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GEOTECHNICAL RECONNAISSANCE OF COVER-COLLAPSE SINKHOLE AREA FOLLOWING PETRINJA 2020 EARTHQUAKE

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Abstract

This paper shows an overview of extensive geotechnical and geological investigation of soils around cover-collapse sinkholes that appeared in a constrained area around Mečenčani and Borojevići villages following the 2020–2021 Petrinja earthquake sequence. A total of 122 new and 49 pre-existing historical sinkholes were recorded, mapped, and classified during the geological and geotechnical reconnaissance fieldwork. Many sinkholes collapsed within an area of only 1.13 km^2, a relatively rare phenomenon associated with earthquakes, thus motivating soil investigations to better understand associated failure mechanisms and underlying conditions. This paper shows an overview of triaxial test data in synergy with soil water retention curves of unsaturated soils detected in the area, along with results of standard physical soil tests. The soil in the area consists of a 4–15 m thick clayey cover with sporadic gravel lenses. Clays are mostly over-consolidated, with varying degrees of saturation ranging from very small to fully saturated. Underneath are intensely karstified Miocene carbonate rocks. Seasonal and climate-change-induced variations in the groundwater table interact with the artesian/subartesian karst aquifer, thus affecting the suction and the shear strength. In addition, soil water retention curves indicate that desaturation is possible for deeper groundwater table levels and can further affect effective stress, shear strength, and interparticle tensile forces. Collapsed sinkholes have predominately vertical walls, indicating brittle failure of a cohesive cover with varying degrees of saturation. Based on the specific geomechanical properties of soils, this paper offers several hypotheses of failure mechanisms based on the synergy of earthquake-induced dynamic loading and hydro-mechanical interactions of unsaturated soil layers and pore pressure dynamics between two interconnected aquifers.

Keywords: cover-collapse sinkholes, karstic aquifer, unsaturated soil dynamics, earthquake, progressive failure

1. Introduction

This paper shows an overview of geological, geotechnical, and geophysical investigations following the M_w 6.4 Petrinja 2020–2021 earthquake sequence. The study shown herein is limited to the small area surrounding two villages, Mečenčani and Borojevići located 20 km SE from the epicenter. Specific geological, seismological, geotechnical, and hydrological circumstances led to the collapse of numerous sinkholes between December 29, 2020 and the end of 2021 [1]. As a result, the reconnaissance team identified and mapped a total of 171 sinkholes, including 122 new and 49 historical sinkholes (Figs. 1 and 2). The occurrence of post-seismic sinkholes has been recorded sparsely and related to subsurface discontinuities [2, 3]. Historical sinkholes in the observed area are scattered and concentrated mostly in the central part around Pašino vrelo spring. New sinkholes are located within two small regions that have the combined area of 1.13 km^2. According to all available data, none of the new cover-collapse sinkholes formed during the main earthquake or strongest foreshocks and aftershocks. For example, a landowner noticed the soil collapsing at the location of the first documented sinkhole (S015) on the afternoon of December 29, about six hours after the main shock.

