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## PRELIMINARY RESULTS OF GEOTECHNICAL AND GEOPHYSICAL INVESTIGATIONS ON SITES WITH LIQUEFACTION OCCURRENCES IN THE GREATER PETRINJA AREA AFTER THE 2020 EARTHQUAKE

### PRELIMINARNI REZULTATI GEOTEHNIČKIH I GEOFIČIKIH ISTRAŽIVANJA LOKALITETA S POJAVAMA LIKVEFAKCIJE NA ŠIREM PETRINJSKOM PODRUČJU NAKON POTRESA 2020.

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#### ABSTRACT

The occurrence of extensive liquefaction during the 2020 Petrinja earthquake in the epicentral area raises many questions, notably the geometries of sedimentary bodies in depth. In the fluvial plains of the Kupa, Glina and Sava rivers, many lines of sand ejecta and cracks at the surface are subparallel to the riverbanks in convex meanders and would reveal buried sand point bars below a thick layer of silts. In order to highlight the different structures and estimate their mechanical properties, geotechnical and geophysical investigations were carried out at different sites along the Kupa river in the Petrinja epicentral area. This work presents the approach adopted for both the site selection and the study methods. Then, we show some preliminary results as well as the perspectives of further studies on liquefied layers.

**Keywords:** Liquefaction, sand point bars, sand dykes, Kupa river, Croatia, geotechnical investigations, geophysical investigations.

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## SAŽETAK

Brojne pojave likvefakcije nastale u aluvijalnim područjima Kupe, Gline i Save tijekom Petrinjskog potresa, 2020. god., postavljaju mnoga pitanja, osobito u vezi s karakterom i svojstvima tla koja su podložna stvaranju visokog pornog tlaka u tlu tijekom potresa i geometrije sedimentnih tijela u podzemlju. Mnoge pojave izbačenog pijeska i pukotine na površini približno su paralelne s riječnim obalama u konveksnim meandrima, te otkrivaju pješčane prudove prekrivene debelim sloja silta. Kako bi se istražile te strukture i procijenile njihove mehaničke osobine, provedena su geotehnička i geofizička istraživanja na više lokacija uz rijeku Kupu na području Petrinje gdje su nakon potresa zabilježene ovakve pojave. Ovaj rad predstavlja pristup odabira lokacije i metode istraživanja te neke preliminarnе rezultate kao i perspektive daljnjih istraživanja likvefakcija.

**Ključne riječi:** likvefakcija, pješčani prudovi, pješčani izboji, rijeka Kupa, Hrvatska, geotehnička istraživanja, geofizička istraživanja

### INTRODUCTION

The 2020 Petrinja earthquake (mainshock:  $M_w$  6.4) caused coseismic deformation, including numerous cases of liquefaction in the alluvial plains of the Kupa, Glina and Sava river. More than 2100 observations related to this phenomenon were recorded as far as about 20 km around the epicenter (mainly sand blows, cracks, ground settlements and lateral spreading) by the Croatian Geological Survey (HGI-CGS).

The occurrence of extensive liquefaction raises many questions, notably regarding the geometries of sedimentary bodies in-depth and the soils leading to significant increase in pore water pressure during shaking. Notably, the Kupa valley in the epicentral area around Petrinja shows numerous sand ejections (shown in Figure 1) and represents an area of specific interest to study the massive initiation of this phenomenon in 2020.

In the 1<sup>st</sup> stage, observations and sand ejecta sampling along the Kupa between Stari Farkašić and Sisak were carried out in April 2022 (black rectangles in Figure 1). This initial field survey guided the 2<sup>nd</sup> stage geotechnical and geophysical investigations in October 2022 at selected areas deemed relevant (sites D1, D2, F1, E1 and E3 in Figure 1) both for the study of paleo-liquefaction related to

older earthquakes and for the study of liquefaction in 2020.

This work presents the findings in April 2022 and the selected sites investigated in October 2022. We then expose the approach and geotechnical or geophysical tests. The first results related to the liquefied zones at depth and the characteristics of the soil are then detailed.

