

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

Chapter 8: Earthen Levee Systems

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8. Earthen Levee Systems

8.1 Introduction and Background

The earthquake-affected area comprises mostly of flat valleys of the rivers Kupa and Sava, with tributaries. Both Kupa and Sava have been meandering and producing layers of soft sediments: layers of soft clays, silts, and sands. In the 1950s, the system of levees was constructed to protect the cities, villages, and agricultural fields from flooding. Understanding that climate changes increase the requirements on the levees, Croatian Waters (in Croatian: Hrvatske Vode), the institution in charge of water management in Croatia, started the process of acquiring the design of the improvements to the existing levee system. Therefore, the new geotechnical investigation was performed before the earthquake, and some of the obtained data are presented here. Immediately after the earthquake, the levees were inspected by the Croatian Waters and local GEER-team members. Different levels of damage and distress signs were noticed on seven levee sections as shown in **Figure 8.1** and **Figure 8.3**.

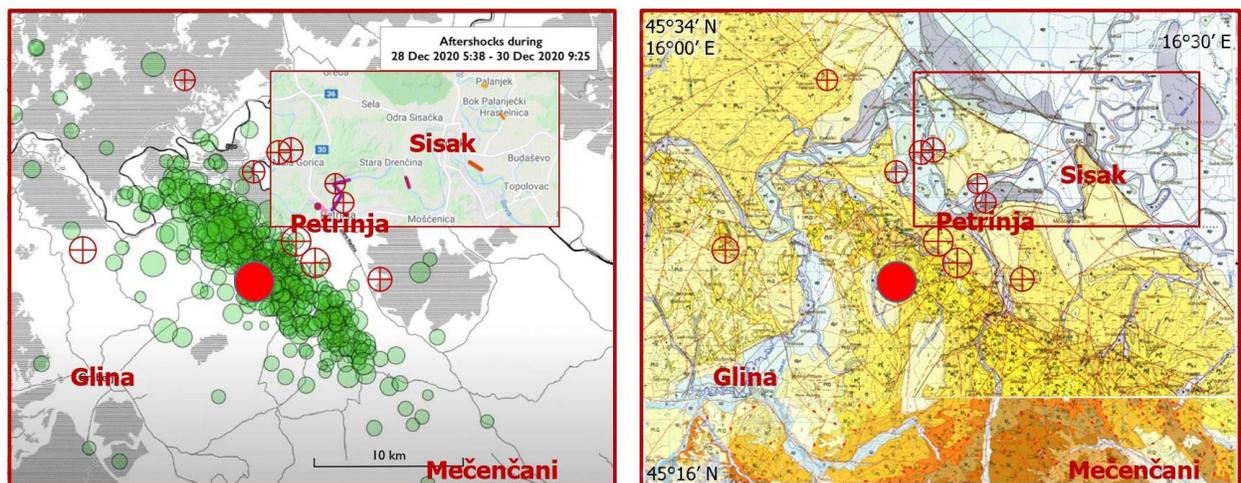


Figure 8.1 (Left) Area damaged in the Petrinja earthquake. The full red circle shows the epicenter of the main shock, green circles show epicenters of earthquakes from 28 December to 30 December at 9:25 (Croatian Seismologic Survey 2020), and red circles with crosses show epicenters of earthquakes of magnitudes above M2.5 from December 2020 to April 2021 in the area. The inner frame shows the area of the damaged levees as given in detail in the next figure. (Right) Geologic maps of affected areas (Pikija 1987, Šikić 2014).

Figure 8.2 shows a section of the geologic map (Pikija 1987) for the damaged areas and **Figure 8.3** is a closeup view of the geology map showing the area of the damaged levees. The upper layers – mostly around 6 to 8 m depth – of the inspected areas consist of clays serving as the foundation for the levees. The levees were built of local clays as well, in a trapezoidal shape. Levee maintenance consists of visual checks of the levees and nurturing the grass cover. Apart from occasional mole holes, no other problems could be noticed. Mostly agricultural fields cover the

dry side of the levees. Two days after the earthquake Croatian Waters started with urgent works on the levees at locations Galdovo and Palanjek. In 3 weeks, the secondary levees or repairs on the levees were finished on six seriously damaged levee sections. Box barriers were used to build secondary levees on Galdovo (740m), Palanjek (250m), Krnjica (530m), and Stara Drenčina (580m). Aftershocks caused deterioration of the damages resulting in the opening of 8 new locations until the middle of March.

