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Liquefaction effects in the 2020 M_w 6.4 Petrinja, Croatia, earthquake

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A B S T R A C T

The 2020 M_w 6.4 Petrinja, Croatia, earthquake triggered widespread liquefaction along the Kupa, Glina, and Sava rivers. The locations of liquefaction ejecta and lateral spreading were identified through a combination of field reconnaissance and interrogation of aerial photographs. Superimposing those locations on the regional geologic map revealed the liquefaction vulnerability of Holocene terrace and flood deposits, Holocene deluvium-proluvium, and Pleistocene loess deposits. Liquefaction caused damage to the land and structures, with ejecta observed both near and far from residential structures. In the free field, the ejection of silty and sandy soil accompanied the extensive ground fracturing. At residential properties, ejecta led to differential settlement, cracks in foundations, walls, and floors, and contamination of water wells. Lateral spreading resulted in the formation of ground and building cracks, house sliding and tilting, pipe breakage, and pavement damage. This article documents these observations of liquefaction and draws conclusions regarding the patterns of liquefaction observed in this earthquake. These observations will be a valuable addition to liquefaction triggering databases as there are relatively few earthquakes with magnitudes less than 6.5 that triggered extensive liquefaction, and they provide additional case histories of liquefaction in Pleistocene deposits.

1. Introduction

On Dec 29, 2020, the M_w 6.4 Petrinja earthquake triggered widespread liquefaction-induced ground failure, resulting in damage to residential structures, bridges, levees, and roads in Sisak-Moslavina County, Croatia (e.g., Ref. [1]). Sediment ejecta and lateral spreading were observed in the predominantly flat valleys surrounding the meandering Sava and Kupa rivers and their tributaries. The earthquake was generated by a dextral strike-slip fault at a depth of 8 km, 4 km to the southwest of the Town of Petrinja [2]. The fault lies in a diffuse boundary zone associated primarily with the ongoing convergence between the Eurasia and Africa plates and the Adria microplate wedged between them [3–5]. It is situated in a transition zone between the Pannonian Basin and the Internal Dinarides [2,4]. The Internal Dinarides belong to the mountain belt formed by the subduction of the Adria microplate beneath the Eurasia plate and are impacted by the extension of the Pannonian back-arc basin [3,6]. The entire region is characterized by complex geodynamic processes that are still not well understood (e.g., Refs. [7], [3–5,8–11]). At the time of the earthquake, the nearest strong motion stations were in the country's capital, Zagreb, approximately 40 km from the fault rupture. The median peak ground acceleration (PGA) recorded at those six stations was 0.11 *g*, while the maximum PGA of 0.20 *g* was recorded at a distance of 47 km from the fault rupture [12]. The PGA near the rupture was estimated at 0.4–0.6 *g* [13,14].

Most residents in the region live in family houses that were typically built by property owners. In some cases, owners added an extra story to the existing single-story houses, often without reinforcing the original structure. Most of the houses affected by the earthquake are masonry structures with shallow foundations and have no basements due to the shallow groundwater table in the region. The construction of houses was supported by limited to no geotechnical investigations prior to the 2020 earthquake.

Post-earthquake field reconnaissance was conducted by a collaborative team representing researchers from the United States and Croatia. Due to the global pandemic, the reconnaissance was conducted both in person and virtually through the use of aerial mapping. The full reconnaissance efforts are documented in the reports by the various teams

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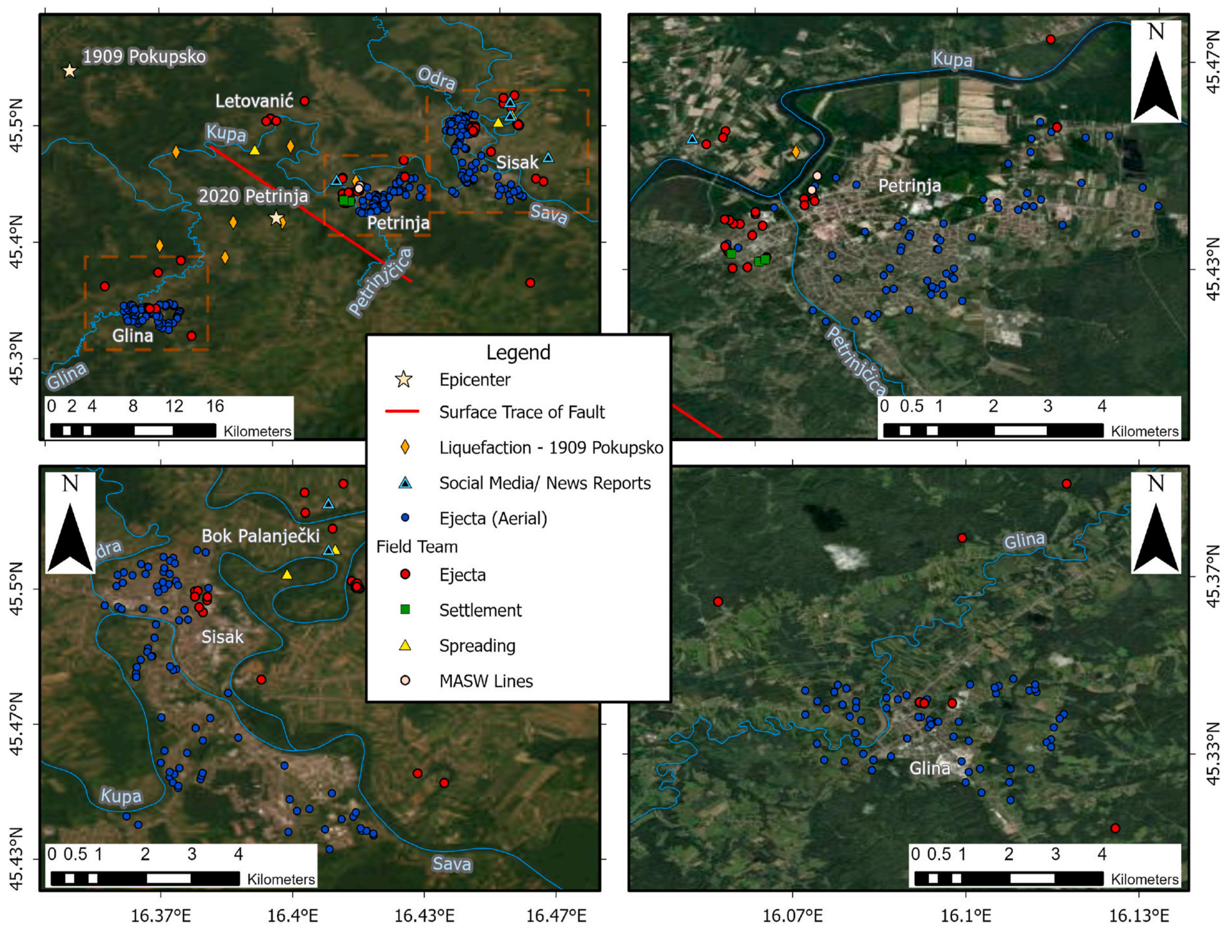