### FEATURES OF SANDY EJECTA ALONG THE KUPA RIVER

Most sandy ejecta at the surface along the Kupa river (shown in Figure 1) are located close to the Kupa riverbanks or abandoned meanders, at around 100 m in elevation (reference system based on HVR571 geoid model). Those flat areas are constituted by Holocene alluvial sediments referred as “ap” and “am” in the geological map of Sisak (Pikija, 1987).

In the sampled areas (labelled A to H in Figure 1), all ejecta are orange-brown sands classified as poorly graded sands with silts (SP-SM in ASTM, 2010) with fine content % FC (passing to 75  $\mu$ m) less than 10 %. Some fine contents estimated by sieving may reach up to 25 %, which then indicates preferentially silty sands SP (ASTM, 2010) for these ejecta. All these SP-SM or SM sands of the Kupa river are prone to liquefaction (Figure 2), according to the grading range of liquefiable soils (Iai et al., 1986).

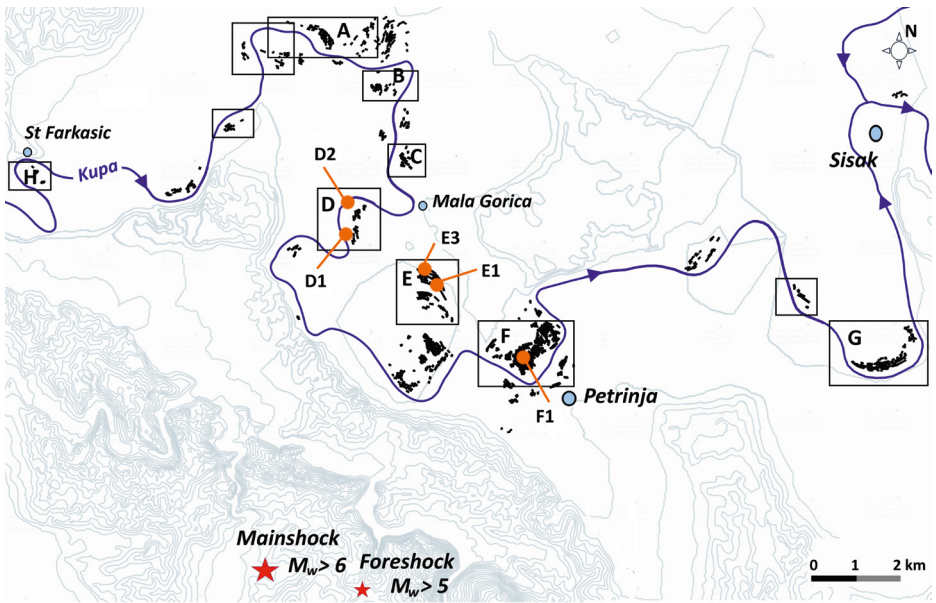


Figure 1. Map of sand ejections and fissures along the Kupa River between St Farkasic and Sisak (Baize et al., 2022) and location of investigated sites