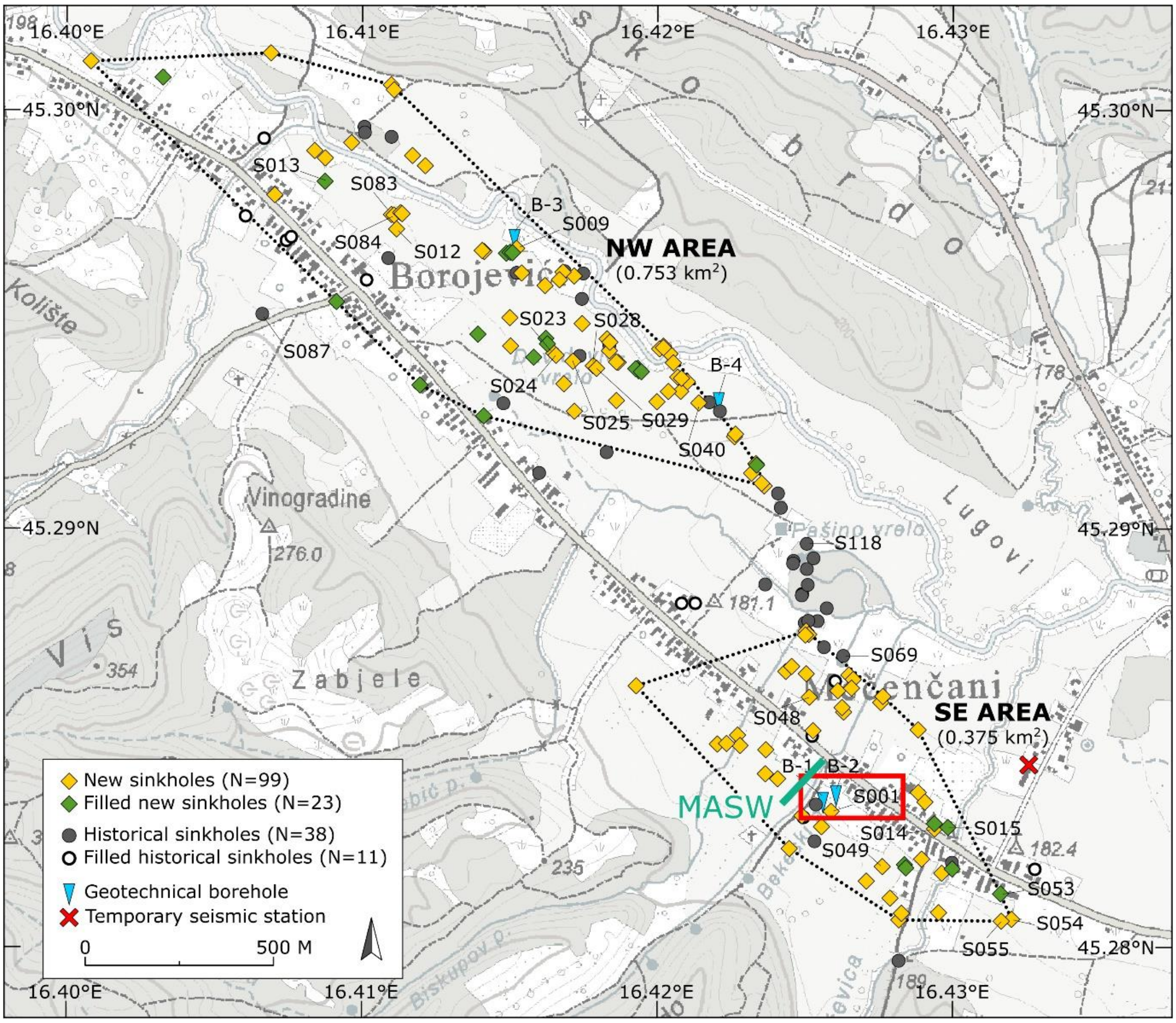

Figure 1. Graphical representation of sinkhole database (modified from [1]). A total of 49 historical sinkholes collapsed before the current seismic sequence (information on 11 previously filled were provided by the locals). Out of the 122 new sinkholes, six were remediated on the basis of geotechnical projects, and 17 were filled by the locals.