Fig. 1. Satellite map of Petrinja, Sisak, and Glina with locations of documented liquefaction sites in the 2020 Petrinja earthquake. The epicenter and inferred surface trace of the causative Petrinja fault [2], locations of the 1909 Pokupsko liquefaction [25], and sites with multichannel analysis of surface waves (MASW) lines (A. Salkovic and I. Salkovic, personal communication, Nov 2023 and Aug 2024) are also shown.

[15–18]. This article summarizes the observations of liquefaction documented by the reconnaissance teams. Historical observations of liquefaction and the depositional environment in the reconnaissance area are reviewed. Following this background, observations of liquefaction and its effects on light-weight residential structures are summarized and selected case histories of differential settlement and lateral spreading are presented. Current liquefaction databases (e.g., Refs. [19, 20]) have relatively few observations from earthquakes with magnitudes less than 6.5 outside of Christchurch, New Zealand, which makes the observations from the M_w 6.4 Petrinja earthquake an important contribution to understanding the risk of liquefaction and its effects from lower magnitude events.

2. Historical observations of liquefaction in Croatia

There are historical records of seismic liquefaction in Croatia, including events in Virovitica (1757), Zagreb (1880), and Pokupsko (1909), which are situated in the Pannonian Basin by the Drava, Sava, and Kupa rivers, respectively. Virovitica is about 100 km to the northeast of Petrinja, while Zagreb and Pokupsko are approximately 50 km and 20 km, respectively, to the northwest of Petrinja. In 1757, the M_w 6.1 earthquake [21] led to ground cracking and the ejection of water followed by yellow sand at two locations in Virovitica and multiple places outside the city [22]. Deep wells became filled with water and sediment and overflowed long after the shaking had ceased [22]. Historical observations of liquefaction were also documented for areas surrounding the Kupa and Sava rivers. During the 1880 M_w 6.2 Zagreb earthquake, the ground cracked and water gushed from the earth alongside the formation of soil boils across the greater Zagreb area [23]. A team of scientists in the field recorded the conically shaped ejecta with diameters ranging from 0.1 m to 0.7 m and comprised primarily of fine alluvial sand from shallow depths [23]. The 1909 M_w 5.9 Pokupsko earthquake produced widespread liquefaction effects that were observed primarily in the Kupa Valley [24,25]. Therefore, these historical records offer evidence of alluvial deposits in Croatia being vulnerable to liquefaction.

3. Liquefaction manifestation in the 2020 Petrinja earthquake

Several reconnaissance teams contributed to mapping and understanding the effects of the 2020 Petrinja earthquake. This included hybrid (virtual and on-site) teams organized by Geotechnical Extreme Events Reconnaissance [18] and Structural Extreme Events Reconnaissance and Earthquake Engineering Research Institute [16] along with Croatian collaborators, field volunteers organized by the Croatian Centre for Earthquake Engineering [17] and faculty from the University of Zagreb and the University of Rijeka [15]. These teams focused on documenting as many aspects of the earthquake, but this article is focused only on manifestations of liquefaction.

Liquefaction manifestations were documented using a combination of field visits, aerial and satellite image analysis, reports from residents, and social media posts (Fig. 1). Direct observations of liquefaction ejecta were made during field reconnaissance efforts at over 70 locations along the Kupa, Glina, and Sava rivers (red circles in Fig. 1). Post-earthquake digital orthophotographs for Drencina, Glina, Moscenica, Petrinja, and Sisak were developed by the Faculty of Geodesy at the University of

