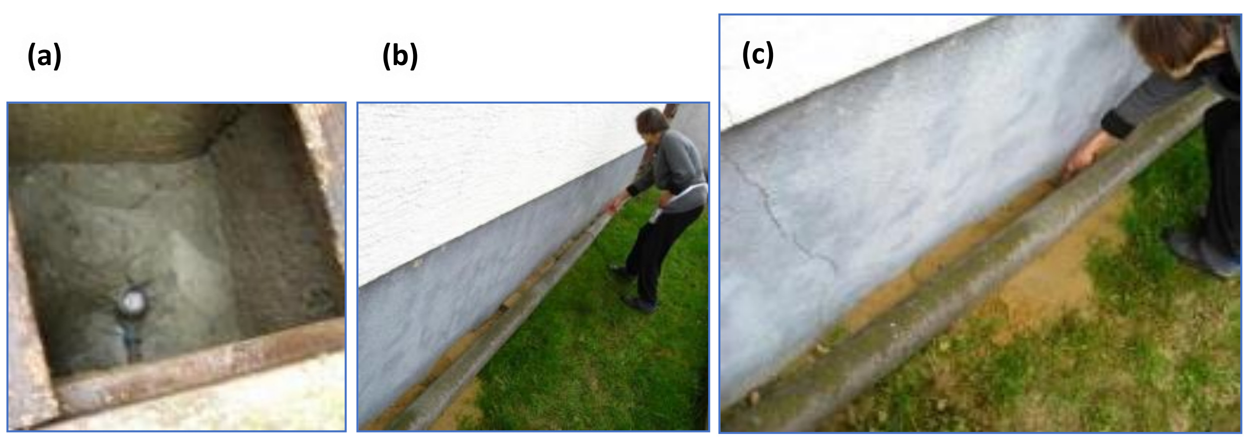

Figure 7.26 (a) Sediment ejecta in the water meter shaft, (b) sand ejecta by the house, and (c) cracks above the foundation near the sand ejecta pointed at by the owner in Petrinja (45.4349N, 16.2683E).

Figure 7.27 (a, b) During the main shock, sandy soil appeared along the fence foundation and the central part of the yard heaved. (c) Several thin cracks appeared in the house wall around the column and the balcony in Petrinja (45.43515N, 16.26844E).

Evidence of liquefaction was found at residential properties in Milana Makanca Street in Petrinja starting from the house number 1 all the way to the house number 44, with the volume of the ejecta around each house measuring typically up to 1.5 m^3 (Gulam 2021). At 11 Milana Makanca Street, liquefaction induced flooding of the property by groundwater mixed with some soil sediments, as illustrated in **Figure 7.28**. The house itself was not damaged, but it was suggested that further investigations be undertaken. In accordance with that, a dynamic penetrometer (DPM 30) test was performed at the house corner (Taus 2021a). The test results provided in **Figure 7.29** show that the soil in the upper 3 m is very loose.

Many water wells in the area were filled with liquefied sandy soil. A well at 8 Milana Makanca Street in Petrinja was seen to eject sand some 150 cm above the ground level, as shown in **Figure 7.30**, causing cracks in the nearby house that was abandoned before the earthquake (also shown, in **Figure 7.30c**). The neighboring house at 10 Milana Makanca Street, also abandoned before the earthquake, had damage in the ceiling visible at **Figure 7.31.**

Figure 7.28 (a) Flooding groundwater and sediment ejecta: (b) south corner, (c) northwest side around the house at 11 Milana Makanca Street, Petrinja (45.436061N, 16.262898E), recorded by the owner, Tomislav Zorčić, minutes after the Mw 6.4 earthquake.