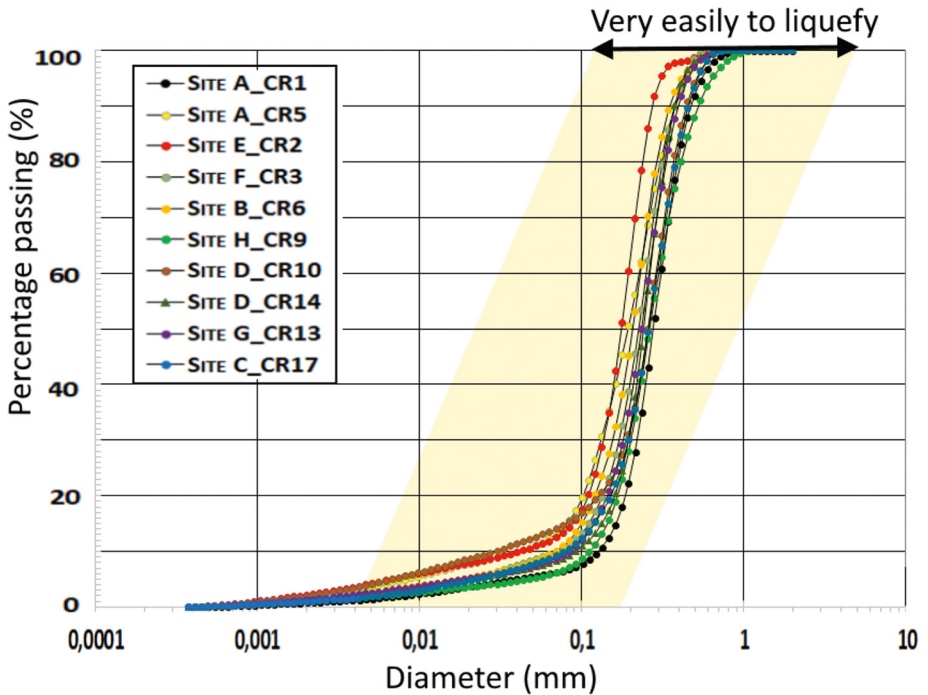


Figure 2. Cumulative particle size- plot for sand ejecta along the Kupa river (laser particle-size)

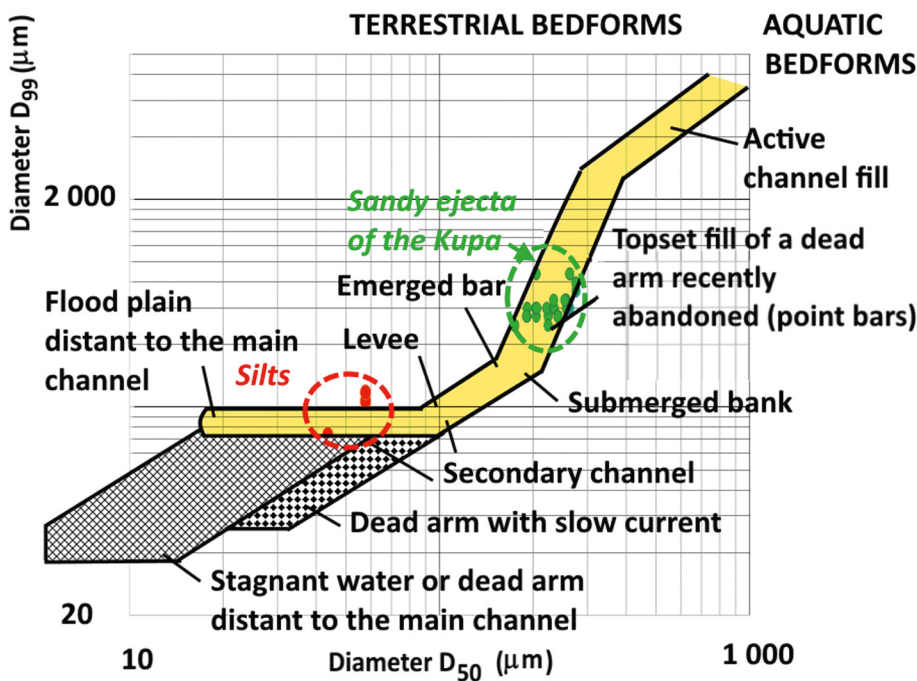


Figure 3. CM pattern and associated terrestrial and aquatic bedforms

The thickness of sand ejecta, often between 20 and 30 cm, can reach 40 cm above the ground surface. They are often distributed in lines and are mostly located at or near cracks which affected the topsoil and the superficial layer of cohesive material (mainly silt or clayey silts). During this reconnaissance phase, hand auger drilling always pierce a thick layer of silt (at least 2 m), without reaching the source of ejecta.

The distribution of ejecta is well-developed in the convex of meanders of the Kupa (A, D, C, E or G on Figure 1). The CM diagram technique (Bravard & Perry, 1999), where the coarsest value at 99% on a cumulative curve ( $D_{99}$ ) and the value median ( $D_{50}$ ) are plotted on a log-log graph (Figure 3), reveals that the sand ejecta likely come from buried sand point bars in the meander bends, beneath the flood plain silts.

These results are consistent with the Kupa fluvial sequence described by Pollak et al., 2021 with 2 m thick silts overlying sands (fine, pure or silty sands) then gravel and coarse sands layers. These buried sandy bars are developed from the middle to lower stretch of the Kupa, in the convex portions of the meanders. The length of these sandy bars would be between 15 and 200 m. They present accretion marks and a crescentic shape in a horizontal plan (Francisković-Bilinski et al, 2011).