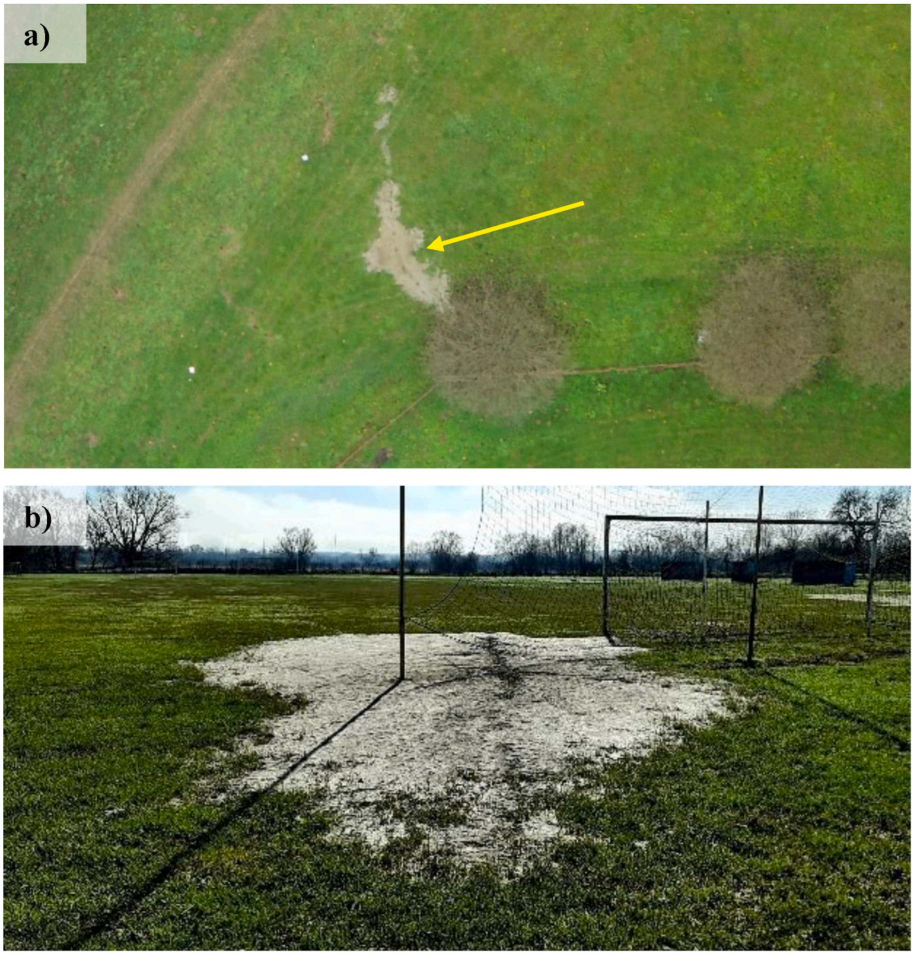

Fig. 2. Liquefaction ejecta in the free field: (a) aerial view of ejecta north of Glina [45.3439N, 16.0847E] (base map: © OpenStreetMap contributors) and (b) ground-level photograph of ejecta in Letovanic [45.506N, 16.198E], northwest of Petrinja.

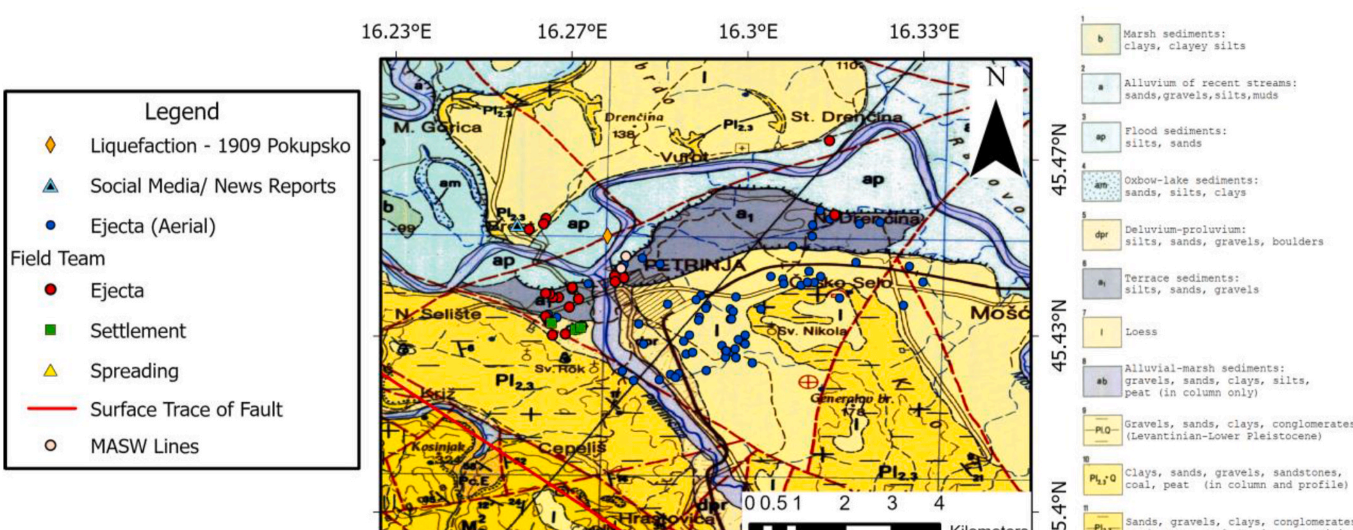

Fig. 3. Geologic map of the Petrinja region [31] showing locations of documented liquefaction case histories. The map legend on the right has been translated from Croatian.

Zagreb. The corresponding aerial photographs were acquired by the Croatian Mountain Rescue Service using the Matrice 300 RTK and Phantom 4 RTK uncrewed aerial vehicles. Satellite imagery for regions around Petrinja and Sisak was available on Google Earth Pro. The orthophotographs were visually inspected for traces of liquefaction ejecta. Locations with evidence of ejecta near Petrinja, Sisak, and Glina

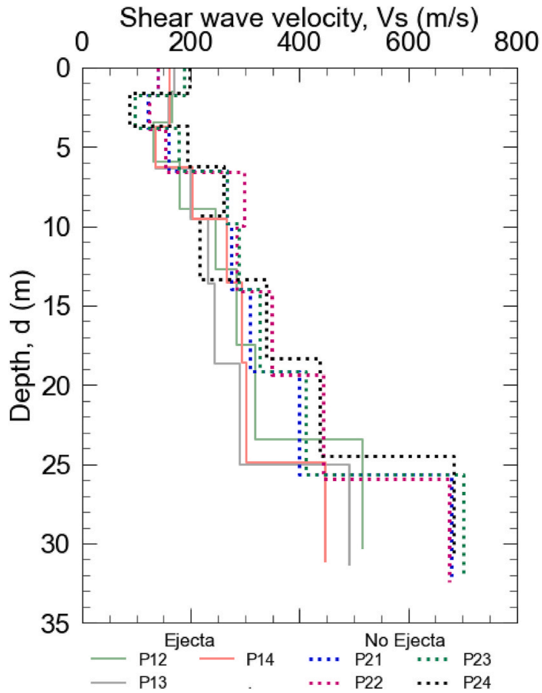

Fig. 4. One-dimensional shear wave velocity profiles of two nearby sites in Petrinja: site with ejecta [45.4484N, 16.2769E] and site without ejecta [45.4461N, 16.2760E] (A. Salkovic and I. Salkovic, personal communication, Nov 2023 and Aug 2024).

