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

Chapter 10: Complementary Geotechnical and Geophysical Investigation Works

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10. Complementary Geotechnical and Geophysical Investigation Works

This chapter summarizes the advanced survey, geophysical, and geotechnical testing methods performed within the scope of the GEER reconnaissance efforts between March 15 and 26, 2021 to complement field observations. Geotechnical investigation works were performed mostly around Mečenčani and Borojevići villages where a substantial number of sinkholes surfaced in the two months following the main shock, from January until mid-March 2021. Investigation works included 5 geotechnical boreholes, in-situ soil classification, and index tests, two Multichannel Analysis of Surface Waves (MASW) profiles in Mečenčani and Borojevići villages and two in Petrinja on-field liquefaction site and 65 Horizontal-to-vertical Spectral Ratio seismic method (HVSR) measurements, 61 HVSR in Mečenčani and Borojevići villages and 4 HVSR in Petrinja near MASW's. This chapter describes the methods and works, including detailed results that are used and embedded in different chapters of this report. It is noted that the NHERI-DesignSafe Data Depot is being utilized to disseminate data from this reconnaissance.

10.1. Horizontal-to-vertical Spectral Ratio (HVSR)

HVSR was performed as an attempt to characterize sediment and clay thicknesses that overlay karstic formation in the area where sinkholes appeared. Additional four measurements complemented MASW profiles in Petrinja. HVSR data was collected using two Nanometrics Trillium Compact broadband three-component seismometers, with a flat response from 100 Hz-20 s. Waveforms were recorded using a Nanometrics Centaur three-component digitizer, where the passive ambient noise was recorded for 25 minutes intervals at 8 locations around the largest sinkhole UVM001, and for 40-60 minutes in the remaining locations. A typical HVRS setup is shown in **Figure 10.1**, and consists of a seismometer, digitizer, a foldable plastic bucket that covers the seismometer to reduce the effects of wind and sun, the GPS sensor, and a battery.

Figure 10.1 Nanometrics setup, with a seismometer aligned to the North.

HVSR analysis was performed using the HVSRweb application that utilizes *hvsrpy* (Vantassel 2020) to allow the processing of ambient noise data in the cloud. HVSRweb is hosted on computing resources made available through the DesignSafe-CI (Rathje et al. 2017, Vantassel et al. 2018). **Figures 10.2** to**10.4** show spatial positions of 61 Nanometrics in the area.

Figure 10.2 Spatial distribution of Nanometrics surrounding Borojevići and Mečenčani.

Figure 10.3 Spatial distribution of Nanometrics around the largest sinkhole S001.

Figure 10.4 Spatial distribution of Nanometrics in the liquefied field in Petrinja.

The time records were divided into 60 s block for processes. Time windows with excessive noise were rejected while the remaining time windows were used to create a spectral average representing the response of each array. The analysis used the time-averaged shear-wave velocity (VS) to a depth of 30 m, VS30 measured in the area. Seismometer recordings were processed immediately following the field reconnaissance using the HVSRweb application (**Table 10.1**), as listed with positions in **Table 10.2** and all the analyses used the following setup:

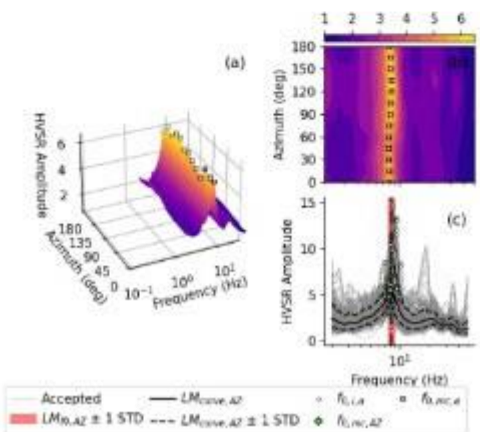
1. Window Length (s): 60 s
2. Cosine Taper Width: 0.1
3. Butterworth Filter: No
4. Konno and Ohmachi Smoothing Coefficient: 40
5. Resampling:
    a. Minimum Frequency (Hz): 3
    b. Maximum Frequency (Hz): 50
    c. Number of Frequency Points: 128
    d. Type: Logarithmic
6. Define Horizontal Component with Multiple-Azimuths
7. Azimuth Interval: 15
8. Distribution of f_0: Lognormal

9. Distribution of Median Curve: Lognormal
10. Apply Frequency-Domain Window-Rejection? Yes
11. Number of Standard Deviations (n): 2
12. Maximum Number of Allowed Iterations: 50

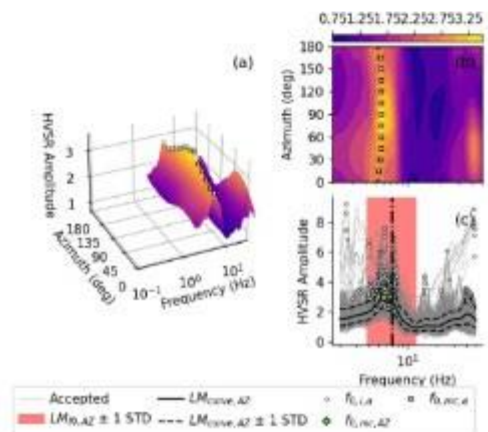
Table 10.1 shows only a smaller number of analyses of collected nanometric data. Weathered karst that contains an underground cavernous system yields a complex signal, which can be further analyzed to determine various horizons of contacts between cover clay soil, weathered karst, and competent karst at the bottom, as it is shown on one example of N-15 nanometric in **Table 10.1.** The rest of the data in **Table 10.1** correspond to selected analyses that yielded a clear peak at f_0. N-62, N-63, N-64, and N-65 show liquefaction field results.

Table 10.1 HVRSweb analysis of ambient noise data.

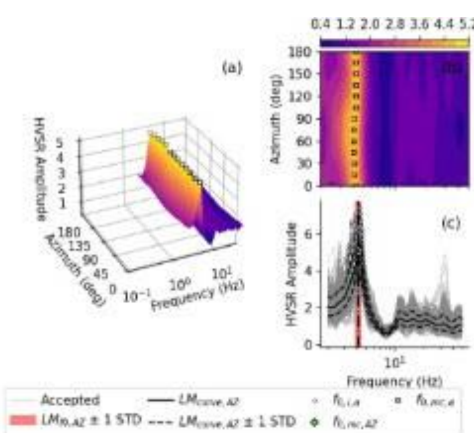
N-1: $f_0 = 8.06$



N-2: $f_0 = 5.65$



N-3: $f_0 = 4.17$



N-4: $f_0 = 12.9$

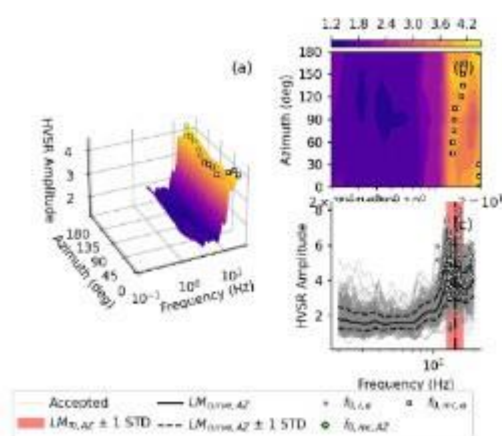
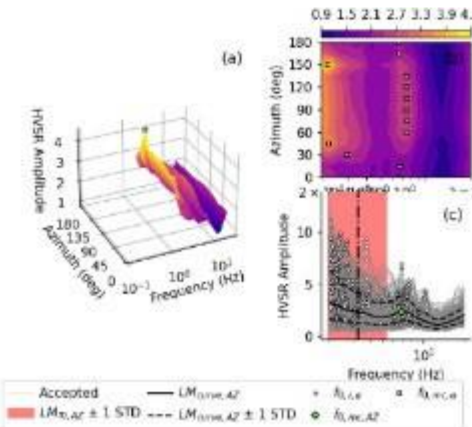
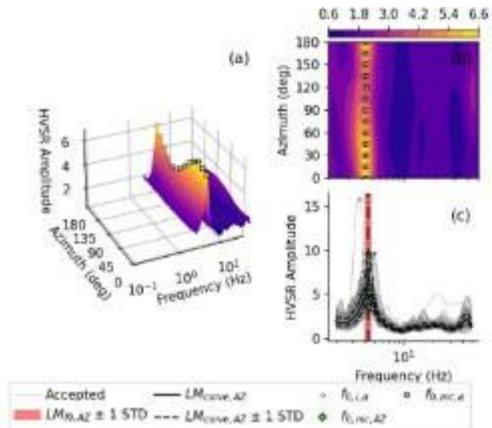


Table 10.1 (cont.) HVRSweb analysis of ambient noise data.