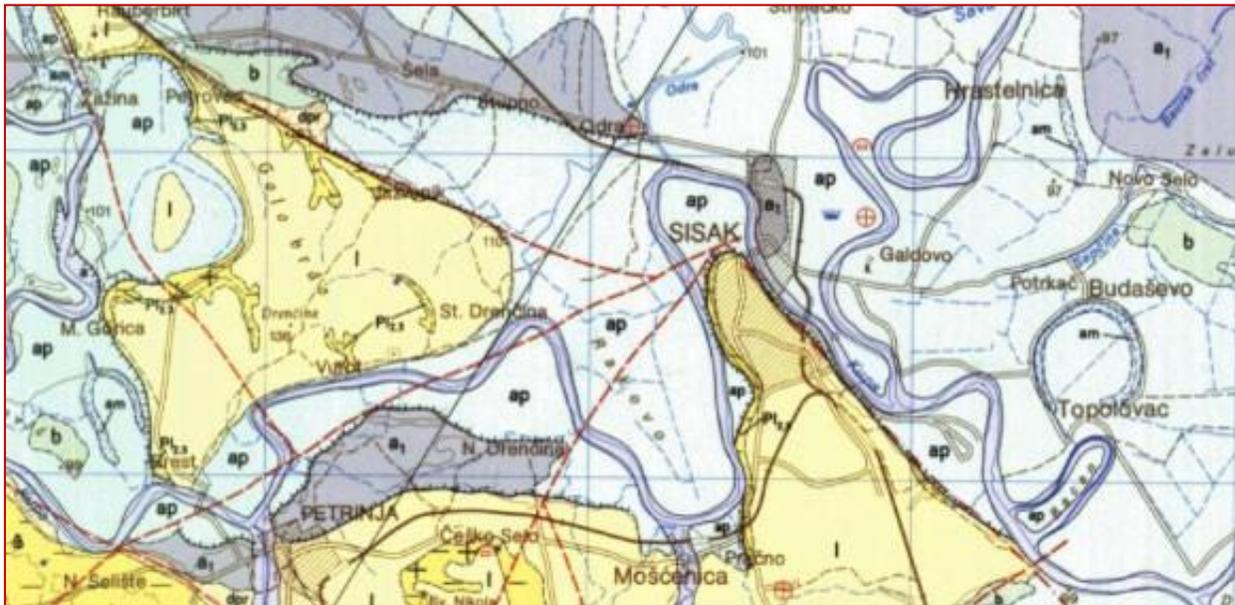


Figure 8.2 Section of the geologic map near Sisak (Pikija 1987) as shown by frame in Figure 8.1.