#### CHOICES OF AREAS AND METHODS FOR FIELD INVESTIGATIONS IN OCTOBER 2022

Several criteria guided the choice of areas to be investigated for the study of 2020 liquefaction features and possible paleo-liquefaction evidence. In particular, the areas selected with liquefaction features must be pristine of any man modification, must be

close enough to the fault zone and located in a convex part of a meander. Moreover, these areas must be permanently saturated: that is the case along the Kupa banks, which are directly connected to the river level.

The sites B, D, E (Figure 1) met all the criteria. However, for accessibility issues, the site B was abandoned. In addition, we selected the site F because a liquefaction evidence related to the 1909 earthquake was described there, close to a high density of sandy ejecta. Nevertheless, this site F shows possible human modification of the river's course in a recent history, with two anomalous right angles to the northwest and southeast.

The site D is in the immediate vicinity of Kupa bank. It includes two sites, site D1 with ejecta lines and cracks subparallel to the direction of the bank, and the site D2 with a lateral spreading extending over a width of more than 70 m from the riverbank (see sites locations on the Figure 1).

Site E encompasses a naturally or artificially abandoned former meander. It includes 2 sites for the investigations, sites E1 and E3, located on the eastern and northern edges respectively.

For the D1, D2, E1 and E3 sites, the guiding idea was to intersect the convex meander by carrying out geotechnical and geophysical cross-sections covering at least of 100 m off the riverbank (see Table 1.). We also prospected up to a depth of 15 m, which is the maximum depth known for surface liquefaction occurrence at that earthquake magnitude (Huang & Yu, 2013; Kavazanjian et al., 2016). For major earthquakes in the early twenty-first century, soil liquefaction is likely to have been triggered at generally shallower depths, up to 6 m (Huang & Yu, 2013). This depth of 15 m is also larger than the difference between the site elevation (~100 m asl) and the channel bottom (~90 m asl) (Kekus, 1984).

For the geotechnical soundings, we opted for dynamic cone penetrometer test (DCPT) for

its relevance of use with geophysical methods. A lightweight (DPL) and a super heavy (DPSH) devices were used, denominated respectively P.A.N.D.A. 3 and Grizzly 3. One of the great advantages of DCPT is its repeatability which allows fine prospection of soils in order to characterize spatial variability of soil. The number of soundings for each site is specified in the Table 1. In addition, several works have shown the interest of DCPT in liquefaction risk assessment and others propose complementary methods to those existing today (Lepetit, 2002; Villavicencio et al., 2016; Hubler & Hanley, 2021; Retamales et al., 2021). The considered spacing between each sounding varies in average from 10 m to 25 m, except for the site D2 where spacing of 5 m and 10 m were considered. The maximum depth reached is 15 m.

To display the geometries at-depth, we chose to use the Electrical Resistivity Tomography (ERT). This technique is an effective technique with which we measure the apparent resistivity along profiles at different depths of investigation (Abu Zeid et al., 2012, Güven et al., 2022). As the resistivity of porous sediment depends on the degree of water saturation and clay content, high values of resistivity tend to indicate coarse-grained materials such as liquefaction deposits (sandy materials) and lower resistivity values are rather associated with fine grained soils (Güven et al., 2022). In this study, we have designed the profiles with an electrode spacing of either 1 or 2 m. For each site, we supplemented the ERT profiles by Ground Penetrating Radar (GPR) profiles with a 200 MHz and 400 MHz antenna. Those two frequencies might be relevant to image contrasting materials in the first meters.

Furthermore, for each site, we drilled 2 or 3 core-boreholes to calibrate the geotechnical soundings and the ERT profiles. Those boreholes were complemented by hand-auger drillings very close to the riv-



erbank for the sites D1 and D2. Six trenches were also excavated to observe the sandy dykes and we collected samples for  $^{14}\text{C}$  or by Optically Stimulated Lumines-

cence (OSL) dating of the liquefied sands. A sampling of sandy dykes was also made to study their mechanical behaviour in the laboratory (cyclic triaxial tests).