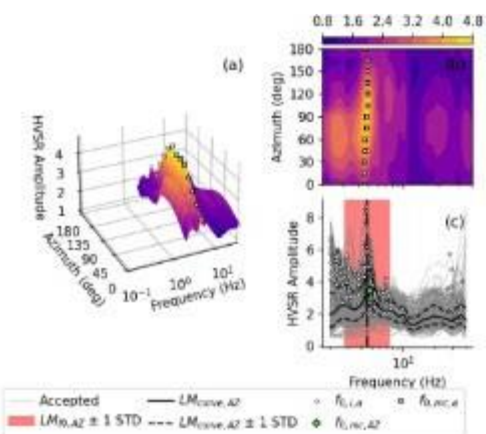
N-5: $f_0 = 6.86$



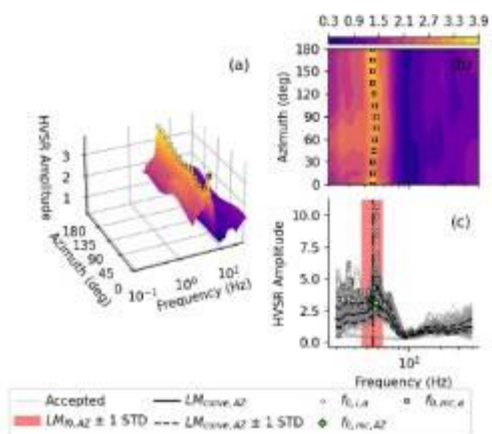
N-8: $f_0 = 4.38$



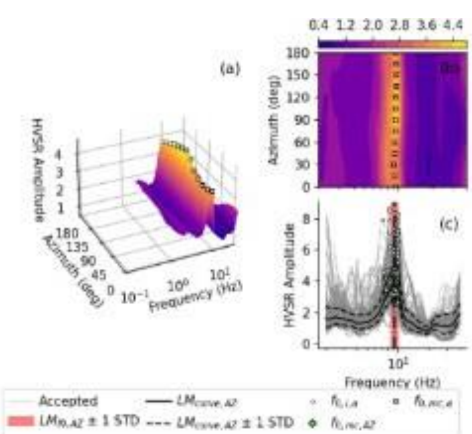
N-11: $f_0 = 4.78$



N-13: $f_0 = 4.90$



N-14: $f_0 = 9.48$



N-15: $f_0 = 4.06$

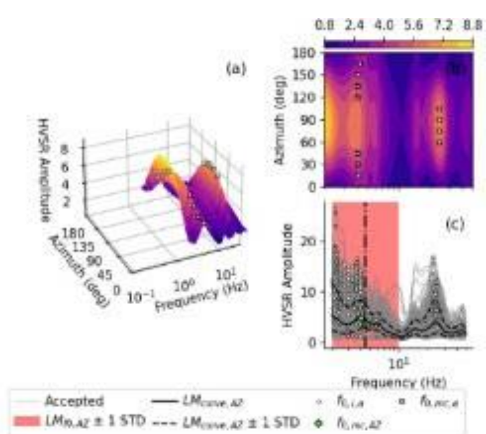
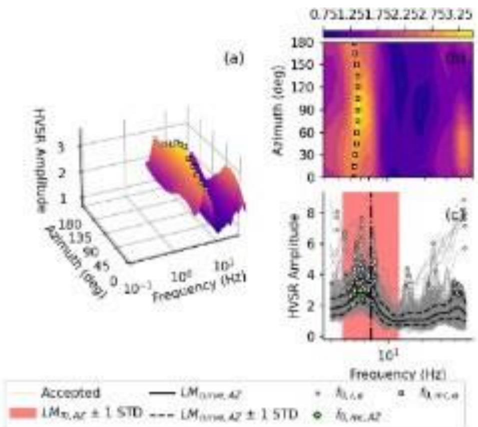
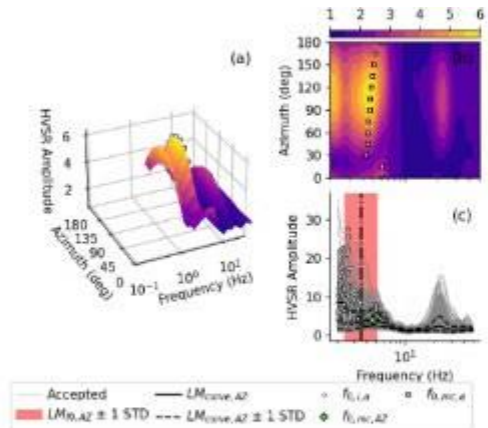


Table 10.1 (cont.) HVRSweb analysis of ambient noise data.

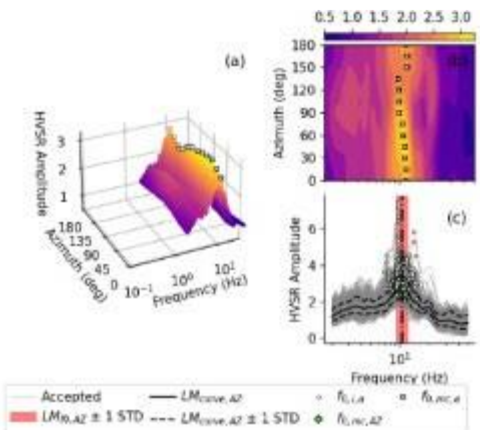
N-19: $f_0 = 5.57$



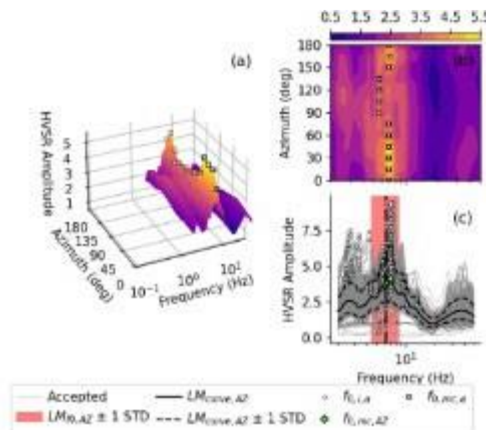
N-21: $f_0 = 4.61$



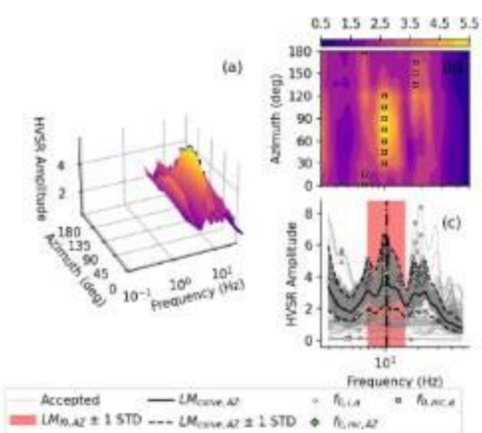
N-23: $f_0 = 10.9$



N-25: $f_0 = 6.92$



N-26: $f_0 = 9.92$



N-62: $f_0 = 26.9$ (Petrinja Liquefaction)

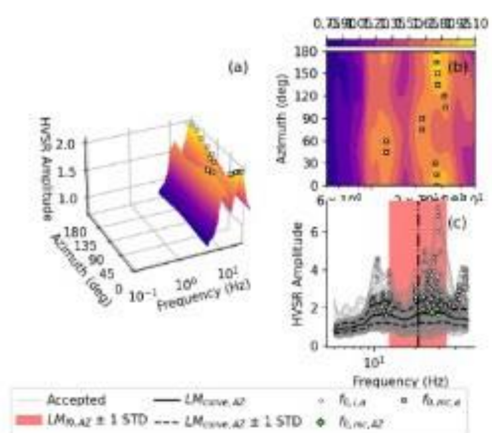
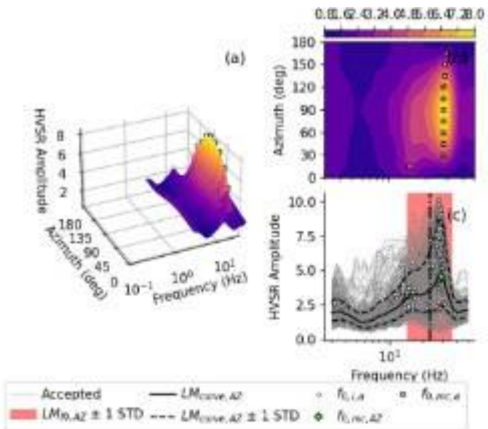
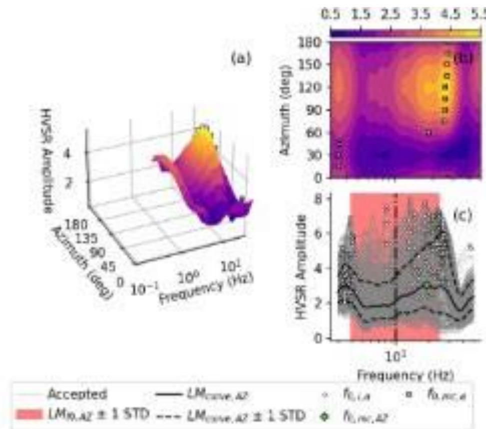


Table 10.1 (cont.) HVRSweb analysis of ambient noise data.

N-63: f_0 = 28.7 (Petrinja Liquefaction)



N-64: f_0 = 18.8 (Petrinja Liquefaction)



N-65: f_0 = 25.7 (Petrinja Liquefaction)

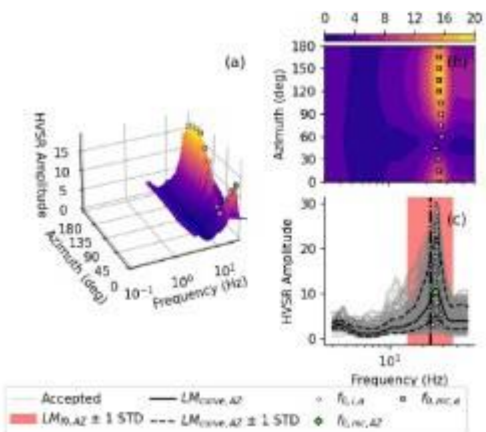


Table 10.2 Geographical positions of all the Nanometrics analyses.

Name	Latitude (N)	Longitude (E)
N-1	45.299619	16.402617
N-2	45.300653	16.403486
N-3	45.296692	16.406081
N-4	45.300031	16.407336
N-5	45.298325	16.408683
N-6	45.297356	16.411283
N-7	45.296025	16.410425
N-8	45.295419	16.407100
N-9	45.293564	16.409775

N-10	45.294767	16.412025
N-11	45.296044	16.413425
N-12	45.296156	16.413769
N-13	45.296272	16.413708
N-14	45.297147	16.414508
N-15	45.290731	16.412222
N-16	45.293394	16.413853
N-17	45.294897	16.415822
N-18	45.296236	16.417139
N-19	45.291119	16.415125
N-20	45.292467	16.416731
N-21	45.294558	16.418317
N-22	45.288203	16.415844
N-23	45.290697	16.420042
N-24	45.292422	16.420061
N-25	45.292750	16.422119
N-26	45.293708	16.423089
N-27	45.285092	16.419381
N-28	45.287769	16.421892
N-29	45.289514	16.423169
N-30	45.290731	16.423447
N-31	45.291939	16.425236
N-32	45.283881	16.422106
N-33	45.285142	16.422933
N-34	45.286764	16.424575
N-35	45.287658	16.424372
N-36	45.285339	16.425444
N-37	45.286025	16.426192
N-38	45.281669	16.423294
N-39	45.283272	16.427617
N-40	45.281233	16.427764
N-41	45.282889	16.429358
N-42	45.284061	16.431828
N-43	45.281078	16.432081
N-44	45.283778	16.426000
N-45	45.283583	16.426292
N-46	45.283333	16.425139
N-47	45.283139	16.425361
N-48	45.282972	16.425722
N-49	45.282750	16.426028

N-50	45.283483	16.425558
N-51	45.283486	16.426136
N-52	45.283506	16.426058
N-53	45.283511	16.425931
N-54	45.283433	16.425825
N-55	45.283367	16.425775
N-56	45.283283	16.425794
N-57	45.283253	16.425881
N-58	45.283258	16.425992
N-59	45.282917	16.430008
N-60	45.282756	16.429886
N-61	45.282536	16.424969
N-62	45.448861	16.276967
N-63	45.447778	16.277125
N-64	45.446525	16.276614
N-65	45.445661	16.276119

10.2 Multichannel Analysis of Surface Waves (MASW)

The main objectives of the Multi-channel Analysis of Surface Waves (MASW) survey carried out was to delineate depth to bedrock, assess soil stiffness, and estimate average shear wave velocities down to 30 m depth. In addition, acquired shear-wave data can be subsequently used further for the analysis of the horizontal-to-vertical spectral ratio (HVSR) measurements conducted and NEHRP (National Earthquake Hazards Reduction Program) or Eurocode 8 site classification based on average shear-wave velocity values of 30 m depth (V_s 30).