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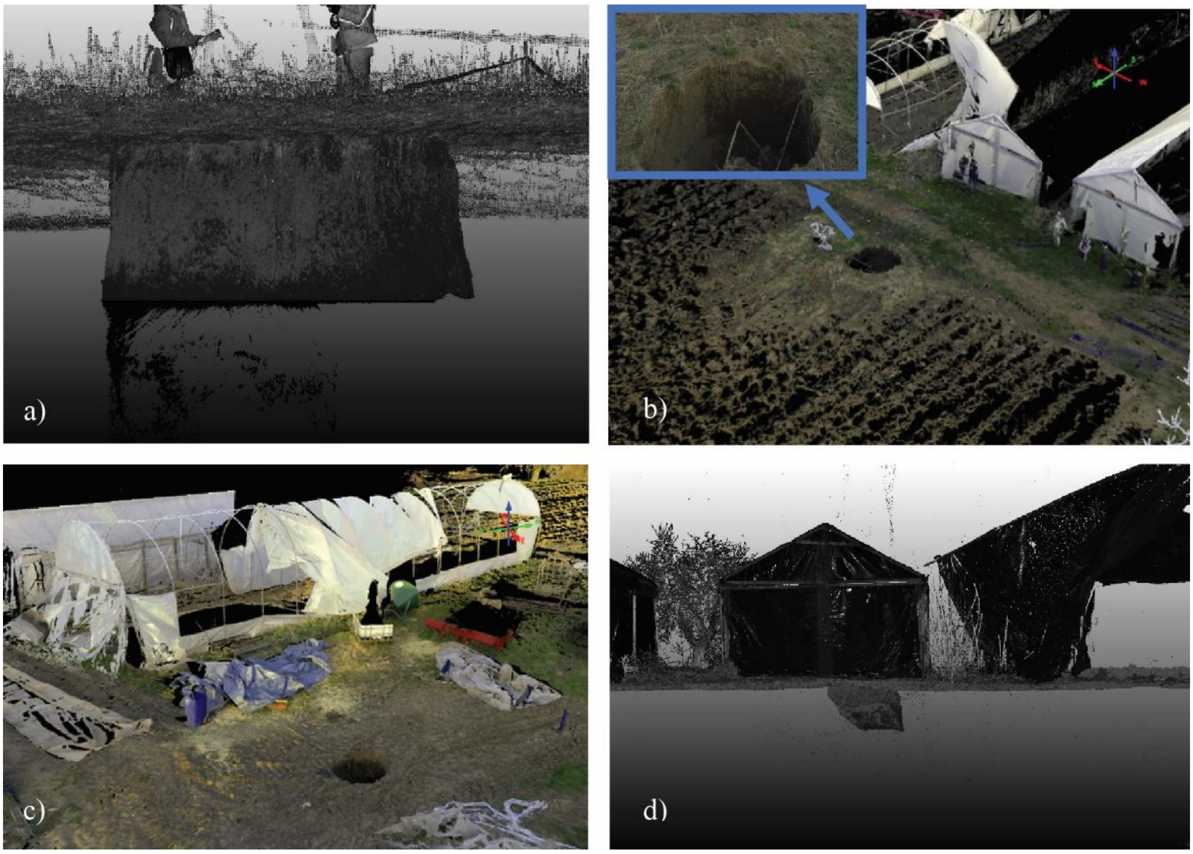

Figure 2. Point-cloud imagery of several representative sinkholes: a) side view of S025 sinkhole; b, d) panoramic view and side view of S054 sinkhole; c) panoramic view of S055 sinkhole.

2. Geological and Hydrogeological Setting and Seismicity

The area where sinkholes occurred is geologically specific, characterized by highly karstified limestones covered by relatively thick clayey soil. Middle Miocene highly porous Lithothamnion limestones and calcarenites are both very susceptible to karstification [4]. Karstified carbonates are directly overlain by a 4–15 m thick sequence of Holocene deluvial–proluvial deposits of clays with interlayers and lenses of gravel and sand [1, 4]. There are relatively few outcrops of karstic rocks in the area. Specifically, out of 1,079 km^2 area of the Bosanski Novi sheet of the Basic Geological Map [5], only a bit more than 60 km^2 is covered by Middle Miocene carbonates. The Sunja river valley in the studied area represents a flat terrain covered with Holocene deluvial–proluvial deposits of low permeability containing a certain amount of water and forming an aquitard. Most households in Mečenčani and Borojevići still use water from shallow dug wells, with an average depth of about 8 meters. The groundwater level fluctuation in the aquitard between dry and wet periods is about 2 m. The aquitard is underlain by a permeable confined karst aquifer, in which the water pressure during wet periods becomes subartesian to artesian [4]. Furthermore, the karst aquifer and overlying low-permeability aquitard are hydraulically connected, and pressure changes in one layer cause changes in hydraulic conditions within the other. During periods of high waters, specifically when the pressure rapidly rises in the karst aquifer, the piezometric level in the karst aquifer is higher than the groundwater level in the overlying aquitard, while during dry periods, the groundwater levels in both layers are equalized.