are shown as purple circles in Fig. 1. An example of a site where ejecta were mapped is presented in Fig. 2a. The absence of ejecta away from Drencina, Glina, Moscenica, Petrinja, and Sisak and near the Kupa, Sava, and Odra rivers is not necessarily due to mitigating factors but rather the limited coverage of aerial photographs. Similarly, the presence of vegetation, structures, and other features in the aerial photographs had the potential to obscure ejecta. There is also some uncertainty associated with the interpretation of ejecta in the aerial photographs due to their limited resolution. The locations of ejecta marked by the cyan triangles in Fig. 1 are approximate as they are based on news and social media posts [26–30].

The region with liquefaction manifestations in the 2020 Petrinja earthquake is underlain by Quaternary deposits, according to the geologic map by Pikija [31]. Fig. 3 illustrates the locations of liquefaction manifestation superimposed on the geologic map for Petrinja. The primary geologic units in the affected areas are Holocene flood (ap) and terrace deposits (a1) near the active river channels, Holocene deluvium-proluvium (dpr), and Pleistocene loess deposits (l). Flood deposits are formed by sedimentation of predominantly fine material that remained in suspension after flooding [31]. They are comprised primarily of clayey and sandy silt (5–12 % clay and up to 20 % sand) and fine sand to a lower extent. Terrace deposits tend to be characterized primarily by sandy silt but can also contain fine gravel. Deluvium-proluvium consists of weathered bedrock products (silt, sand, gravel, and boulders) carried down a slope in a gradual, relatively continuous manner as well as by torrential flows. Loess represents sediment of aeolian origin comprised of silt with typically 7–10 % sand and 4–14 % clay [31].

Evidence of liquefaction in Pleistocene loess deposits is an important observation from this earthquake. Although the majority of liquefaction case histories in the literature involves Holocene deposits, there is previous evidence of liquefaction in Pleistocene deposits (e.g., Refs. [32–36]), and saturated Pleistocene loess deposits are considered highly susceptible to liquefaction under strong seismic shaking [37]. In Petrinja, the liquefaction observations within mapped Pleistocene units were all within 10 km of the fault and close to the rivers (Fig. 3), where high water tables would be expected. A few locations with liquefaction ejecta were within areas mapped as the Late Pliocene deposits (Pl,Q and $Pl_{2,3}$). However, these locations are near the contact with the younger Quaternary deposits (ap, dpr, and l). Given the scale and date of the geologic map, the locations of these contacts are approximate. Therefore, it is possible these manifestations occurred within the aforementioned Quaternary sediments.

Liquefaction ejecta were frequently observed in the free field, typically emerging through extensive ground cracks (Fig. 2). The groundwater table was often near the ground surface. In Petrinja, a multichannel analysis of surface waves (MASW) was conducted after the earthquake to compare the subsurface conditions at free-field sites with and without ejecta (A. Salkovic and I. Salkovic, personal communication, Nov 2023 and Aug 2024). The data were acquired using a 24-channel array of 4.5 Hz vertical geophones at 2-m intervals and a sledgehammer as a seismic source [18]. The Geometrics Geode seismograph was used to record the seismic data in a roll-along acquisition fashion, moving the array 10 m between shots. The total length of the array with four rolls was 86 m. For each position, strikes were conducted at −4.0 m, 0 m, 4 m, 8 m, and 12 m. Data reduction and analysis were

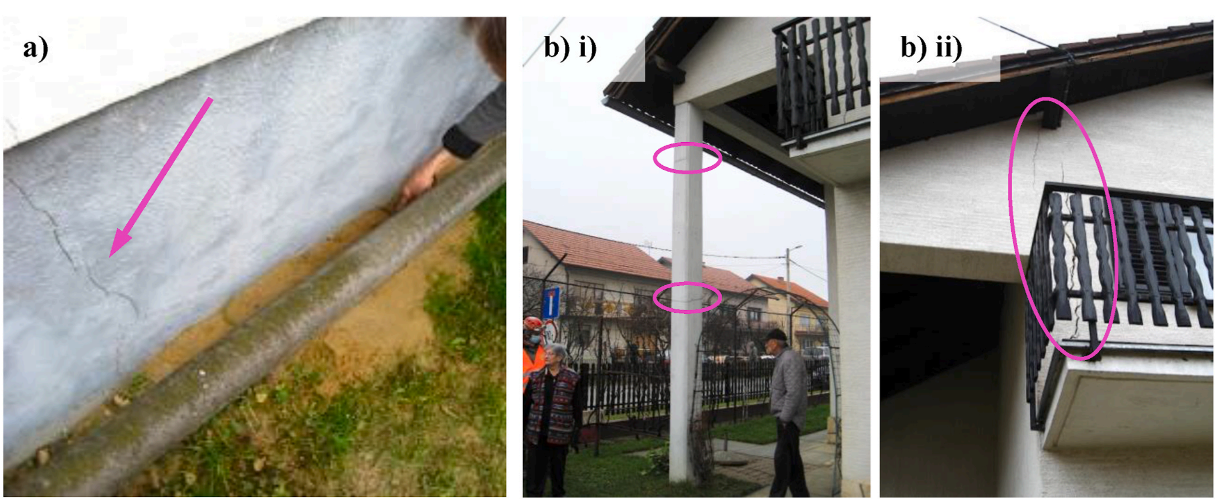

Fig. 5. Structural damage associated with liquefaction: (a) diagonal foundation crack adjacent to sandy ejecta [45.4349N, 16.2683E] and (b) co-located damage at [45.43515N, 16.26844E] with (i) horizontal cracks in column adjacent to uplifted ground and ejecta and (ii) vertical cracks in exterior wall adjacent to the column shown in (i).