A total of four sites were selected for the survey. Two sites in the Mečenčani and Borojevići area (**Figures 10.6** to **10.8**) and two sites in Petrinja - one where clear evidence of liquefaction in form of sand boils was present (**Figure 10.9**) and a nearby site without sand boils present.

Figure 10.6 Spatial distribution of MASW - Mečenčani and Borojevići.

Figure 10.7 MASW spread near the largest sinkhole S001 in Mečenčani.

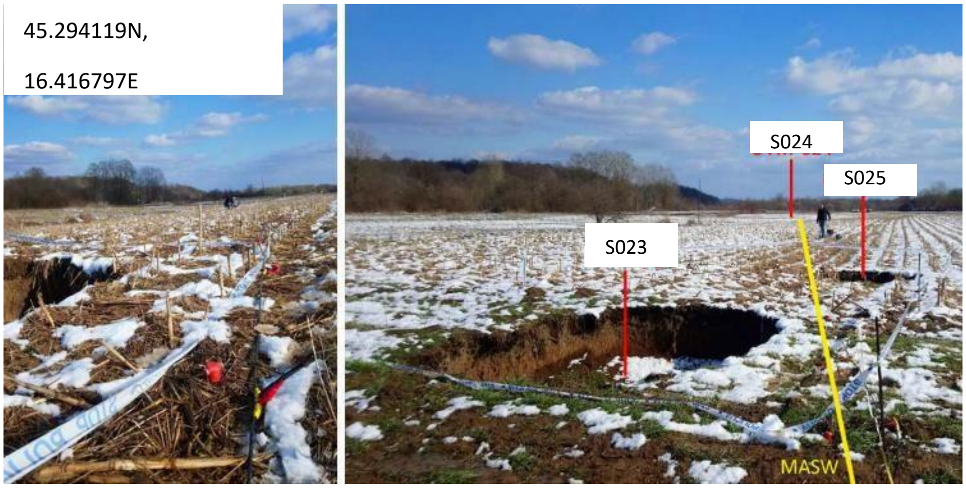


Figure 10.8 MASW spread adjacent to three small sinkholes S023, S024, S025 in Borojevići.

Figure 10.9 MASW in Petrinja on a site with sand boils.

Field data acquisition involved a 24-channel geophone array with 4.5 Hz vertical geophones spaced at 2 m intervals and a sledgehammer used as a shot source. A 24 channel 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 an array with 4 rolls was 86 m. For eachposition shots were conducted at -4.0 m, 0, 4 m, 8 m, 12 m. The same field setup (**Figure 10.10**) was used on all four sites.

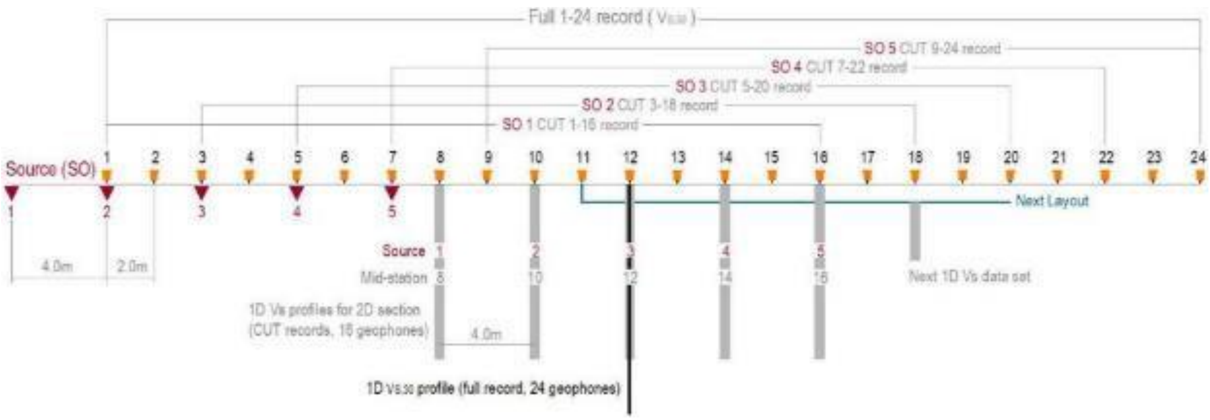


Figure 10.10 Survey layout for 24 channel array.

Data reduction and analysis were performed using the SurfSeis software developed by the Kansas Geological Survey (KGS). Dispersion curves analysis was then performed for each shot gather in the multi-record file by examining the change in phase velocity vs. frequency using the fundamental mode component of the dispersion data. Non-linear inversion modeling of each dispersion curve was performed and resulted in a 1D mid-point representation of shear wave (V_s) profile (**Figure 10.11** and **Figure 10.14**). Interpolation of the 1D data produced a 2D grid of the V_s data (**Figure 10.12**, **Figure 10.13,** and **Figure 10.15**). Color-filled contoured plots were then generated from the V_s grid.

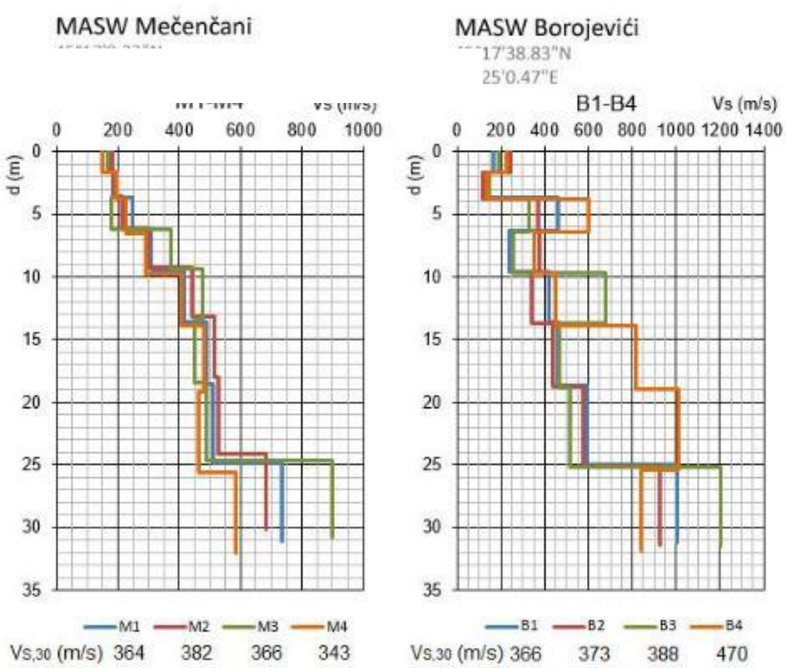


Figure 10.11 1D shear wave (*Vs*) profiles with calculated average shear-wave velocity values of 30 m depth (*Vs*30) in Mečenčani (45.283425N, 16.425781E) and Borojevići (45.294119N, 16.416797E).

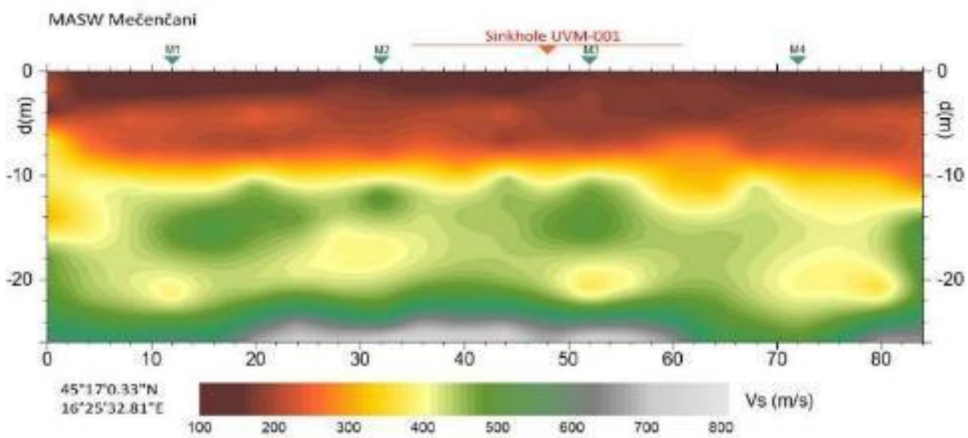


Figure 10.12 2D shear wave (*Vs*) profile adjacent to the largest sinkhole in Mečenčani (45.283425N, 16.425781E).

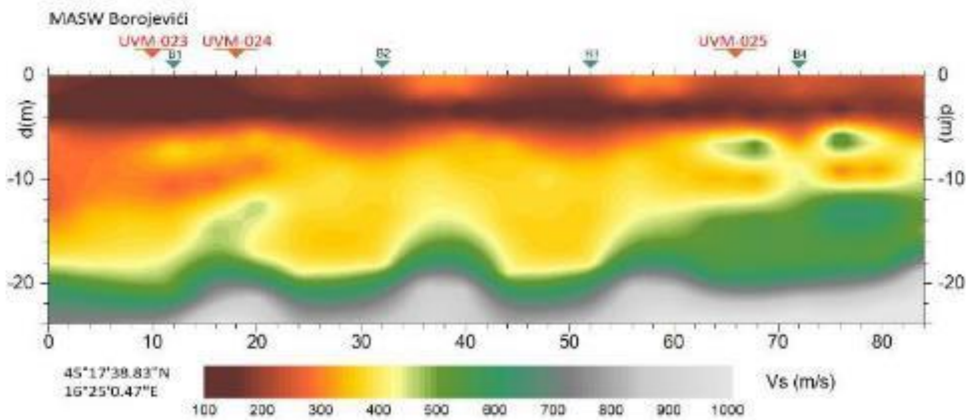


Figure 10.13 2D shear wave (*Vs*) profile adjacent to three small sinkholes in Borojevići (45.294119N, 16.416797E).