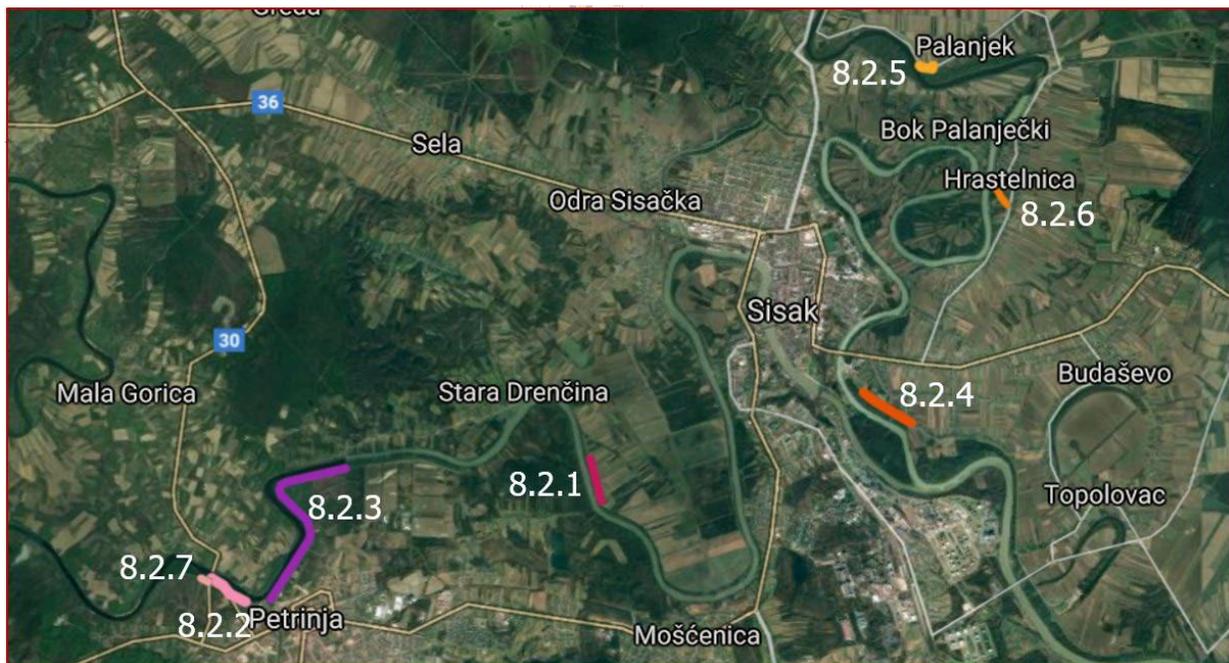


Figure 8.3 Locations of damaged levees on the Google Map as shown by frame in Figure 8.1. Individual stretches of the levees are shown in the corresponding indicated subchapters.

8.2 Performance of Levees during Croatia M_w 6.4 earthquake

On six sections (**Figure 8.3**) longitudinal cracks appeared on the levees or near them. Near a few of the cracks, sand ejecta was visible, but around most of the damaged sections, ejecta was found on the distance of several meters or more. Damage was also observed on the connection of two perpendicular levees (Palanjek) and on the connection of a levee and a canal (near bridge Brest) where cracks perpendicular to the levee were seen. Typical damage is shown by location in the following sections with some additional details on the subsurface conditions where available.

8.2.1 Section of the levee south from Stara Drenčina, on the left bank of the Kupa river

The levee on the left bank i.e. eastern side of the Kupa river near Stara Drenčina exhibited a series of longitudinal cracks with some being near the levee on both sides throughout the 550m section. This levee was built around 30 m from the river, is 2 m in height with an approximately trapezoidal cross-section with side slopes of around 30° . This section is at a distance of 11 km from the epicenter.

The crack which spreads across the crest and continues down the slope of the levee extending for about 30 m along both sides of the levee is shown in **Figure 8.4** and **Figure 8.5** from above, in **Figure 8.7** on the field side, and **Figure 8.8** and **Figure 8.9** on the river side. Cracks are vertical in general but irregular in shape, so a maximum depth of 2 m was measured.

On both sides in the field irregular ejecta was found, the longest stretch being approximately 60 m long as seen in the air photo in **Figure 8.10**.

Information on the subsurface soil conditions through a borehole conducted by Geokon-Zagreb in 2015 (Geokon-Zagreb 2016) for the upgrade of the levee was available near the crack and is shown in **Figure 8.12**. The levee is underlain by 7 m of clays, which are underlain by a 0.50m clayey sand layer, and finally a mixture of poorly graded gravel and sand.



Figure 8.4 Cracks across and along the levee (Photo documentation: Geokon – Zagreb LLD, January 7, 2021, 45.4614N, 16.3358E).



Figure 8.5 Cracks across and along the levee (Photo documentation Geokon – Zagreb LLD, January 7, 2021, 45.4614N, 16.3358E).



Figure 8.6 Crack across and along the levee (21.2.2021.; 45.46142N, 16.33580E). Secondary levee is visible in the distance.

In the first days after the earthquake, Croatian Waters started building a secondary levee far enough on the field side to prevent flooding. The cracks on the river side and the deformation of the slope towards the river make the riverbank unstable.



Figure 8.7 Crack across and along the levee (21.2.2021.; 45.46130N, 16.33592E).



Figure 8.8 At the river side of the levee crack is 2 m deep (21.2.2021.; 45.4612192N, 16.3358308E).



Figure 8.9 At the river side of the levee (21.2.2021.; 45.4612015N, 16.3358606E).



Figure 8.10 Ejecta in the field: length approximately 60m (Photodocumentation Geokon-Zagreb d.o.o.; January 7 2021; 45.46006N, 16.33759E).



Figure 8.11 Ejecta in the field (21.2.2021.; 45.4611943N, 16.3358866E).