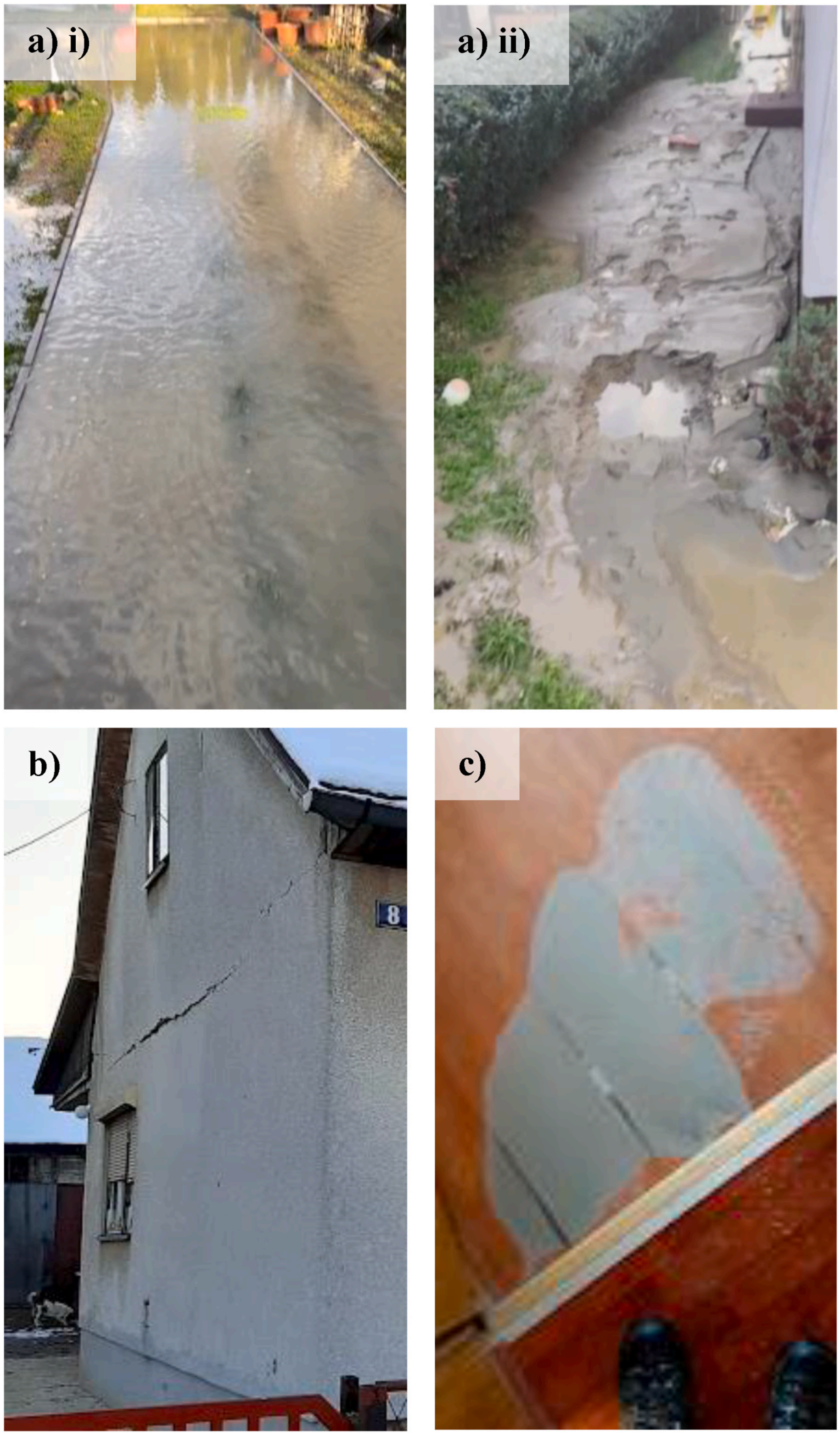

Fig. 6. Liquefaction effects at Milan Makanac St: (a) (i) liquefaction-induced flooding and (ii) sediment ejecta at 11 Milan Makanac St [45.4361N, 16.2629E], (b) structural damage, as evidenced by horizontal crack between the first story and the attic, at 8 Milan Makanac St [45.4359N, 16.2627E], and (c) ejecta inside the house at 10 Milan Makanac St [45.4358N, 16.2628E].

performed using the SurfSeis software developed by the Kansas Geological Survey. Dispersion curves in a multi-record file were analyzed for each sledgehammer strike by examining the change in phase velocity versus frequency using the fundamental mode component of the dispersion data. Non-linear inversion modeling of each dispersion curve was performed and resulted in one-dimensional mid-point representation of the shear wave (Vs) profile [18]. As shown in Fig. 4, the average shear wave velocities in the depth ranges from 0 m to 6 m and from 9.5 m to 18.5 m at the site with ejecta are comparable to the average shear wave velocities in the same depth

Fig. 7. Residential water well partially filled with liquefaction ejecta at Drenacka St, Petrinja [45.456224N, 16.316443E].

ranges at the site without ejecta (150 m/s vs. 140 m/s and 260 m/s vs. 270 m/s, respectively). However, the site without ejecta has stiffer soil in the depth range from 6 m to 9.5 m compared to the site with ejecta (270 m/s vs. 190 m/s).