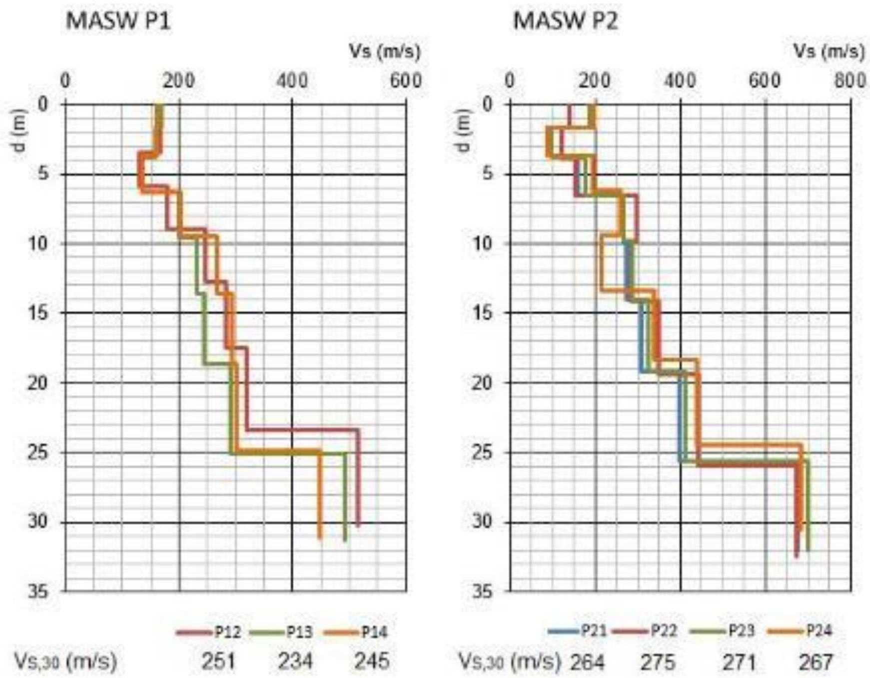


Figure 10.14 1D shear wave (*Vs*) profiles with calculated average shear-wave velocity values of 30 m depth (*Vs*30) - MASW P1 and P2 in Petrinja (45.448303N, 16.276936E).

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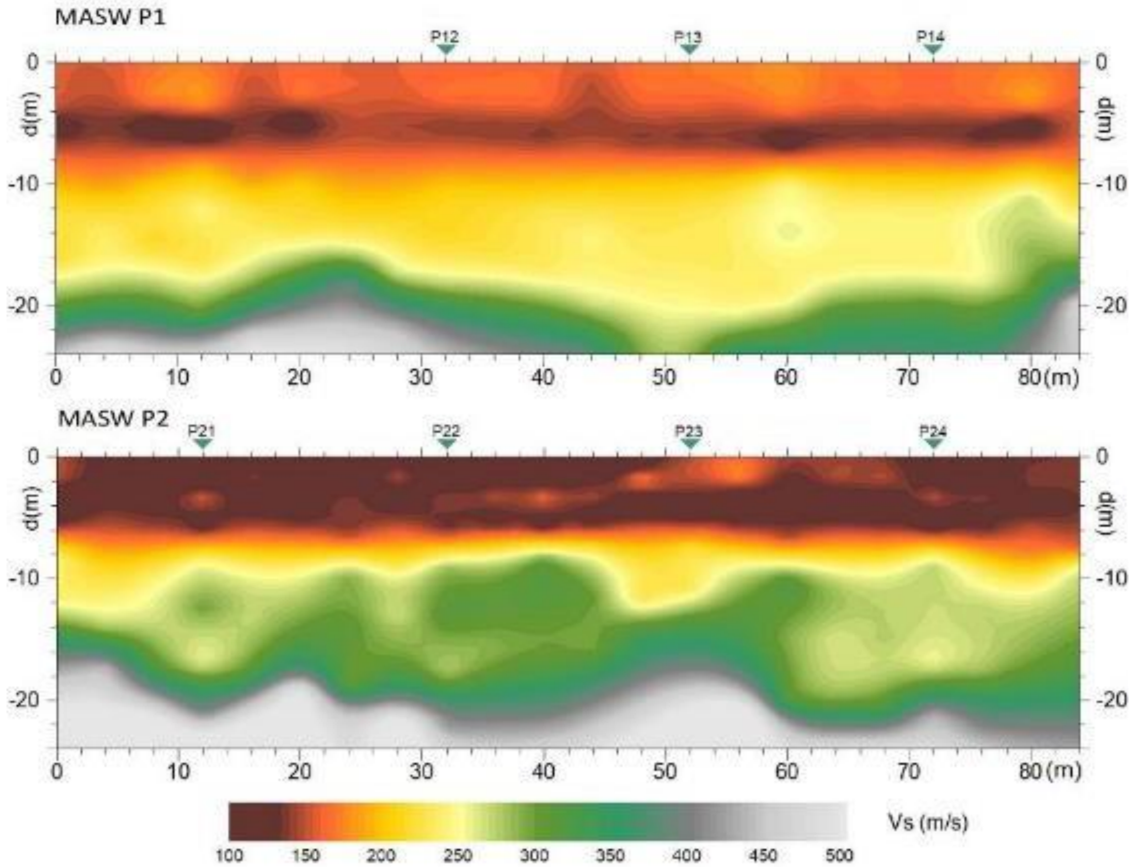


Average Layer Vs			
Layer (m)	P1 Vs (m/s)	Vs Diff. $(V_1-V_2)/V_2$ (%)	P2 Vs (m/s)
0-2	165	> 22.4	135
2-4	151	> 17.8	128
4-8	156	< -15.7	185
8-16	238	< -17.8	290

Average $V_{S,30}$			
Interval (m)	P1 $V_{S,30}$ (m/s)	$V_{S,30}$ Diff. $(V_1-V_2)/V_2$ (%)	P2 $V_{S,30}$ (m/s)
	243	< -9.7	269

Figure 10.15 2D shear wave (*Vs*) profiles in Petrinja.

10.3 Geotechnical Investigation Works

Geotechnical site investigations and sampling was performed on 3 locations close to the cover collapse sinkholes No. S015 (location 1), S001 (location 2, boreholes B-1 and B-2) in Mečenčani (**Figure 10.16a)**) and S009 (location 3, borehole B-3) and S040 (location 3, borehole B-4) in Borojevići **Figure 10.16a)**). Field work was performed at location 1 (S015) on February 23, 2021, at location 2 (S001) on March 23, 2021, and at location 3 (S009 and S040) on March 26, 2021.

a) Mečenčani
(**S001**: 45.283352N, 16.425852E; **S015**: 45.282922N, 16.429898E)

b) Borojevići
(**S009**: 45.296609N, 16.415221E; **S040**: 45.292921N, 16.422418E)

Figure 10.16. Map of field testing and soil sample locations (background image from Google Earth).

10.3.1 Location 1 (S015)

At location 1 (**Figure 10.17**) the following equipment was used:

1. Eijkelkamp liner sampler, set for hard soils, Φ 50 mm, with plastic sample liners (https://en.eijkelkamp.com/products/augering-soil-sampling-equipment/liner-sampler-set-sb-uk.html)
2. Eijkelkamp field inspection vane tester, the standard set for measurements to 200 kPa (20 t/m^2) and a depth of 3 m, standard vane 16 x 32 mm *(https://en.eijkelkamp.com/products/field-measurement-equipment/field-inspection-vane-tester.html),* and
3. DPL-dynamic penetrometer light (manually driven) SD-10 (ZNWiG) compatible with the Eurocode 7: Geotechnical design - Part 3: Design assisted by field testing.

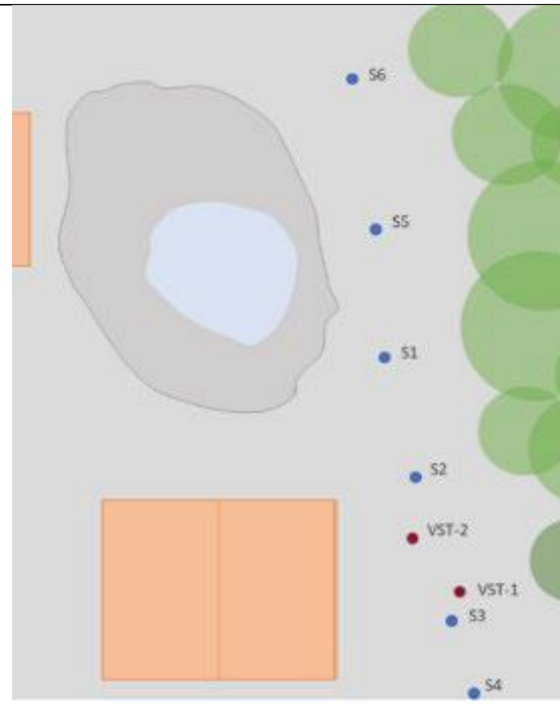
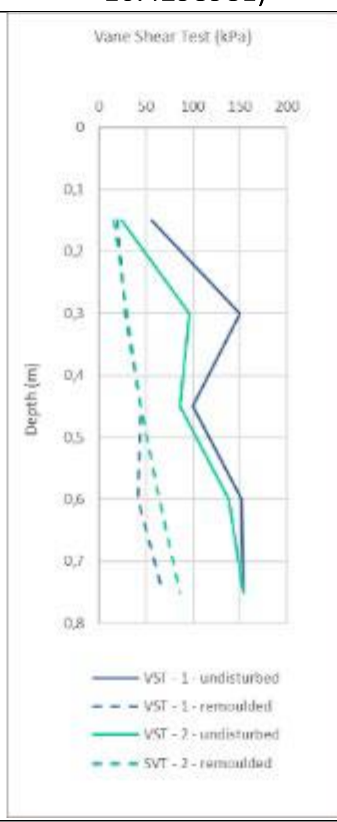
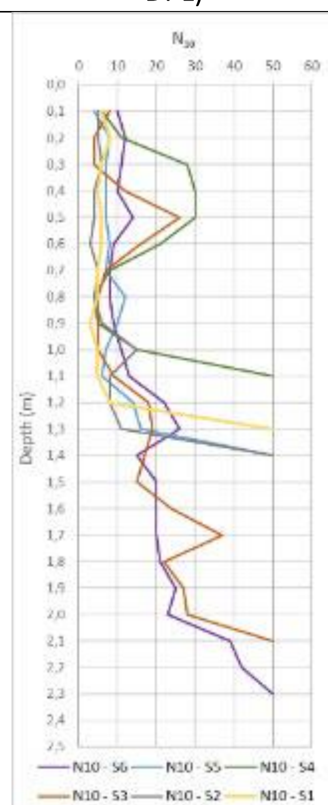
	
a) sinkhole S015 (45.282922N, 16.429898E)	b) testing positions (VST-vane shear test, S-DPL)
	
c) VST	d) DPL

Figure 10.17 Field work at location 1 (S015).

All the equipment was manually driven. Because of that fact together with the appearance of a shallow layer (depth of approximately 1.0 – 2.0 m) of coarse gravel with cobbles, field testing results are relevant only for a very shallow vertical profile (as shown in **Figure 10.17c** and **10.17d**). Two undisturbed samples were also taken (0.0 - 0.3 m; 0.3 - 0.6 m), preserved in the original plastic foil. Grain-size analyses and Atterberg limit test, which were performed in the Geotechnical laboratory at the Faculty of Mining, Geology and Petroleum Engineering University of Zagreb, showed that these samples belong to the group CL – sandy lean CLAY according to the ASTM classification (ASTM D 2487).