Site	Invest. length	Number of geotech. sounding	Geophy. lines.	Num. of geol. drilling	Trenches of 2 m in depth				
			ERT	GPR		Num.	Sampling of dykes	Shear vane test	Dating
D1	210 m	16	3	4	3	2	yes	yes	yes
D2	130 m	14	3	7	2	2	yes	yes	yes
E1	110 m	9	3	2	2	1			
E3	130 m	8	3	2	0	0			
F1	130 m	10	3	3	3	1			

**Table 1.** Summary list of field survey in October 2022

In addition, several shear vane tests were led in the trenches: the aim was to measure the undrained shear strength of the cohesive silty layer for further modelling related to their fracturing. Finally, drone flights for each site were carried out to help distinguish between natural and artificial structures.

### PRELIMINARY RESULTS

As a preliminary remark, due to space limitations of the format, geophysical results are not shown here. An example of correlation with the ERT resistivity profile is presented for site E1 in Luong et al. (this issue).

#### *Summary description of the general stratigraphy*

All geotechnical soundings for each site presents similar curves from 0 to 15 m of depth (an example is shown in the Figure 4). The correlations with the core-boreholes point out (from the ground surface to the bottom):

The whole thickness of silty layers is 3 m on average but can reach almost 4 m (site F1). The sediments are mainly silty clays to clayey silts; they become coarser below 2 m in

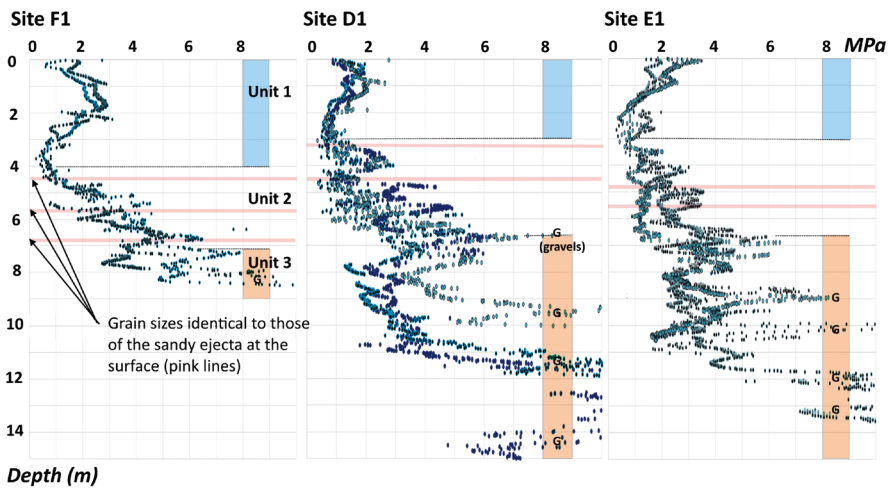
depth. The first levels of sands are found at a depth of 3-4 m. Those fine soil layers correspond to the Unit 1 on the Figure 4 with a decrease of the soil strength ( $q_d$ ) below 2 m up to the bottom of the unit.

Below the Unit 1, there is a succession of silty fine sands between ~3 m and 6 to 7 m, depending on the sites. In these sands, layers are made of rounded grains. The trend of the soil strength ( $q_d$ ) is a general increase up to the bottom, but several layers of sands stand out with low  $q_d$  values below 2 MPa (likely loose sands).

Around a depth of 6-7 m, gravel layers are found and alternated between 8 and 11 m with fine sand layers with low  $q_d$  values below 2 MPa.. The general trend in this Unit 3 is an increase of the soil strength ( $q_d$ ) with depth. The gravel levels are always highlighted by high values ( $q_d$ ) above 8 MPa.

#### *Liquefiable soils and plausible sources of sand ejecta at the surface*

The level of the Kupa river rose from 98.7 m to 100.6 m at the Farkašić station, between Dec. 27<sup>th</sup> and 31<sup>st</sup> 2020.