4. Effects of liquefaction on residential properties: selected case histories

This section presents an assessment of liquefaction-induced damage at residential properties with the focus on ejecta and lateral spreading. Subsurface conditions at some properties were evaluated using dynamic probing medium, specifically the DPM30 device manufactured by Pagani Geotechnical Equipment. The DPM30 uses rods with a diameter of 20 mm and the conical tip with a cross-sectional area of 10 cm^2 at the base. A 30-kg hammer is dropped from the height of 20 cm, and the number of blows required to drive the tip 10 cm into the soil, N_{10}, is counted. The N_{10} can be converted into dynamic point resistance using the Dutch formula described in EN ISO 22476–2:2005 (Geotechnical investigation and testing—Field testing—Part 2: Dynamic probing). Specifically, the theoretical energy of a blow, which is equal to the weight of the hammer times the height of the fall, is divided by the cross-sectional area of the cone and the average penetration per blow to obtain the unit point resistance, r_d. This value is then adjusted for the inertia of the driving rods and hammer after the impact with the anvil, which produces the dynamic point resistance, q_d (EN ISO 22476–2:2005). The q_d values are comparable to tip resistance values obtained by static penetrometer tests [38]. Dynamic probing is less reliable in soft soil types and at larger depths because the measured resistance can be significantly affected by skin friction. Other factors that have the potential to influence the dynamic probing results are explained in EN ISO 22476–2:2005.

Direct correlations between the DPM30 data and engineering soil parameters are lacking. Blow counts from DPM30 can be approximately converted to the equivalent standard penetration test (SPT) blow counts, N_{SPT}, by adding N_{10} for each 30 cm interval and multiplying by 0.77 [39–41]. The N_{SPT} can be then corrected for hammer efficiency, effective overburden stress, etc. to estimate common properties like relative density (e.g., using the [42] correlation). The average energy efficiency of DPM30 is expected to be 72–73 % [39,43]. It is also worth noting that the penetration resistance is affected by the mean particle size [42]. For example, the blow count would be lower in fines-containing sand than in clean sand, which would lead to underestimation of relative density in sand with fines [42].

4.1. Liquefaction ejecta and differential settlement

Liquefaction ejecta caused differential settlement of some light-weight residential structures in Petrinja. Ejecta were identified in yards and adjacent to house foundations. Diagonal cracks in foundations and exterior walls were typically initiated near the ejected soil (Fig. 5a). At one property, horizontal cracks appeared in the isolated house column (Fig. 5b–i), while vertical cracks were visible in the exterior wall of the second story near the column (Fig. 5b–ii). This property had ejecta along the fence foundation about 2 m from the column and the uplifted ground near the column.

Examples of liquefaction-induced damage at residential properties in Milan Makanac St, Petrinja, are presented in Fig. 6. The property at 11 Milan Makanac St sustained liquefaction-induced flooding wherein the discharged groundwater was mixed with sediment ejecta (Fig. 6a). Although the structure was not visibly damaged, the DPM30 testing revealed soil whose penetration resistance to a depth of 8.5 m ranged typically from 1 MPa to 3 MPa, indicating loose material. At 8 Milan Makanac St, sandy material was ejected through the well into the air to a height of about 1.5 m above the ground surface, according to the resident of the adjoining property. Traces of ejecta were visible on the rim of the well and on the surrounding ground. Approximately 5 m from the well, a horizontal crack developed in the exterior wall of the house, between the first story and the attic (Fig. 6b). At 10 Milan Makanac St, the house adjacent to this well had ejecta on the floor (Fig. 6c) and a horizontal crack in the ceiling along the wall.

Sediment ejecta often appeared in residential water wells that extended through non-liquefiable soil layers into the underlying liquefiable sandy soil (Fig. 7). Wells filled with sediment ejecta were rendered unusable after the earthquake.

4.2. Lateral spreading

Lateral spreading was observed in the villages of Bok Palanjecki (northeast of Sisak) and Stari Brod (northwest of Petrinja), as shown in Fig. 1. In Bok Palanjecki, lateral cracks were observed on both banks of the meandering Sava River. While no structural damage was noted, a private driveway was offset horizontally by up to 10 cm and vertically by up to 30 cm. In Stari Brod, approximately 2 km from the fault rupture, lateral spreading and ejecta were identified for several residential properties along the Kupa River. Ejecta were observed around the houses and in the open areas of the properties at 83, 94, 97, 98, 99, 110, and 110A Izisce St (Fig. 8a). Liquefied soil was also ejected through water wells. At 97 Izisce St, sandy ejecta were found both outside the well and 6 m below ground surface inside the well. Lateral spreading affected the properties at 94, 97, 98, and 99 Izisce St. Fig. 8a shows two major sets of cracks: one across the level ground farther away from the river, roughly along the northwestern facade of the houses (Fig. 8b), and another closer to the Kupa River, along the transition zone between the level and sloping ground (Fig. 8c). These cracks indicate this portion of the ground moved laterally toward the Kupa River due to liquefaction of underlying sandy layers.

At 97 Izisce St, the house was slightly tilted toward the river, suggesting ground movement toward the river. However, the house was not severely damaged even though the adjoining patio settled notably relative to the house. At 98 Izisce St, the house sustained substantial damage due to differential settlement and sliding. The same crack observed in the backyards at 97 and 98 Izisce St propagated through the house at 99 Izisce St, inducing severe damage (Fig. 9a–d). This and additional cracks throughout the house also caused damage to the pipes (Fig. 9c and d). The DPM30 testing near the foundation of the 99 Izisce St house revealed low penetration resistances in the upper 7 m of the soil profile (Fig. 9e). The penetration resistances in the approximate depth range at 98 Izisce St were comparable, while those at 97 Izisce St were slightly higher (by about 1 MPa) in the 2.7–3.9 m and 5.9–7.0 m depth ranges. Fig. 9e also shows the approximate N_{SPT} at the house at 99 Izisce