VST could be performed only to the depth of 0.75 m, showing the trend of undrained strength increase with depth, and 1.5 to 5.4 times smaller strength in remolded state comparing to the undisturbed strength. Six dynamic penetration tests were conducted at the site of the sinkhole S015. In all six probes, the test was terminated at depths of 1.1 m to 2.3 m because the probe penetrated negligible at 50 blows. The occurrence of water was observed at a depth of 1.7 m only at the DP03 probe. Based on the visible walls of the sinkhole and the number of blows per 10 cm of cone penetration, N_{10}, three units could be distinguished: a surface layer and lean clay with a low resistance to cone penetration (N_{10} 3-15 blows); second unit where fine gravel is present (N_{10} 15-42 blows), and bedrock or large cobbles with N>50. When handling the probe, the friction of the metal against the gravel grains was felt in the second layer. With the appearance of coarse gravel (grains with a diameter of 20 cm were visible in the sinkhole), penetration was no longer possible. By visual inspection of the sinkhole and DPL results, up to the depth of 1-1.5 m, a yellowish-brown sandy lean clay can be seen. Below that depth, the content of coarse gravel and cobbles increases. The water level was pretty high, at the depth of approximately 2.0 m, and the soil was visible moist from the depth of 1.5 m.

10.3.2 Location 2 and 3 (S001, S009, S040)

At the locations, 2 – Mečenčani (boreholes B-1 and B-2) and location 3 – Borojevići (boreholes B-3 and B-4) boring is performed by solid rod bottom auger without casing and without the use of drilling fluid (**Figure 10.18**). Besides, standard penetration test (SPT), DPL-dynamic penetrometer light (manually driven) SD-10 (ZNWiG), soil sampling and groundwater table measurements have been done. Disturbed samples were continuously taken (auger sampling) and undisturbed samples (drive sampling with split tube sampler Φ 85 mm) were taken at intervals of approximately 1 m followed by SPT (disturbed samples Φ 35 mm). DPL was performed close to boreholes B-1 and B-2 at location 2 and those results are presented in **Figure 10.18c**.

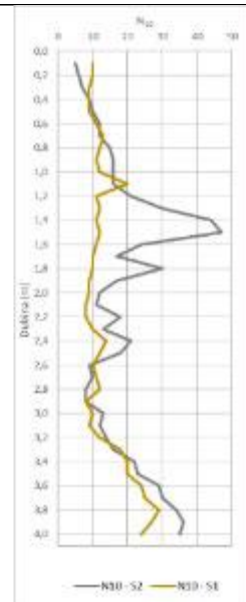
		
a) Drilling equipment (45.283301N, 16.425622E)	b) sinkhole S001 and testing positions (45.283352N, 16.425852E)	c) DPL

Figure 10.18 Field work at location 2 (S001).

Two dynamic penetration tests were conducted at the site of the sinkhole S001. For both probes, the test was terminated at a depth of 4.0 m, as the declared maximum penetration depth for the equipment was reached. No occurrence of water was observed during testing. S2 probe (**Figure 10.18c**) showed small values of N_{10} to the depth of 3.2 m (N_{10} 8-14 blows), only one reading showed a higher value (at 1.1 m, N_{10} was 20 blows). Below the depth of 3.3 m N10 was 18-29 blows. S1 probe showed significantly higher values of N_{10}. The maximum value (N_{10} 47 blows) was measured at the depth of 1.5 m.

10.3.3 Laboratory Testing and Results

A laboratory testing program was undertaken at the Geotechnical laboratory of the Faculty of Mining, Geology and Petroleum Engineering University of Zagreb from February to March 2021. The following index tests were performed following applicable American Society for Testing and Materials (ASTM) standards:

1. Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis (ASTM 6913M)
2. Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis (ASTM D7928)
3. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (ASTM D4318)
4. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (ASTM D2216)

5. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (ASTM D 854)
6. Geotechnical investigation and testing - Laboratory testing of soil - Part 2: Determination of bulk density (ISO 17892-2:2014; EN ISO 17892-2:2014)

Based on the field description and identification and laboratory results, each sample was classified according to ASTM D2487: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) and ASTM D 2488: Standard Practice for Description and Identification of Soils (Visual-Manual Procedures).
Summary of laboratory test results for the boreholes B-1 and B-2 are presented in Tables 1, 2, and 3 (Appendix 1). The summary of grain-size distribution curves and plasticity charts are shown for the location 2 (UVM-01) boreholes B-1 and B-2 in **Figure 10.19**. and **Figure 10.20** respectively. For the location Borojevići, the same is presented in **Figure 10.21**.

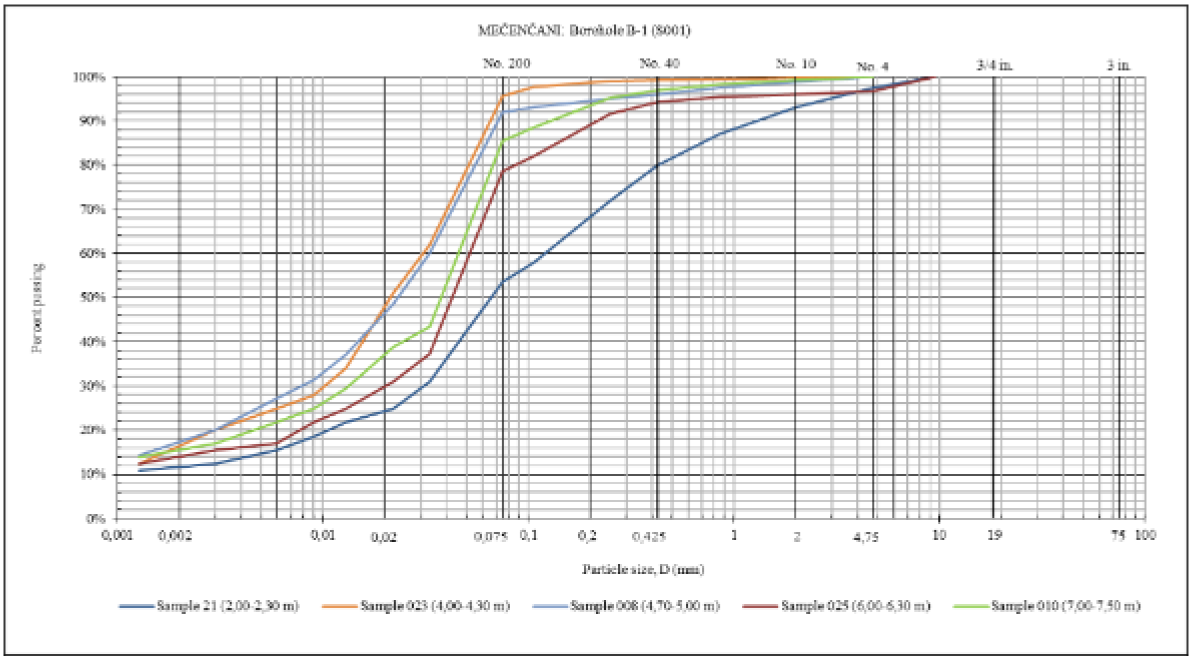


Figure 10.19 Mečenčani: B-1 (S001).

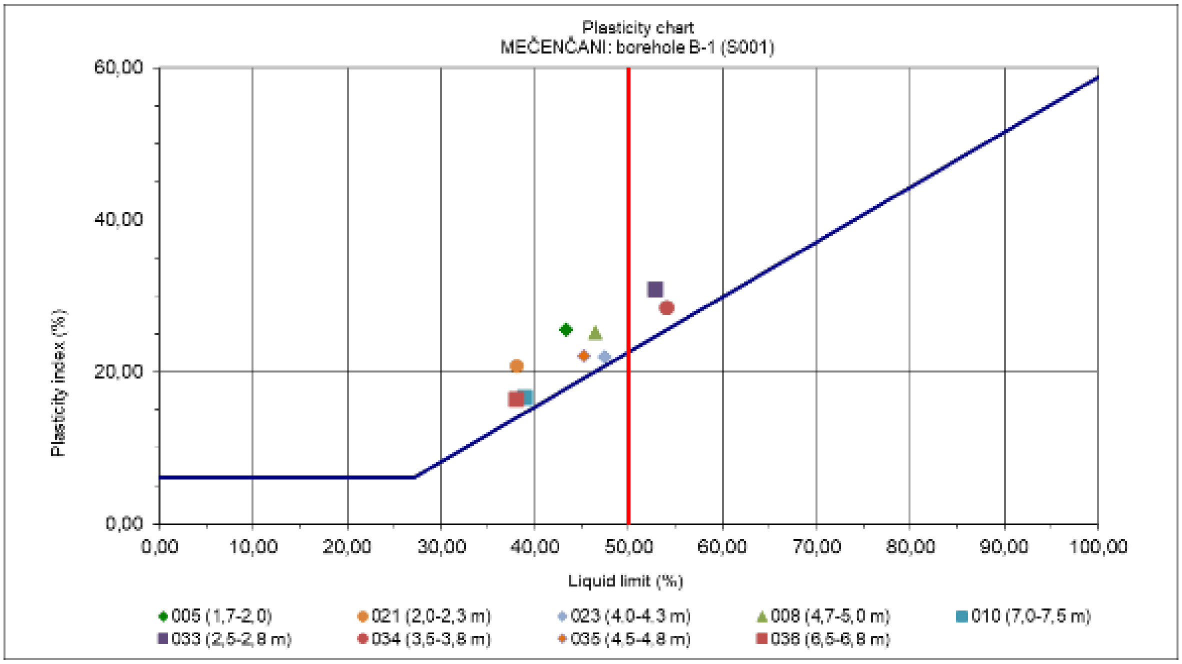


Figure 10.19 (cont.) Mečenčani: B-1 (S001).