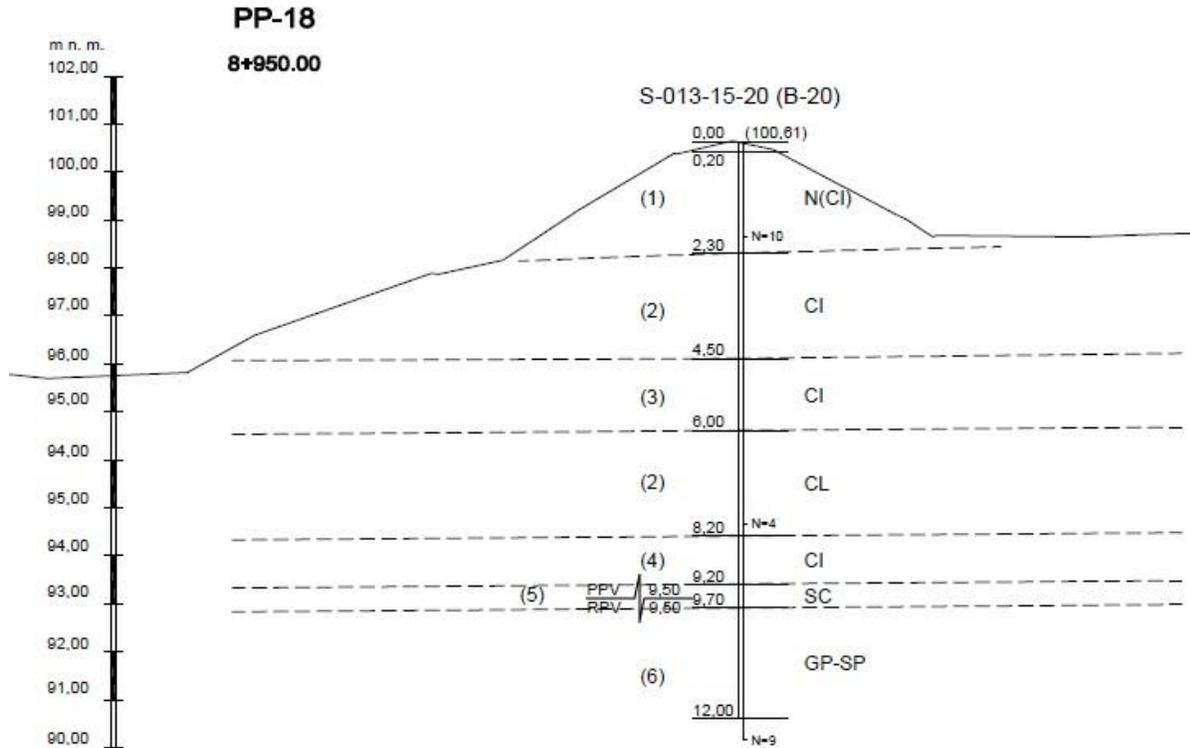


Figure 8.12 Cross-section of the levee south from Stara Drenčina, on the left bank of the river Kupa at the position 45.46134N, 16.33583E (Geokon – Zagreb LLD 2016).

8.2.2 Section of the levee south near Petrinja, on the right bank of the Kupa river from the Bridge Brest to the Beach

Along the levee from Bridge Brest downstream to the Beach, on the right (southern) bank, cracks have been found along with the tow as shown in Figure at the distance of about 1m and width up to 7 cm. Liquefied sand was ejected on the other side of the levee, in the fields. Previous geotechnical investigation (Geokon-Zagreb LLD, 2021) shows the presence of silty sand from the depth of about 2 to 4m to about 5.5 to 5.8m.



Figure 8.13 Typical cracks near the levee toe (6 February 6, 2021; 45.4450N, 16.2660E).



Figure 8.14 Liquefied sand ejecta on the field side of the levee (45.4453N, 16.2649E).

8.2.3. Section of the levee south near Petrinja, on the right (southern) bank of the Kupa river from the Beach towards east

Along the levee from the Petrinja Beach, at a length of 4 km, cracks are visible on both sides the levees. Cracks are irregular in shape and the maximum measured depth is 2m. Typical cracks are shown in the **Figure 8.15-17**. In some locations, liquefied sand ejecta is found. **Figure 8-18** shows one of the cracks with liquefied sand. Croatian Waters in the first days after the earthquake started building secondary protection visible in **Figure 8-19**.



Figure 8.15 One of the deep cracks in the levee north of Petrinja (February 19, 2021; 45.4593N, 16.2738E).