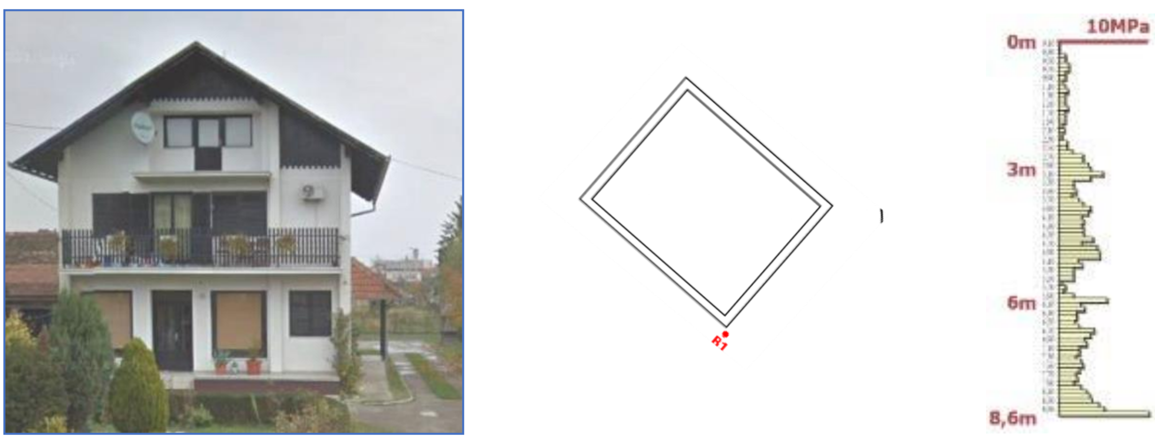

Figure 7.29 The house at 11 Milana Makanca Street in Petrinja (45.436061N, 16.262898E), test location at the southern corner of house, and DMP 30 test results (Taus 2021a).

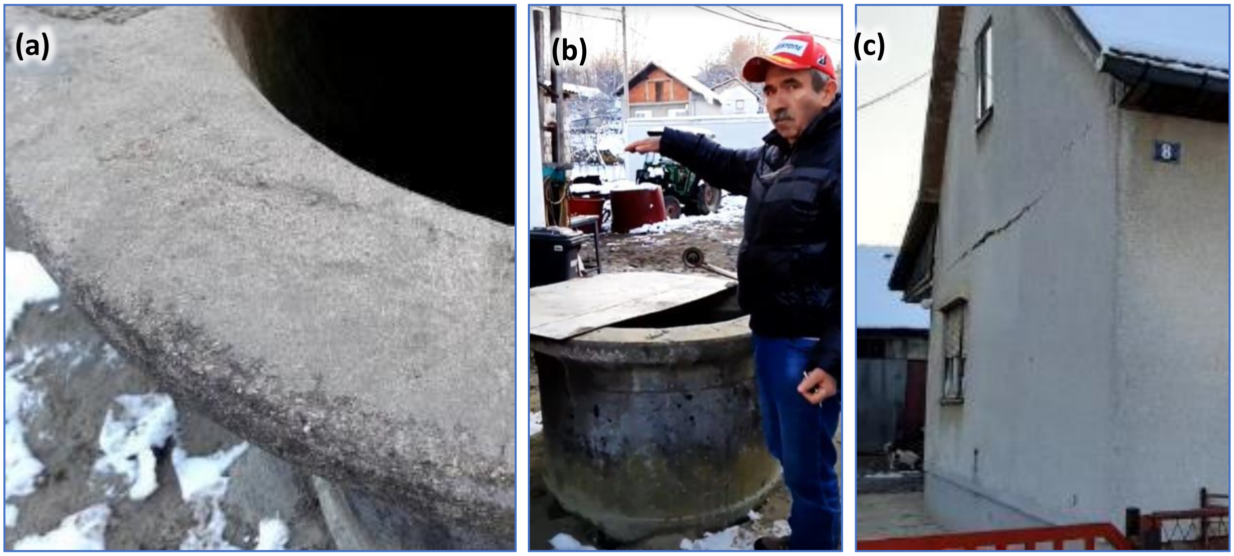

Figure 7.30 (a) Rim of the water well at 8 Milana Makanca Street in Petrinja (45.4359N, 16.2627E) covered by the ejected sand. (b) A neighbor shows that during the earthquake sand and water were ejected upward from this well, around 150 cm above the ground level. (c) The abandoned house near the well.