The Petrinja earthquake sequence started with two strong foreshocks on December 28, 2020, the first occurred at 05:28 UTC with M_L 5.1 and the second one at 6:49 UTC with M_L 4.7. The mainshock

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occurred a day later (December 29, 2020, 11:19 UTC, M_L 6.2). The main earthquake caused widespread damage in Petrinja and the surrounding villages, and seven people lost their lives. According to the Croatian Seismological Survey data, the epicentral intensity was estimated to be VIII–IX EMS. At the onset of the Petrinja sequence, the closest seismic station was more than 30 km from the epicentral area, and six additional stations provided more accuracy. Nevertheless, in the first 60 days of the sequence, 4,430 events were located within 50 km of the mainshock. The bulk of the Petrinja sequence epicenters are elongated in the NW–SE direction across roughly 20 km in length and 2–4 km in width, within the Hrastovica Hill between the Kupa and Petrinjčica rivers. The mainshock is positioned in the central cluster part and has a hypocentral depth of about 8 km. The strongest foreshock of the December 28, 2020 (M_L 5.1) occurred within the main cluster, about 2 km easterly from the mainshock.

3. Geotechnical Investigation

Geotechnical and geophysical investigations at two sites in the Mečenčani and Borojevići area have been performed within the scope of the GEER reconnaissance efforts between March 15 and 26, 2021. Geotechnical investigation included drilling four boreholes by manually operated solid stem auger, field identification and classification of drilled core, Standard Penetration Test (SPT) and manually driven Dynamic Penetrometer Light (DPL), GW observations in boreholes, and collection of disturbed and undisturbed soil samples for further laboratory testing. Boreholes B-1 and B-2 were drilled on March 23, 2021 in Mečenčani village, close to the largest sinkhole in the area, S001 (Fig. 3). They were drilled in mostly clayey soil to a depth of 8.0 m and 7.6 m, respectively. Other two boreholes, B-3 and B-4 were drilled on March 26, 2021 in Borojevići village (near S009 and S040 sinkholes), close to the Sunja river (Fig. 1) to the depths of 4.0 and 2.5 m, respectively. Further advancement of boreholes below these depths was not possible due to presence of very stiff marly clay or increased content of gravel size particles.

Standard Penetration Test (SPT) was performed in all boreholes at approximately 1.0 m intervals by using a mechanical drive-weight unit with a standard donut-type hammer according to ASTM standard [6]. Split-barrel sampler was used with the exception of boreholes B-3 and B-4 below the depths of 3.0 m or 4.0 m, respectively, where it was replaced by a conical probe.

Two dynamic penetration tests were conducted near the S001 sinkhole (Fig. 3) with the manually driven dynamic penetrometer light (DPL). Dynamic penetrometer SD-10 (ZNWiG) compatible with the Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing, was used [7]. 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 [4].