Figure 8.16 Typical cracks on the river Kupa side of the levee north from Petrinja (19 February 2021; 45.4591N, 16.2739E)



Figure 8.17 Typical cracks on the river Kupa side of the levee north from Petrinja (February 19, 2021; 45.4592N, 16.2740E).



Figure 8.18 Typical crack on the field side of the levee north from Petrinja with liquefied sand ejecta (19 February 2021; 45.4613N, 16.2748E)



Figure 8.19 Secondary levee built by Croatian Waters (19 February 2021; 45.46180N, 16.2775E).

8.2.4 Section of the levee south in Galdovo, on the left (eastern) bank of the Sava river

The levee on the left bank i.e. the eastern side of the Sava river in Galdovo Bridge experienced a series of longitudinal cracks with some being near the levee on both sides of the 1000 m section. The levee is approximately 3 m in height with a trapezoidal cross-section, sitting 100 m to 140 m away from the river bank. This section is at a distance of 16 km from the earthquake epicenter. The liquefaction near the levee was most dramatic as seen in the video recorded about 100m from the levee on the protected side (Pavlić, 2020) – a snapshot is shown in **Figure 8.20**.



Figure 8.20 A snapshot from the video made during the M6.4 earthquake near Galdovo levee (Udruga Kas, recorded by Daniel Pavlić (Pavlić, 2020) (45.4735, 16.3926)

The longitudinal cracks are up to 50 cm wide and there is also vertical displacement observed as can be seen in **Figure 8.21 a-c**. A nearby boring from the year 2013. (Geokon-Zagreb LLD 2021) shows the presence of medium density sand at 5 m depth as shown in **Figure 8.21d**. Regarding the widespread liquefaction in the area, this could suggest that liquefaction may have played a role in the deformation of the levee and surrounding ground. Croatian Waters built a secondary levee to protect 800m of the primary levee. The densest are the cracks around the discharge pipe through the levee - where Croatian Waters built separate protection as seen in **Figure 8.22**.