Figure 7.31 (a) Traces of sand ejecta and (b) the crack in the ceiling inside the house at 10 Milana Makanca Street in Petrinja (45.4358N, 16.2628E).

DPM 30 testing was also performed at several locations in Glina, approximately 12 km from the epicenter, to evaluate the subsurface conditions. Evidence of liquefaction was identified in the streets as well as at the properties. Liquefaction effects were especially notable in the streets along the former riverbed of the Maja River. DMP 30 testing was performed at one of these locations (20 6. kolovoza 1995. Street) with the results presented in **Figure 7.32.** The test results show that the soil in the upper 3 m of the profile (especially from the 1.5-m to 3-m depth) is extremely loose. Similar soil conditions were observed across the street (25 6. kolovoza 1995.

Street), as shown in **Figure 7.33**. Slightly stronger soils were found at the nearby location (35 6. kolovoza 1995. Street), as shown in **Figure 7.34**.

Figure 7.32 The house at 20 6. kolovoza 1995. Street (45.3430N, 16.0911E), test location at the western corner, DMP 30 test results, and characteristic ejecta (Taus 2021b).

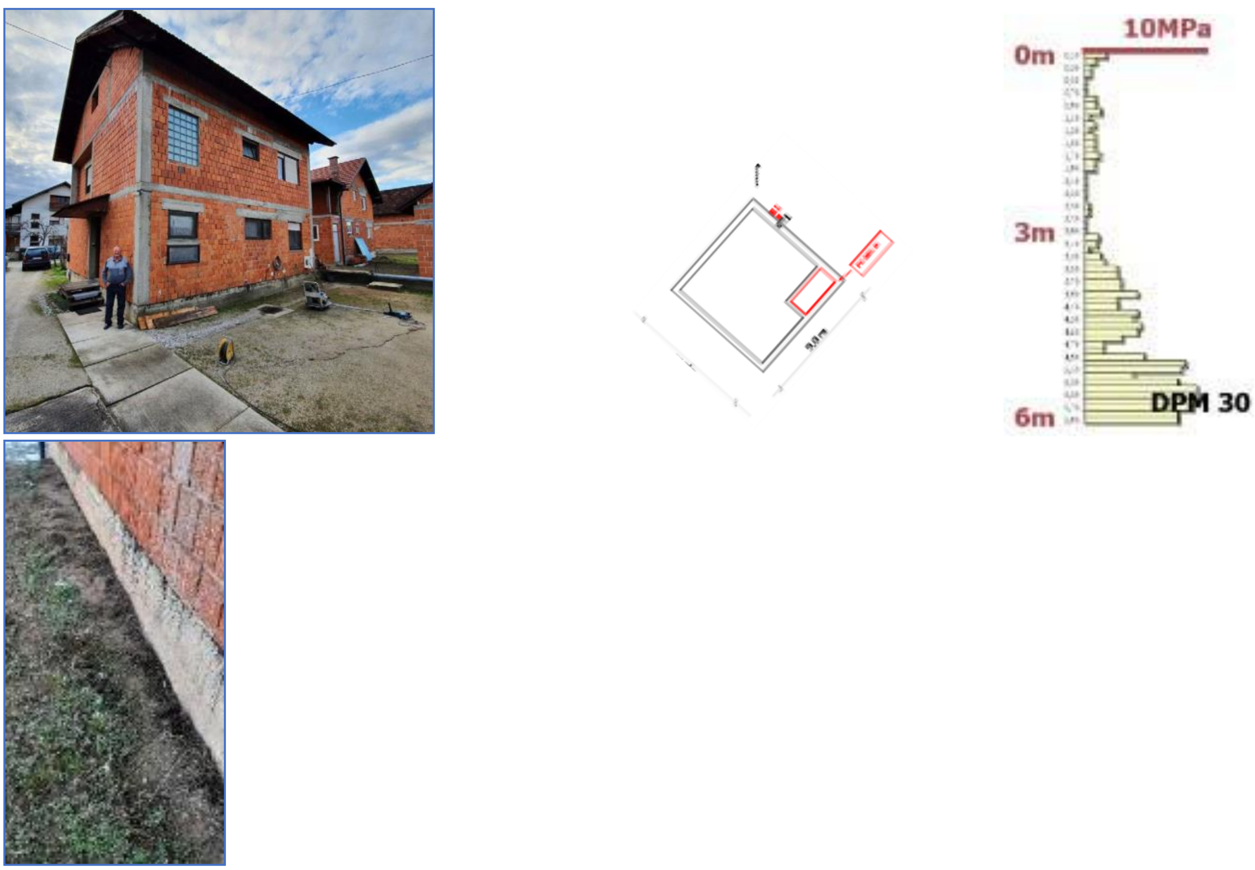