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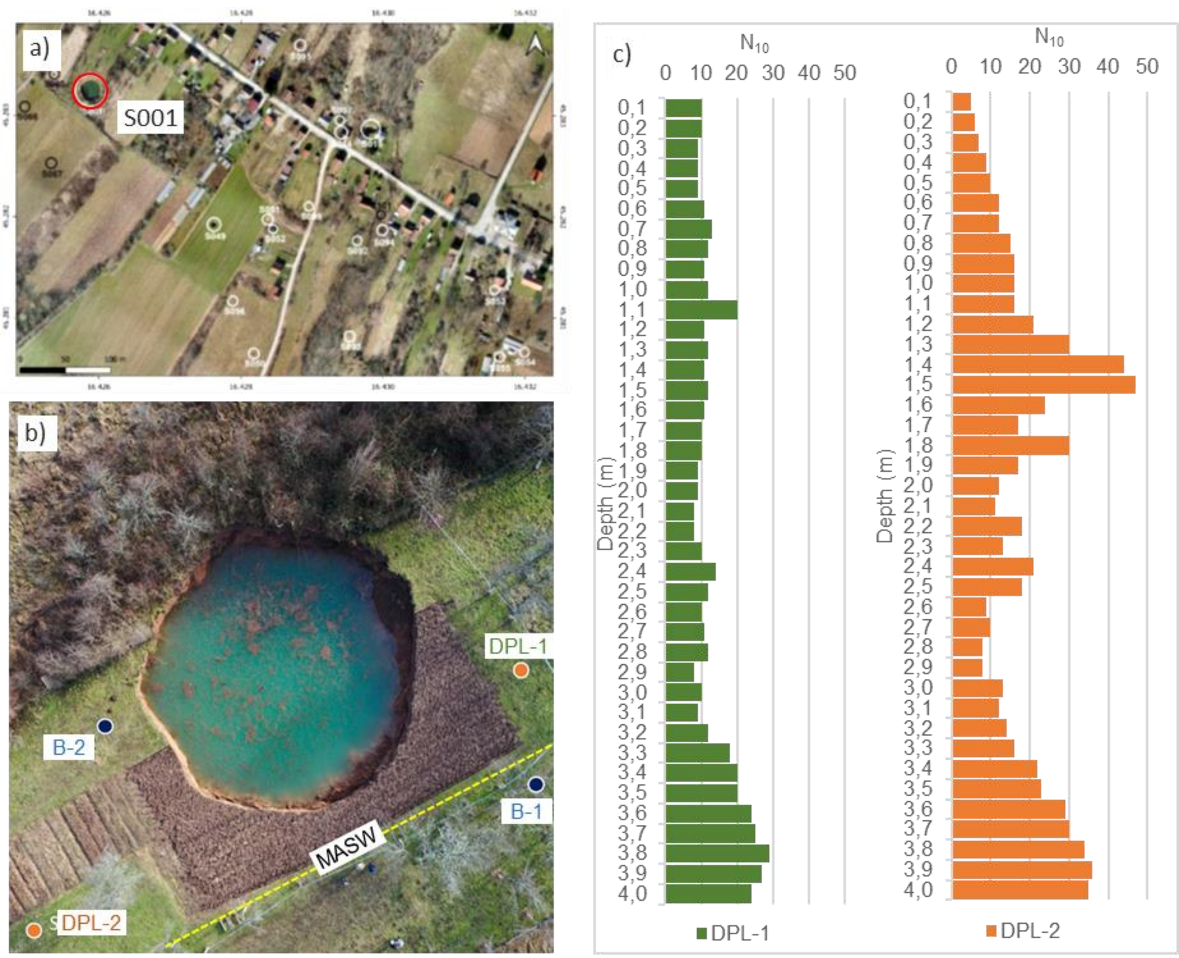

Figure 3. a) Areal image of cover-collapse sinkholes in Mečenčani village (red – S001 sinkhole) b) Locations of geotechnical and geophysical investigations around S001 sinkhole; c) DPL and corresponding test results.

Groundwater tables (GWTs) in boreholes B-1 and B-2 were initially detected at 4.7 and 4.0 m below the ground level, respectively. GWTs rose shortly after the drilling was completed, whereby the subsequent GWTs in both boreholes closely corresponded to the GWT inside the S001 sinkhole (Fig. 4).

Based on the field description and identification, as well as laboratory test results, soil samples were classified according to visual and manual procedures [8] and the Unified Soil Classification System (USCS) [9], thus enabling construction of a representative soil profile close to the largest S001 sinkhole (Fig. 4). Vertical cross sections through boreholes B-1 and B-2 indicate that approximately top 0.5 m consists of fill with organic content (denoted by F), followed by approximately 3.5 m of sandy lean and fat clay that is firm to stiff and contains sparse traces of limestone particles up to 20 mm in diameter in borehole B-1 and up to 50 mm in diameter in borehole B-2, and is classified as CL/CH. The third layer consists of stiff to very stiff lean clay and lean clay with sand that is classified as CL. At the bottom of boreholes, either gray lean (marly) clay (CL in borehole B-1) or a very moist clayey sand with gravel (SP-SC/SC in borehole B-2) was found.