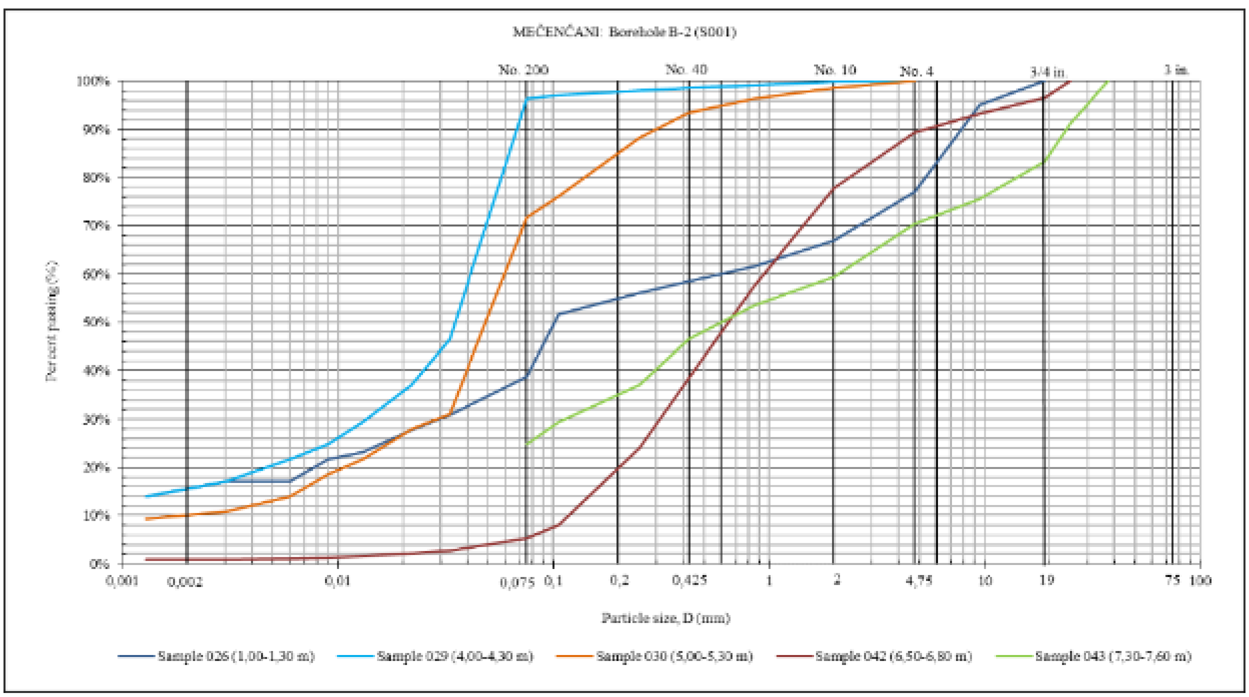


Figure 10.20 Mečenčani: B-2 (S001).

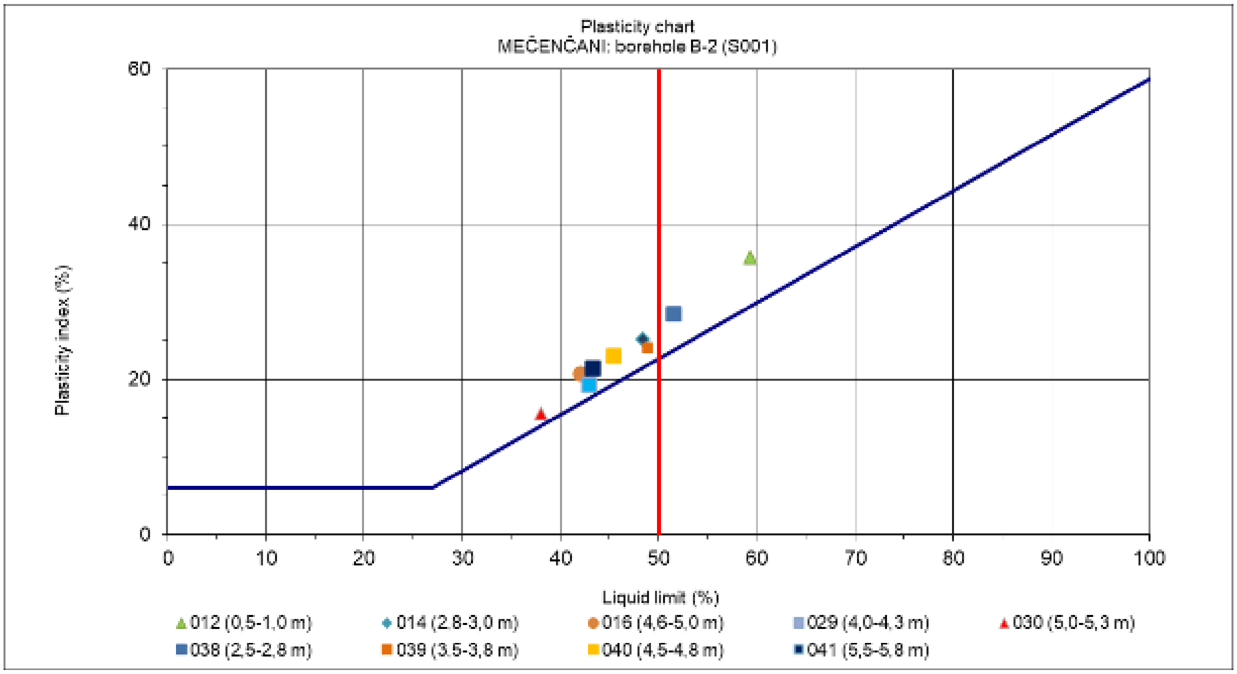


Figure 10.20 (cont.) Mečenčani: B-2 (S001).

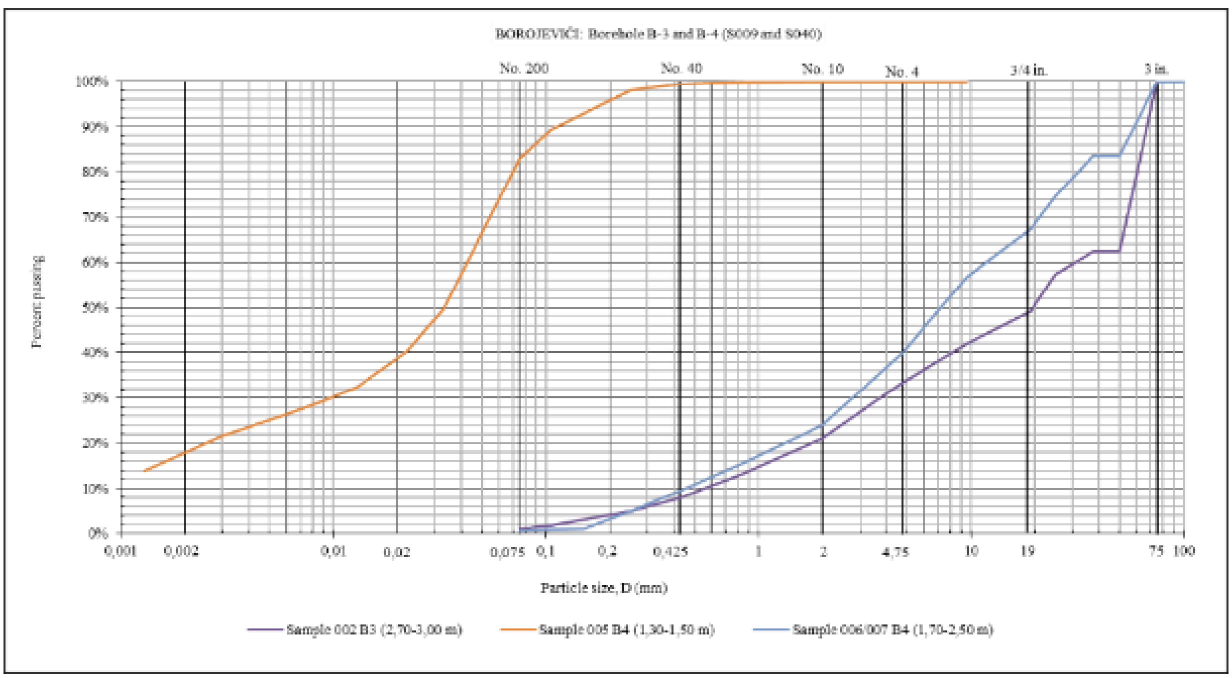


Figure 10.21 Borojevići: B-3 and B-4 (S009 and S040)

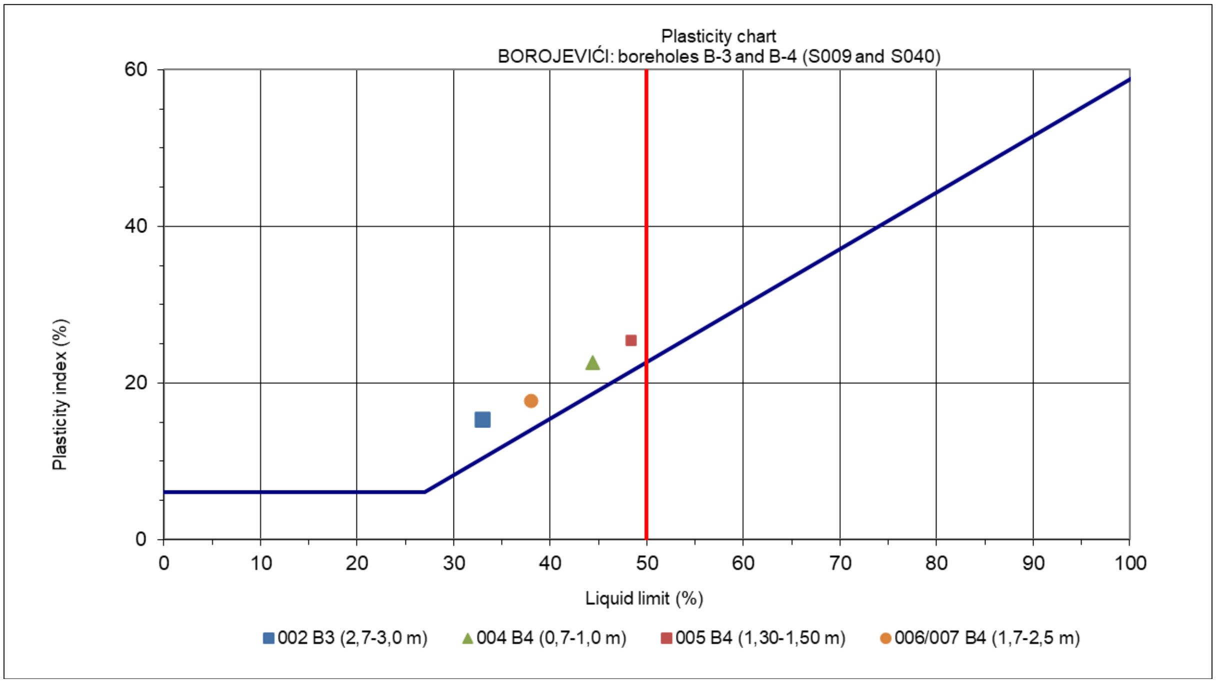


Figure 10.21 (cont.) Borojevići: B-3 and B-4 (S009 and S040)

Two samples of rock material were obtained from the borehole from the abandoned core previously drilled by Geotehnicki Studio L.L.D, in Borojevići 101 location near a private house. Later on, Geotehnicki Studio Ltd. kindly provided the borehole log for GEER. It was possible only to perform one point load strength index test per sample. The test is performed according to Suggested Method for Determining Point Load Strength of the International Society for Rock Mechanics (ISRM, 1985). The obtained values (**Figures 10.22** and **10.23**) for corrected Point Load Strength Index $I_s(50)$ show that tested samples belong to weak rock (R2).