Figure 7.33 The house at 25 6. kolovoza 1995. Street (45.3431N, 16.0911E), test location near the northern corner, DMP 30 test results, and characteristic ejecta (Taus 2021c).

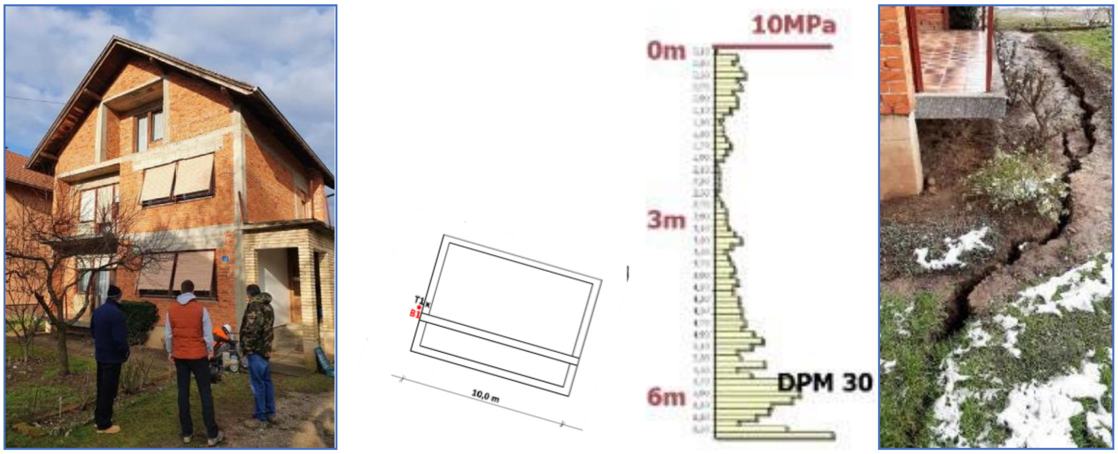

Figure 7.34 The house at 35 6. kolovoza 1995. Street (45.3429N, 16.0920E), location of the testing near the eastern wall, DMP 30 test results, and characteristic crack (Taus 2021d).

7.6 Concluding Remarks

Extensive evidence of liquefaction was observed throughout the Kupa, Glina, and Sava river valleys. The field observations of liquefaction primarily occurred in areas mapped as either flood sediment or diluvium-proluvium on the geologic map by Pikija (1987). These Holocene units are described as primarily consisting of silts and sands. Liquefaction observations outside of these units primarily occurred near contact with one of these two units. All observations were within 17 km of the epicenter indicating that strong shaking was likely. Liquefaction within loose, saturated alluvial sediments near the epicenter has been widely observed in previous earthquakes and as such, these observations were expected.

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