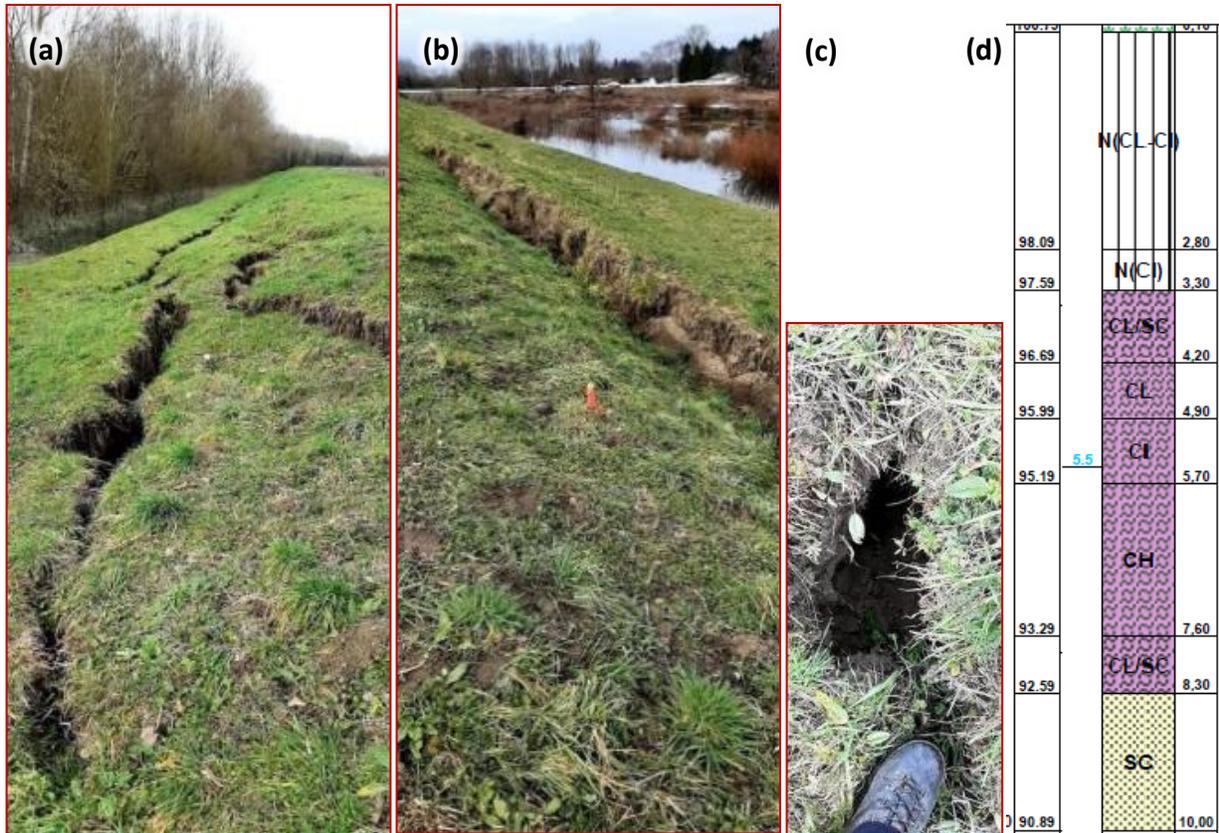


Figure 8.21 (a) Some of the cracks at the river side of the levee (45.4704728N,16.3957025E), and (b) on the opposite side (45.47059N,16.3954E), (c) typical crack (45.4705N,16.3957E). (d) Borehole done in the year 2017 (Geokon-Zagreb LLD 2021) on a nearby location shows the presence of clayey sand at the depth of around 5 m below the ground surface – the upper 3.3 m represent the levee.



Figure 8.22 Two air views of the southern part of the damaged levee with a high level of the Sava river. The white sandbags were installed right after the earthquake on the discharge pipe location, also the secondary levee was built. (Photo documentation of Geokon – Zagreb LLD, 45.4708 16.3952).

8.2.5 Section of the levee in Palanjek, on the left bank of the Sava river

At a distance of 19.5 km from the epicenter, the levee on the left bank of the Sava river was damaged over a length of approximately 250m in the area shown in **Figure 8.23**. Transverse cracks followed by vertical displacement of about 50 cm occurred near the location where two levees meet as shown in **Figure 8.24**. Longitudinal cracks along the road and the toe are shown in **Figure 8.25**, together with some ejecta on the river side. On the field side, more sand was ejected to the surface as seen in **Figure 8.26a**. A sand layer was found at a depth of about 5m as shown in **Figure 8.26b**.



Figure 8.23 Map of the damaged section of the levee on the left bank of the Sava river near Palanjek.



Figure 8.24 (a,b) Transverse cracks and settlement. (45.518732N, 16.4028826E), (c) longitudinal cracks along the levee toe on the eastern side.



Figure 8.25 (a) Sand ejecta in the field, longitudinal cracks along the levee along the toe and (b) along the crest and settlement. (45.51874, 16.402). (c) Transverse crack on the road on the levee crest (Photo documentation Geokon – Zagreb LLD).

(a)



(b)

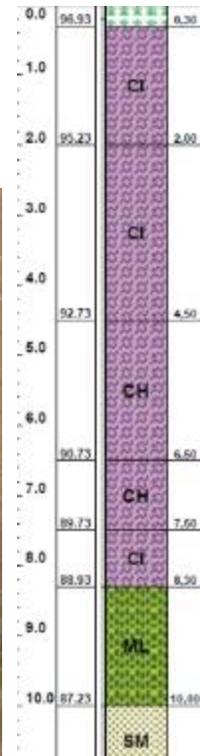


Figure 8.26 (a) Aerial view of the liquefaction in the field near Palanjek. (45.520N, 16.402E, Photo documentation Geokon – Zagreb LLD. (b) Borehole from 2013 (Geokon-Zagreb LLD 2021) on a nearby location shows the presence of clayey sand at the depth of around 5 m below the ground surface.

8.2.6. Section of the levee in Hrastelnica, on the left bank of the Sava river

At a distance of 19km from the epicenter, along the section of the left bank of the Sava river, sand ejecta are visible on both sides of the levee, on the levee slopes, near the toe, and in the fields. In addition to some smaller areas, sand ejecta are visible on the river side in the field along the stretch of 40 m of the levee, and at a distance of 40 m or more as seen in **Figure 8.27**. A similar area is covered with sand on the opposite side as shown in **Figure 8.28**. A nearby borehole from 2017 (Geokon-Zagreb LLD 2021) shows the presence of a sand layer at a depth of 3 m (**Figure 8.28c**).



Figure 8.27 (a, b) Liquefied sand on the river side of the levee near Hrastelnica from the levee toe to the distance of 40 m, and cracks on the levee (45.5007N, 16.4162E).