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Point Load Index Test Report

Work Item:	21-008	Received:	3/16/2021
Client:	Geotechnical Extreme Events Reconnaissance		
Project:	GEER Petrinja 2021		
Field Sampl.:	Dr. sc. Ingrid Tomac	Sampling Date.:	3/17/2021
Lab Prepar:	E. Oršulić, dipl. ing. geot.	Prepar. Date:	4/2/2021
Sample Handling:	The sample was not protected from moisture changes.		
Location:	Borojevići		
Litolological Description:	Limestone, calcarenite to calcrudite, composed of numerous bioclasts of red algae Lithotamnium and small bioclasts, peloids and intraclasts. Rock is characterized by significant intragranular porosity.		
Lab. No:	21-008-001	Depth:	between 6-12 m

Length l (mm)	Width W (mm)	Density (kg/m3)			
57,5	73,0	2062			

Sample Characteristics

Strength Index $I_{S(50)}$	Effective Diameter D_e	Correction Factor F
1,33 MPa	**73,1 mm**	**1,186**

Method:	ISRM Suggested method for determining point load strength, 1985		
Comments:			
Failure Validity:	Correct	Duration:	15 s
Equipment:	Robertson Research	Date:	4/7/2021

Responsible Person:	No. and Report Date:	Lab Director:
P. Hrženjak Dr. sc. Petar Hrženjak	21-008-001PLTR 9. 04. 2021.	P. Hrženjak Dr. sc. Petar Hrženjak

Figure 10.22 Point load Index test – Borojevići.

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Point Load Index Test Report

Work Item: 21-008 Received: 26. 03. 2021.

Client: Geotechnical Extreme Events Reconnaissance

Project: GEER Petrinja 2021

Field Sampl.: Dr. sc. Ingrid Tomac Sampling Date.: 17. 03. 2021.

Lab Prepar: E. Oršulić, dipl. ing. geot. Prepar. Date: 2. 04. 2021.

Sample Handling: he sample was not protected from moisture changes.T

Location: Borojevići

Litolological Description: Compact limestone composed of Lithotamnium bioclasts, gastropods and fine-grained bioclasts, intraclasts and peloids. Rock is characterized by visible intragranular porosity.

Lab. No: 21-008-002 Borehole: B-1 Depth: 6.15-6.25 m

Length l (mm)	Width W (mm)	Density (kg/m3)			
54,9	112,5	2290			

Sample Characteristics

Strength Index $I_{S(50)}$	Effective Diameter D_e	Correction Factor F
1,66 MPa	**88,0 mm**	**1,290**

Method: ISRM Suggested method for determining point load strength, 1985

Comments:

Failure Validity: Correct Robertson Duration: 20 s

Equipment: Research Date: 4/7/2021

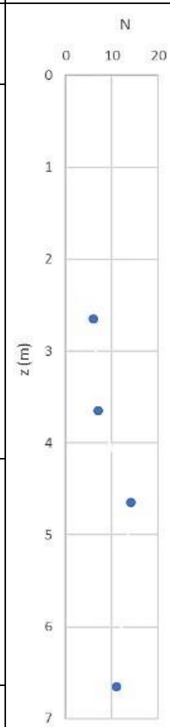
Responsible Person:	No. and Report Date:	Lab Director:
P. Hržnjak Dr. sc. Petar Hrženjak	21-008-002PLTR 9. 04. 2021.	P. Hržnjak Dr. sc. Petar Hrženjak

Figure 10.23 Point Load Indexs test – Borojevići.

Representative borehole log profiles are presented in **Figures 10.24** to **10.27**.

BOREHOLE LOG	**B-1** **Mečenčani (S001)**		
Project GEER Petrinja	**Date** 23.03.2021.	**Equipment** Portable rotary power auger	**Coordinates** 45.283301, 16.425622

SAMPLES AND TEST					SPT	
Depth (m)	Water lever	Interval (m)	ASTM class	Soil description		Fines / S / G
0.0		0.50		ORGANIC SOIL Dark brown organic soil, trace of limestone subangular particles D_{max} 1 mm; from 0.30 to 0.50 m little of particles, subangular to subrounded, D_{max} 50 mm.		
1.0 2.0 3.0		4.00	CL/CH	Sandy lean CLAY / Sandy fat CLAY Dark yellowish brown sandy lean/fat CLAY of medium to high plasticity, firm to stiff. In the upper part of a layer trace of limestone particles D_{max} 20 mm.		
4.0 5.0 6.0		6.50	CL	Lean CLAY / Lean CLAY with sand Yelowish brown lean CLAY of low to medium plasticity, stiff to very stiff. Sand content increases with depth. From 5.30-5.50 m interlayered by very moist gravelly clay (N>50).		
7.0 8.0		8.0	CL	Lean CLAY Gray lean (marly) CLAY of low plasticity, stiff.		
				BEDROCK		



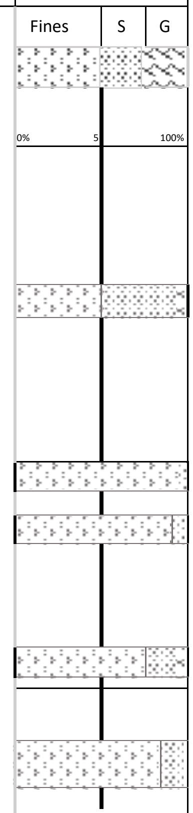


Figure 10.24: Borehole log B1

BOREHOLE LOG	**B-2** **Mečenčani (S001)**		
Project GEER Petrinja	**Date** 23.03.2021.	**Equipment** Portable rotary power auger	**Coordinates** 45.283416, 16.426094

SAMPLES AND TEST

Depth (m)	Water lever	Interval (m)	ASTM class	Soil description
0.0				**ORGANIC SOIL** Dark brown organic soil, trace of limestone
1.0 – 4.0			CL/CH	Sandy lean CLAY / Sandy fat CLAY Dark yellowish brown sandy fat/lean CLAY of medium to high plasticity, stiff. From 0,40 to 0,45 m little of particles, subangular, D_{max} 10 mm. From 1,30-1,50 m interlayered by clayey sand with gravel (SC), few particles,
4.0 – 6.0			CL	Lean CLAY / Lean CLAY with sand Yellowish brown lean CLAY of low to medium plasticity, very stiff. Sand content increases with depth.
7.0 – 8.0		7.60	SP-SC/SC	Poorly graded SAND with clay/ Clayey SAND with gravel Yellowish brown poorly graded sand with clay. Gravel content increases with depth, very moist, medium density. At 6,60 m a cobble (rounded, Dmax 90 mm) was found, folowed by the interlayer of a lean clay.

SPT

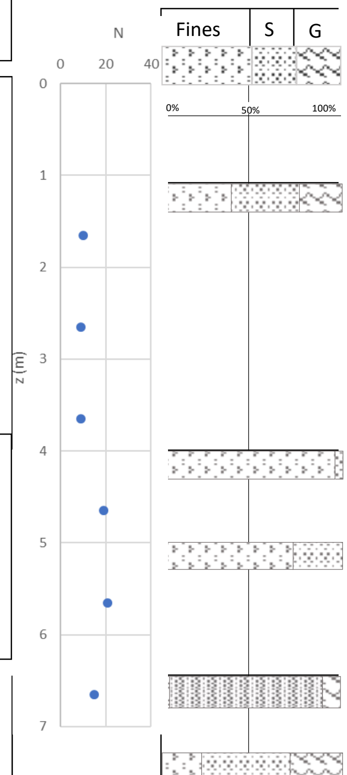


Figure 10.25: Borehole log B2

BOREHOLE LOG	**B-3** **Borojevići (S009)**		
Project GEER Petrinja	**Date** 26.03.2021.	**Equipment** Portable rotary power auger	**Coordinates** 45.296609, 16.415221



SAMPLES AND TEST					SPT			
Depth (m)	Water lever	Interval (m)	ASTM class	Soil description		Fines	S	G
0.0		0.30		ORGANIC SOIL, dark brown				
1.0		1.40	CL	Lean CLAY Yellowish brown lean clay of medium plasticity, stiff. Limestone concretions in traces.				
2.0 3.0 4.0		4.00	GP	Poorly graded GRAVEL with sand Yellowish brown coarse to fine poorly graded gravel with sand, soft, medium density. From3,10 m very moist.				
5.0 6.0		5.80		COBBLES ?				
7.0				BEDROCK				

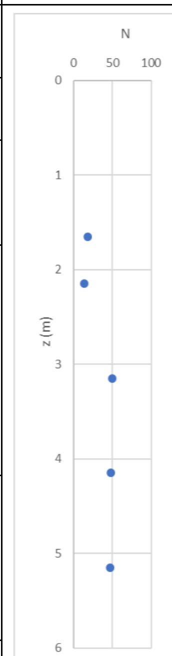
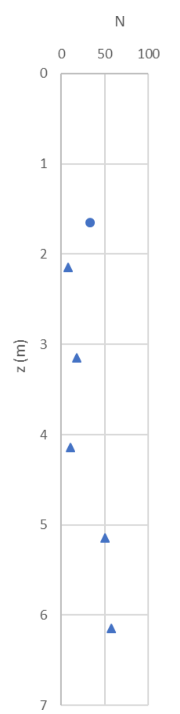


Figure 10.26: Borehole log B3

BOREHOLE LOG	**B-4** **Borojevići (S040)**		
Project GEER Petrinja	**Date** 26.03.2021.	**Equipment** Portable rotary power auger	**Coordinates** 45.292921, 16.422418

SAMPLES AND TEST				
Depth (m)	Water lever	Interval (m)	ASTM class	Soil description
0.0		0.40		ORGANIC SOIL, dark brown
1.0		1.20	CL	Lean CLAY with sand Yellowish brown lean clay with sand, medium plasticity, stiff. Limestone concretions in traces.
2.0		2.50	GW	Well graded GRAVEL with sand Yellowish brown coarse to fine well graded gravel with sand, soft, medium density. From 2,30 very moist.
3.0				
4.0		4.50		
5.0				COBBLES ?
6.0		6.50		
7.0				BEDROCK

SPT



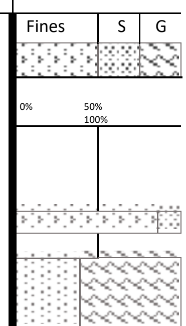


Figure 10.27: Borehole log B4

APPENDIX 1

Table 1: SUMMARY LABORATORY TEST REPORT – MEČENČANI; B-1 (S001)