**Figure 4.** Variations in mechanical strength ( $q_d$ ) with depth - Examples of Grizzly results for the sites F1, E1 and D1. The lithologies encountered on the core-boreholes are in blue: Unit 1 (silt layers), in white: Unit 2 (alternation of fine and silty sands layers) and in pale orange: Unit 3 (gravels and coarser and fine sands layers)

At the time of the earthquake, the level of underground water was then very close to the ground surface in the studied sites and, consequently, most of the soil units were water saturated and should be assessed.

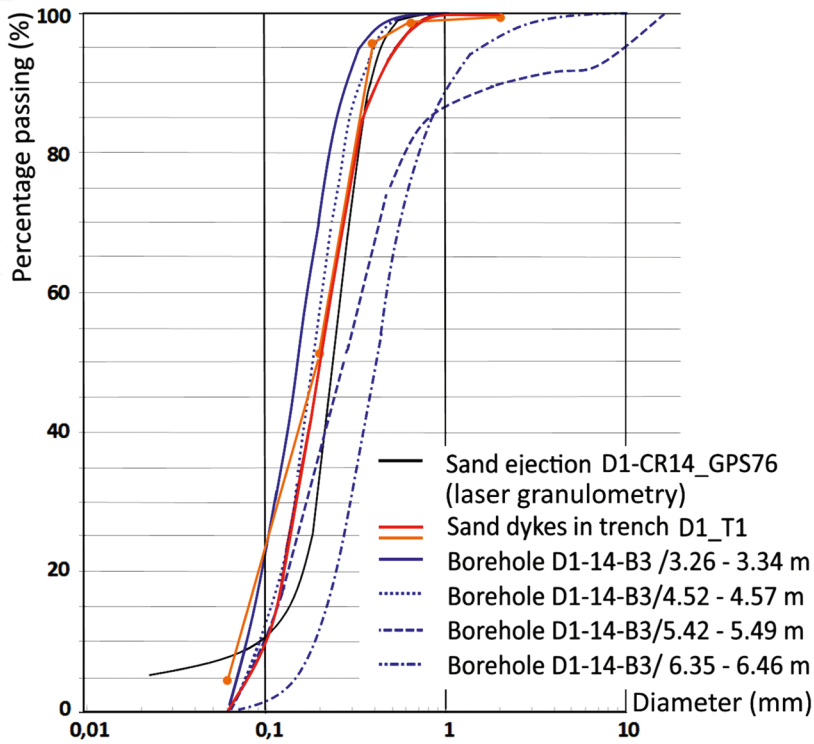
As for Unit 1, no evidence of liquefaction of silty materials was observed at the ground surface in the studied area. The few grain size analyses on samples of the Unit 1 with low apparent plasticity tend to indicate silt material (ML or MH in ASTM, 2010) with 65-90 % material below 75  $\mu\text{m}$  and 3 % of clay content (mainly montmorillonite from X-ray analysis which is a swelling clay).

Consequently, the susceptibility to liquefy for these soils could not be ruled out according to the criteria for fine soils (e.g. Seed et al., 2003), in particular between depth of 2 and 3 m where these soils have low  $q_d$  values and are coarser (sands), just above the top of the sandy Unit 2. In addition, the undrained

shear strength ( $S_u$ ), measured in the trenches of D site when the water table was below Unit 1 (around 5.5 m of depth), reveal low local values between 40 and 70 kPa at site D2: this corresponds to SPT values lower than 15, according to existing correlations for ML or MH soils (Reid & Taylor, 2010).

As for Unit 2, the grain size analysis reveals that the surface sand ejecta have the same curves as those of the borehole samples in Unit 2 (pink lines on the Figure 4 for sites F1, D1 and E1 and Figure 5 for the site D1). At these depths between 3 and 6 m, geotechnical soundings present the lowest values in the Unit 2. In addition, for the site D1, the permeabilities estimated for the sand dykes are between 1 and 1.5  $10^{-4}$  m/s and they are the same as those estimated between 4.5 and 4.8 m in borehole. Consequently, the depth interval 3-6 m of depth seems to be the most plausible source for sand ejecta (SP-SM or SM) at the surface.