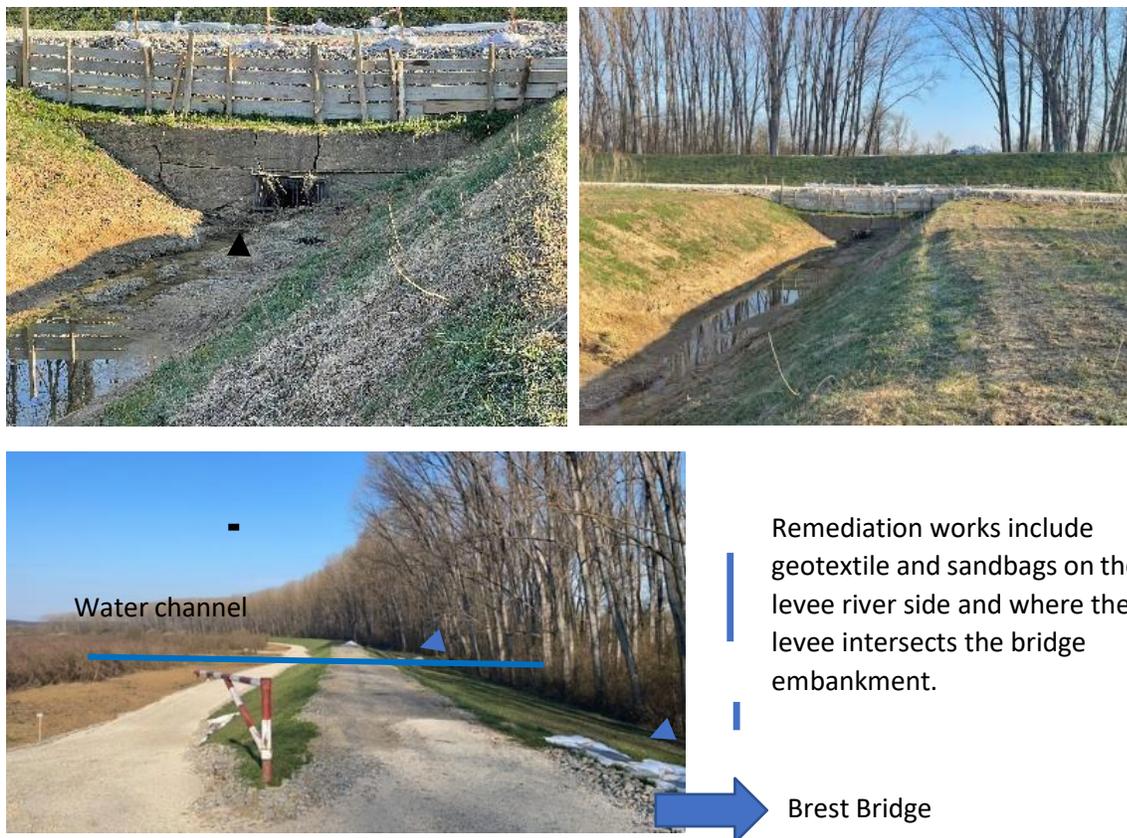
Figure 8.28 Liquefied sand on the dry side of the levee near Hrastelnica (45.5015N, 16.4163E). Borehole from 2017 (Geokon-Zagreb 2021) on a nearby location shows the presence of clayey sand at the depth of around 5 m below the ground surface.

8.2.7. The section near the Brest Bridge in Brest Pokupski, near Petrinja (Ingrid Tomac)

A levee south of Brest Bridge along the Kupa river was damaged in two locations. The first location is at the contact of the levee and the bridge embankment and the second is where a water channel perpendicularly crosses the levee. **Figure 8.29** shows the plan view and **Figure 8.30** damaged concrete channel under the levee and remediation works that were performed immediately after the earthquake. The images were taken on March 22nd, 2021.



Figure 8.29 Plan view of the Brest Bridge and levee damage in Brest Pokupski, near Petrinja (45.4476N, 16.259E) (source: Ingrid Tomac)



Remediation works include geotextile and sandbags on the levee river side and where the levee intersects the bridge embankment.

Brest Bridge

Figure 8.30 Levee damage and remediation works on the south bank Kupa river levee near the Brest Bridge in Petrinja (45.4478N, 16.2583E; 45.4475N, 16.2595E) (source: Ingrid Tomac).

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