University of Zagreb
FACULTY OF MINING GEOLOGY AND PETROLEUM ENGINEERING

Ordered by: **GEER** **Project:** **GEER Petrinja** Mečenčani. B

Adress: **Project designation:** 21-005

SUMMARY LABORATORY TEST REPORT

Sample ID	Borehole log	Depth	Sample type	Method / Type of testing / Symbol	ASTM 6913M ASTM D7928 Grain size analyses G			ASTM D 2216 Water content w	EN ISO 17892 – 2:2014 Unit weight γ	Dry unit weight γ_d	ASTM D 4318 Atterberg limits LL		Plasticity index PI	Consistency index I_c
					G	S	Fines	w	γ	γ_d	LL	PL	PI	I_c
(-)	(-)	(m)		USCS/Unit	(%)	(%)	(%)	(%)	Mg/m³	Mg/m³	(%)	(%)	(%)	(-)
21-005-001	B - 1	0.0 – 0.3	D-A					26.8						
21-005-002	B - 1	0.3 – 0.7	D-A					17.3						
21-005-003	B - 1	0.7 – 1.0	D-A					25.3						
21-005-004	B - 1	1.0 – 1.3	D-A					15.7						
21-005-005	B - 1	1.7 – 2.0	D-A	CL				23.7			43.4	17.9	25.5	0.77
21-005-021	B - 1	2.0 – 2.3	TkW	CL	2.6	43.8	53.6	23.2	1.91	1.55	38.0	17.2	20.8	0.71
21-005-033	B - 1	2.5 – 2.8	D-SPT	CH				29.1			52.8	21.9	30.9	0.77
21-005-006	B - 1	2.7 – 3.0	D-A					29.9						
21-005-034	B - 1	3.5 – 3.8	D-SPT	CH				30.1			54.0	25.5	28.5	0.84
21-005-007	B - 1	3.7 – 4.0	D-A					27.9						
21-005-023	B - 1	4.0 – 4.3	TkW	CL	0.0	4.4	95.6	32.2	1.93	1.46	47.4	25.4	22.0	0.69
21-005-035	B - 1	4.5 – 4.8	D-SPT	CL				24.5			45.2	23.1	22.1	0.94
21-005-008	B - 1	4.7 – 5.0	D-A	CL	0.0	8.0	92.0	30.7			46.4	21.2	25.2	0.62
21-005-009	B - 1	5.7 – 6.0	D-A					32.4						
21-005-025	B - 1	6.0 – 6.3	TkW	CL	3.2	18.2	78.6	22.1	2.06	1.68	41.2	23.1	18.1	1.06
21-005-036	B - 1	6.5 – 6.8	D-SPT	CL				24.9			38.0	21.5	16.5	0.79
21-005-010	B - 1	7.0 – 7.5	D-A	CL	0.0	14.5	85.5	28.8			38.9	22.2	16.7	0.60

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Ordered by: **GEER**
Adress:

Project: **GEER Petrinja** Mečenčani. B
Project designation: 21-005

Table A.2: SUMMARY LABORATORY TEST REPORT – MEČENČANI; B-2 (S001)

SUMMARY LABORATORY TEST REPORT

Sample ID	Borehole log	Depth	Sample type	Method: Type of testing	ASTM 6913M ASTM D7928 Grain size analyses			ASTM D 2216 Water content	EN ISO 17892 – 2:2014 Unit weight	Dry unit weight	ASTM D 4318 Atterberg limits		Plasticity index	Consistency index
				Symbol	G	S	Fines	w	γ	γ_d	LL	PL	PI	I_c
(-)	(-)	(m)		USCS/Unit	(%)	(%)	(%)	(%)	Mg/m^3	Mg/m^3	(%)	(%)	(%)	(-)
21-005-011	B - 2	0.0 – 0.15	D-A					26.5						
21-005-012	B - 2	0.5 – 1.0	D-A	CH				23.7			55.8 / 59.3	22.7 / 23.6	36.2 / 35.7	0.96 / 1.00
21-005-026	B - 2	1.0 – 1.3	TKW		22.9	38.3	38.8	20.1	1.99	1.66				
21-005-037	B - 2	1.5 – 1.8	D-SPT					18.3						
21-005-013	B - 2	1.8 – 2.0	D-A					24.6						
21-005-038	B - 2	2.5 – 2.8	D-SPT	CH				27.8			51.5	23.0	28.5	0.83
21-005-014	B - 2	2.8 – 3.0	D-A	CL				28.1			48.4	23.3	25.1	0.81
21-005-028	B - 2	3.0 – 3.3	TKW											
21-005-039	B - 2	3.5 – 3.8	D-SPT	CL				28.9			48.9	24.8	24.1	0.83
21-005-015	B - 2	3.8 – 4.0	D-A					28.6						
21-005-029	B - 2	4.0 – 4.3	TKW	CL	0.0	3.6	96.4	25.3	2.00	1.60	42.9	23.7	19.2	0.92
21-005-040	B - 2	4.5 – 4.8	D-SPT	CL				23.8			45.4	22.3	23.1	0.93
21-005-016	B - 2	4.6 – 5.0	D-A	CL				22.4			42.0	21.3	20.7	0.95
21-005-030	B - 2	5.0 – 5.3	TKW	CL	0.0	28.3	71.7	22.5	2.05	1.68	38.0	22.4	15.6	0.99
21-005-041	B - 2	5.5 – 5.8	D-SPT	CL				24.4			43.3	21.9	21.4	0.88
21-005-017	B - 2	5.8 – 6.0	D-A					22.5						
21-005-018	B - 2	6.3 – 6.8	D-A					25.7						
21-005-042	B - 2	6.5 – 6.8	D-SPT		10.5	84.1	5.4	23.5						
21-005-019	B - 2	6.8 – 7.0	D-A					23.4						
21-005-043	B - 2	7.3 – 7.6	D-SPT		29.5	45.7	24.8	9.3						

Table A.3 SUMMARY LABORATORY TEST REPORT – BOROJEVIĆI; B-3 (S009) & B-4 (S040)

University of Zagreb
FACULTY OF MINING GEOLOGY AND PETROLEUM ENGINEERING

Ordered by: **GEER**
Adress:

Project: **GEER Petrinja** Borojevići, B-
Project designation: 21-006

SUMMARY LABORATORY TEST REPORT

Sample ID	Borehole log	Depth	Sample type	Method: Type of testing	ASTM 6913M ASTM D7928 Grain size analyses			ASTM D 2216 Water content	EN ISO 17892 – 2:2014 Unit weight	Dry unit weight	ASTM D 4318 Atterberg limits		Plasticity index	Consistency index
				Symbol	G	S	Fines	w	γ	γ_d	LL	PL	PI	I_c
(-)	(-)	(m)		USCS/Unit	(%)	(%)	(%)	(%)	Mg/m^3	Mg/m^3	(%)	(%)	(%)	(-)
21-006-001	B - 3	0,50 – 1,00	D-A					24,3						
21-006-002	B - 3	2,70 – 3,00	D-A	CL	66.5	32.5	1.0	12,0			32,90	17,56	15,34	1,36
21-006-003	B - 4	0,00 – 0,30	D-A					29,2						
21-006-004	B - 4	0,70 – 1,00	D-A	CL				26,3			44,40	21,70	22,65	0,80
21-006-005	B - 4	1,30 – 1,50	D-A	CL	0.0	17.1	82.9	28,6			48,40	22,99	25,41	0,78
21-006-006	B - 4	1,70 – 2,00	D-A					18,5						
21-006-006+7	B - 4	1,70 – 2,50	D-A	CL	59.9	39.1	1.0	20,9			38,00	20,22	17,78	0,96
21-006-007	B - 4	2,00 – 2,50	D-A					23,2						

10.4 Terrestrial Surveys

Terrestrial surveys were performed during reconnaissance works between March 15 and March 26, 2021. Leica RTC360 lidar scanned about 60 sinkholes and Galdovo Bridge, and the scans are deposited in DesignSafe Data Depot.

References

ASTM D2216-19 (2019). *Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass*. Available at: www.astm.org. ASTM International,West Conshohocken, PA.

ASTM D2487-17e1 (2017). *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).* Available at: www.astm.org. ASTM International, West Conshohocken, PA.

ASTM D4318-17e1 (2017). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. Available at: www.astm.org. ASTM International, West Conshohocken, PA.

ASTM D6913 / D6913M-17 (2017). *Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis*. Available at: www.astm.org. ASTM International, West Conshohocken, PA.

ASTM D7928-17 (2017). Standard Test Method for Particle-Size Distribution (Gradation) of Fine- Grained Soils Using the Sedimentation (Hydrometer) Analysis. Available at: www.astm.org. ASTM International, West Conshohocken, PA.

ASTM D854-14 (2014). *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*. Available at: www.astm.org. ASTM International, West Conshohocken, PA.

ISO 17892-2:2014 and EN ISO 17892-2:2014 (2014) *Geotechnical investigation and testing - Laboratory testing of soil - Part 2: Determination of bulk density.* Available at: https://www.iso.org/standard/55244.html. International Organization for Standardization.

DD ENV 1997-3:2000 (2000) Eurocode 7: Geotechnical design - Part 3: Design assisted by field testing. Available at: https://geotechnicaldesign.info/ec7p3.html. European Committee for Standardization, Brussels, Belgium.

Eijkelkamp Soil&Water. (2018). *Foil Sampler Set B Manual* Available at: https://en.eijkelkamp.com/products/augering-soil-sampling-equipment/liner-sampler-set- sb-uk.html. Eijkelkamp Soil and Water, Giesbeek, the Netherlands.

Eijkelkamp Soil&Water. (2009). *Field Inspection Vane Tester Operating Instructions*. Available at: https://en.eijkelkamp.com/products/field-measurement-equipment/field-inspection-vane-tester.html. Eijkelkamp Soil and Water, Giesbeek, the Netherlands.

Vantassel, J., Cox, B., Wotherspoon, L. and Stolte, A. (2018). *Mapping depth to bedrock, shear stiffness, and fundamental site period at Centreport, Wellington, using surface-wave methods:Implications for local seismic site amplification*. Bull. seism. Soc. Am., 108(3B), p1709–1721

Rahtje E.M., Dawson C., Padgett J.E., Pinelli J-P., Stanzione D., Adair A., Arduino P., Brandenberg S.J., Cockerill T., Dey C., Esteva M., Haan F.L.Jr., Hanlon M., Kareem A., Lowes L., Mock S., Mosqueda G.

(2017). *DesignSafe: New Cyberinfrastructure for Natural Hazards Engineering*.Nat. Hazards Rev. 18(3), p06017001.