**Figure 5.** Site D1 - Comparison of cumulative particle size plots between sand dykes, a sand ejection and the identified sands at-depth

In the Unit 3, the grain size becomes coarser beyond 6 to 7 m, depending on the site. The hydraulic context in Unit 3 is also less conducive to water overpressure than for Unit 2, which is topped by a less permeable silty layer (Unit 1) which prevents rapid drainage in the Unit 2. Nevertheless, this result must be confirmed by sieve analysis on fine sands with low  $q_d$  values, located between 8 and 11 m. Those sediments could also be a source of ejecta.

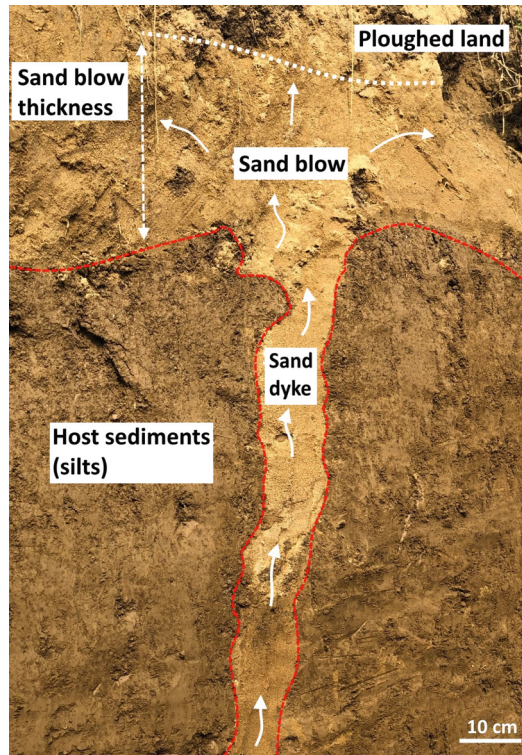
**Observations related to the typology of sand dykes in the host formation (Unit 1)**

In the trenches of sites D1 and D2, the sand dykes below their ejecta are clearly visible in the silt layer (Unit 1 – host formation). We found in the trenches other dykes that do not reach the surface, pinching out in the

upper part of the silt layer. These may be related to paleo-liquefactions.

In the lower half of the trenches, they are between 10 and 15 cm wide, and their edges in the silt can be underlined by little cracks with millimetre-scale opening. The dyke filling does not seem to contain any clast of the host formations, nor their extrusive part (sand blow in Figure 6). However, some small balls of rolled clayey silt of centimeter diameter were found in one single sand injection at the bottom of the T2 trench at site D2.

The source layers of the dykes were not reached in the trenches and then they are deeper than 2 m, but the grain size range of their sand filling clearly points out probable sources from 3-4 m depth, as shown before (Figure 5).



**Figure 6.** Site D1 - Example of sand dyke in trench T1

All the dykes appear to be recent enough without clues of weathering or bioturbation below the top soil and, consequently, linked to the 2020 event. One sand dyke with upward termination, buried below the upper part of the silty Unit 1 could be observed. It could correspond to a pre-2020 liquefaction event. The  $^{14}\text{C}$  dating will allow to propose a date for this event.

### CONCLUSIONS AND PERSPECTIVES

The sandy ejecta along the Kupa riverbanks in the epicentral area probably originates from sandy point bars buried under silty layers and located preferentially in the convex parts of meanders. Given this context, this work first presents the choice of

- 1° the areas to be investigated preferentially,
- 2° the methods to unveil the geometries of

deep liquefied zones and to infer the soils conditions conducive to water overpressure during the ground shaking.

The ejected sands, found either at the surface or in the sand dykes, are poorly graded sands with silts (SP-SM) or silty sands (SM). They most likely correspond to loose sandy layers between 3 and 6 m below the ground surface, according to our soundings. These first results need to be complemented and validated by additional analyses currently underway. The correlations between geotechnical soundings and geophysical results (ERT or GPR profiles) will enable to map the liquefied bodies at depth, for all investigated sites.

Once the depth geometries are well defined, including the liquefiable layers, Kupa riverbank profile modelling is also envisaged to

study the fracturing of the silty cohesive layer and the lateral spreading at site D2.

In parallel, laboratory studies have been started on the cyclic behaviour of these sands in order to assess, in particular, the impact of the strong foreshock.

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