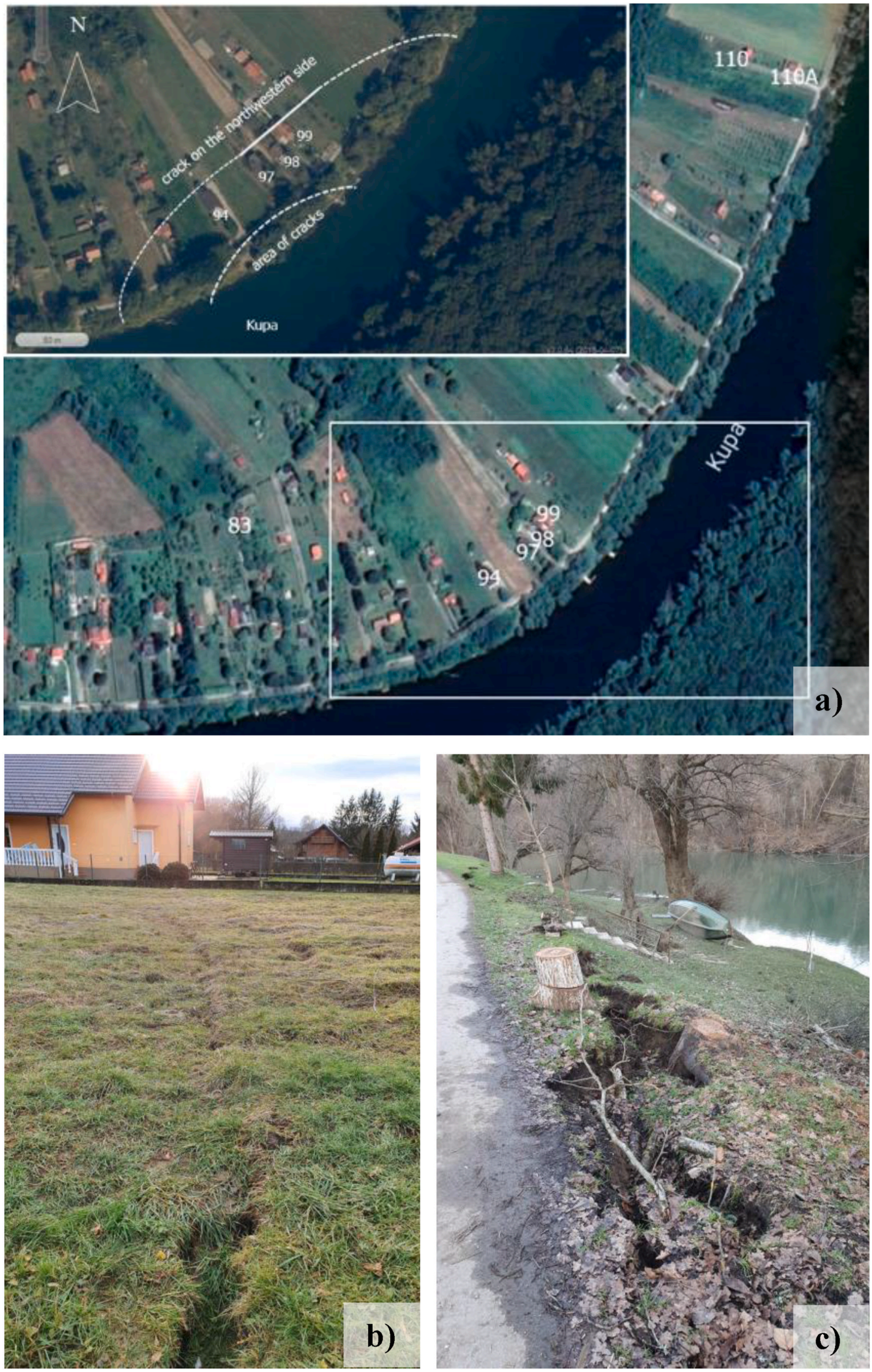

Fig. 8. Liquefaction-induced damage in Stari Brod [45.480N, 16.183E]: (a) distribution of properties impacted by ejecta (83, 94, 97, 98, 99, 110, and 110A Izisce St) and lateral spreading (94, 97, 98, and 99 Izisce St), (b) crack along the northwestern exterior side of the houses (shown as solid line in panel a), and (c) parallel ground fissure in greater proximity to the Kupa River (shown as shorter dashed curve in panel a).

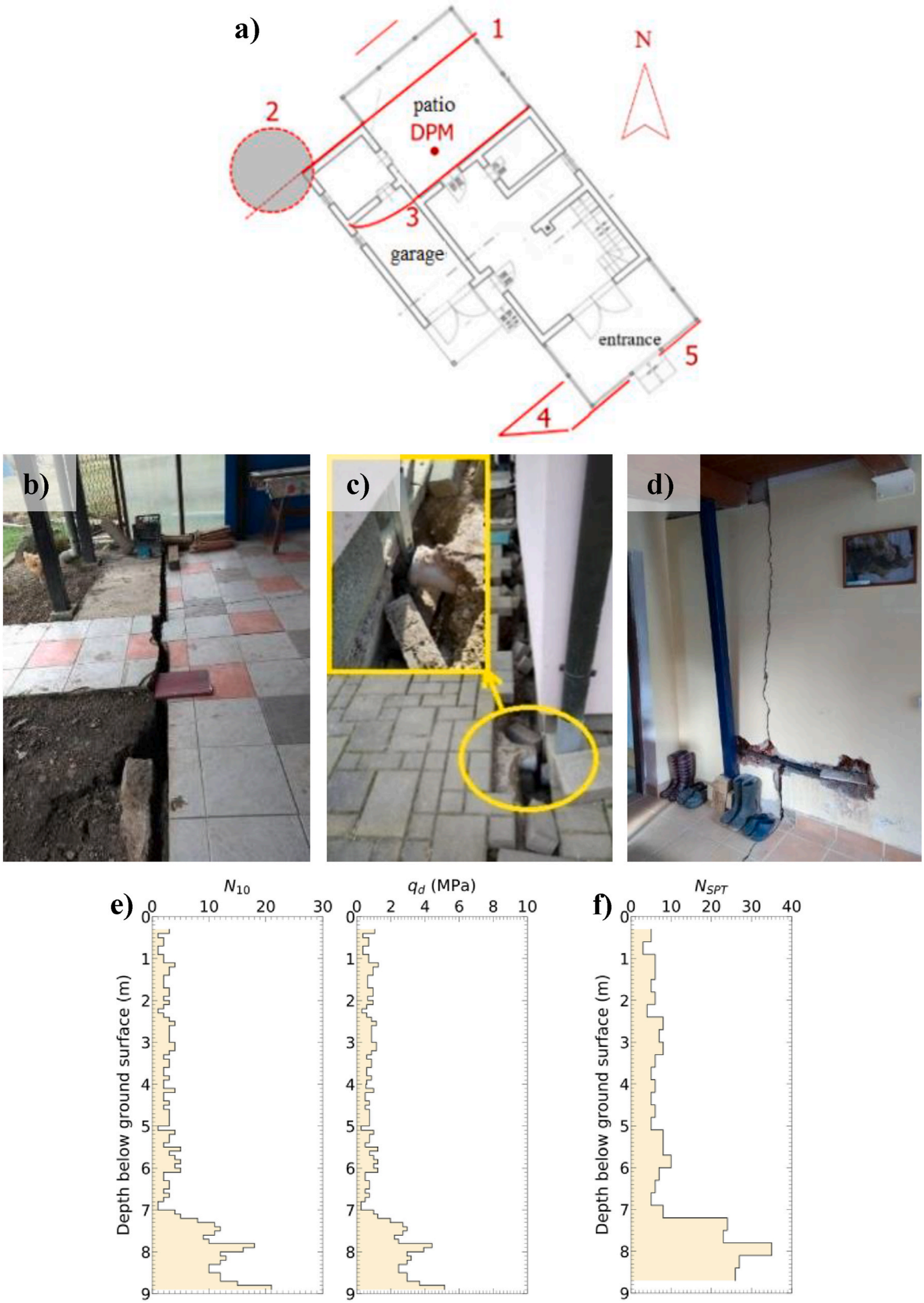

Fig. 9. Damage documentation and subsurface investigation at 99 Izisce St, Stari Brod [45.48023N, 16.18434E]: (a) floor plan showing documented cracks in red, (b) crack through the patio (marked as crack 1 in the floor plan) with depth exceeding 1 m, horizontal separation of 10 cm, and vertical displacement of 8 cm, (c) uplifted ground with displaced pavers and ruptured roof drainage pipe (marked as crack 2 in the floor plan), (d) water-pipe rupture caused by crack through the wall and floor (marked as crack 3 in the floor plan), (e) dynamic probing medium (DPM30) [45.48025N, 16.18429E] blow count per 10 cm penetration, N_{10}, and dynamic point resistance, q_d, versus depth, and (f) equivalent standard penetration test (SPT) blow count per 30 cm penetration, N_{SPT}, versus depth. Cracks denoted by 4 and 5 in the floor plan indicate cracks in pavement and southeast wall, respectively.

St. The upper 7 m of the profile would classify as loose, while strata below this depth would classify as medium dense. However, there is significant uncertainty in this correlation with SPT blow count and no energy measurements are available from the DPM30 testing, which would allow for more robust interpretation of these data or consideration of other factors like rod friction. Additionally, no parameters other than N_{10} or q_d are obtained from the DPM30 testing. Given these uncertainties and limitations, additional fieldwork, including cone penetration testing (CPT) with pore water pressure measurements and detailed logging of continuous, high-quality soil samples, should be performed at these locations to better understand the subsurface conditions and improve the usefulness of these case histories.

5. Concluding remarks

The 2020 M_w 6.4 Petrinja, Croatia, earthquake triggered liquefaction at multiple locations, causing widespread damage to the land and lightweight residential structures in parts of Sisak-Moslavina County. Both on-site and remote inspections were conducted to assess liquefaction-related damage and document observations of ejecta to allow future teams to collect in-situ data at these sites. Ejecta and lateral spreading were observed in the vicinity of the Kupa and Sava rivers and their tributaries, within 20 km of the rupture, where strong shaking of 0.3–0.6 *g* was estimated. Holocene flood and terrace deposits, Holocene deluvium-proluvium, and Pleistocene loess deposits were identified as deposits with surface manifestation of liquefaction. Historical observations of liquefaction near the fault indicated that liquefaction of loose saturated sediments near the active stream channels could be expected.

Extensive fracturing of the ground accompanied by silty and sandy ejecta was commonly observed in the free field. Ejecta at residential properties caused differential settlement of houses and contamination of water wells. In the village of Stari Brod, lateral spreading involved the movement of land toward the Kupa River, which damaged four neighboring houses. Dynamic probing medium (DPM30) testing at those properties revealed low dynamic resistances at shallow depths, indicating loose sandy layers. Multichannel analysis of surface waves (MASW) in the free field indicated that the site without ejecta had stiffer soil at depths of 6 m–9.5 m compared to the site with ejecta.

Existing liquefaction case history databases contain data from relatively few earthquakes with magnitudes less than 6.5. Observations from the 2020 Petrinja earthquake and previous earthquakes in this region demonstrate that widespread liquefaction can occur due to these lower magnitude events. Similarly, the literature contains a limited number of liquefaction case histories involving Pleistocene loess, yet these deposits manifested liquefaction in the 2020 Petrinja earthquake.

This study sought to collect perishable data on observations of surface manifestations of liquefaction and liquefaction-induced damage, but further work is needed to collect in-situ data at these locations to maximize the usefulness of these case histories. The studies should involve field investigations, laboratory testing, and numerical analysis to improve the understanding of liquefaction susceptibility, triggering, and associated effects in the region in conjunction with a thorough geologic model.

CRediT authorship contribution statement

Zorana Mijic: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sonja Zlatović:** Writing – review & editing, Visualization, Investigation, Formal analysis, Conceptualization. **Jack Montgomery:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Katerina Ziotopoulou:** Writing – review & editing, Investigation, Conceptualization. **Verica Gjetvaj:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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