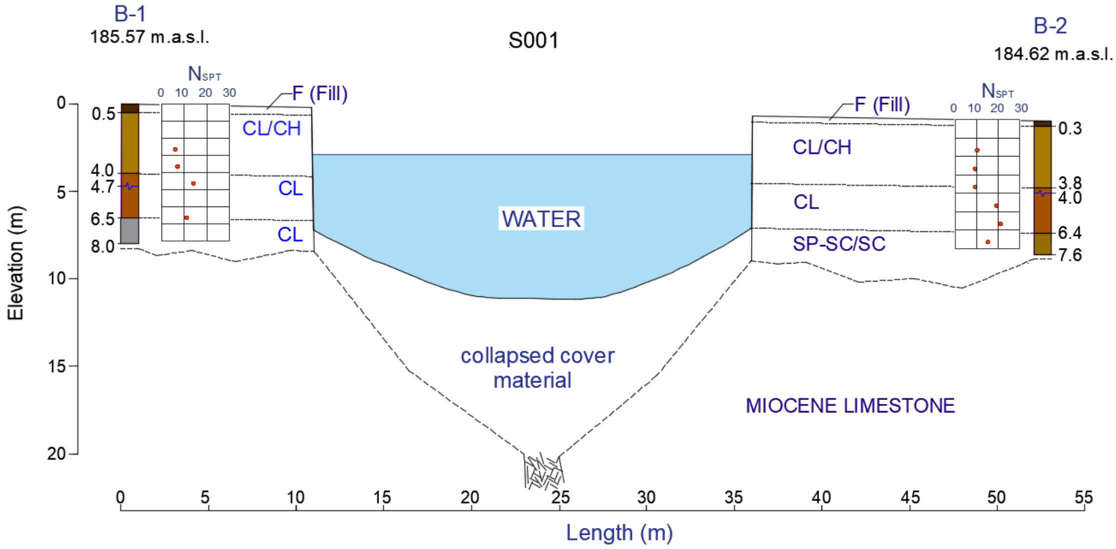

Figure 4. Vertical cross-section through S001 sinkhole, and borehole logs for B-1 and B-2 (modified from [1]).

Soil profiles reconstructed on the basis of boreholes B-3 and B-4 indicate top 0.2 to 0.3 m of fill with organic content (denoted by F). This is followed by about 1 m of lean clay (CL) that is underlain by 2.5 m of poorly-graded gravel (GP) in borehole B-3, and about 1 m of well-graded gravel (GW) in borehole B-4.

Multichannel Analysis of Surface Waves (MASW) has also been performed just along the edge of S001 (Fig. 3) in order to delineate the depth to bedrock, assess soil stiffness, and estimate average shear wave velocities [4]. 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. Fig. 5 shows two-dimensional interpretation of the MASW profile near S001 shows that lower shear wave velocities of 180–220 m/s occur until 5–6 m depth, under which slightly higher velocities 300–400 m/s were recorded corresponding to depths between 6 and 10 m. Relatively uniform strata down to 25 m are shown in green and yellow colors, which has heterogeneous 400–500 m/s velocities, which could represent weathered and saturated Miocene carbonates. It can be concluded that the compact rock layer appears below 25 m, geologically characterized as compact Middle Miocene carbonates [4]. According to the MASW, depth of S001 of about 10–13 m is most likely also the depth of the carbonate-cover contact.

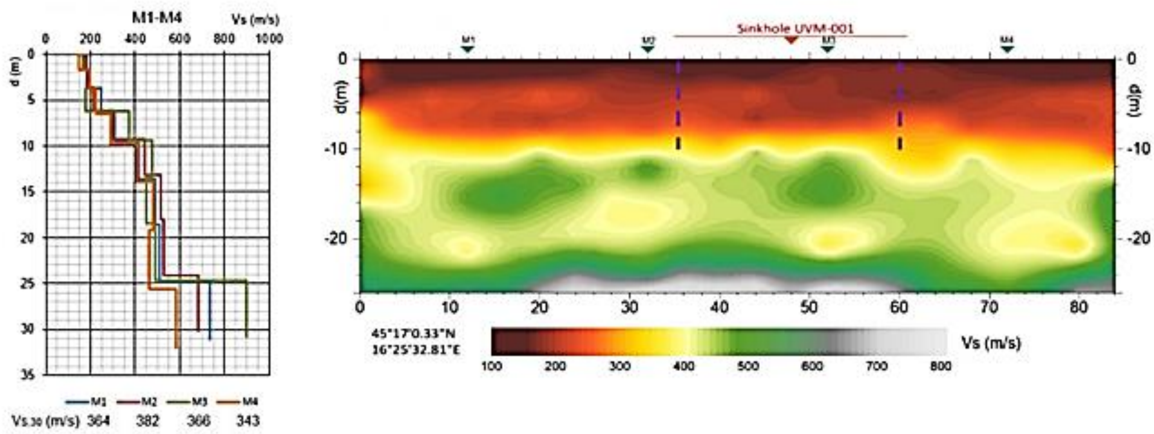

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Figure 5. Results of MASW investigation in Mečenčani close to the largest sinkhole S001 (modified from [4]).
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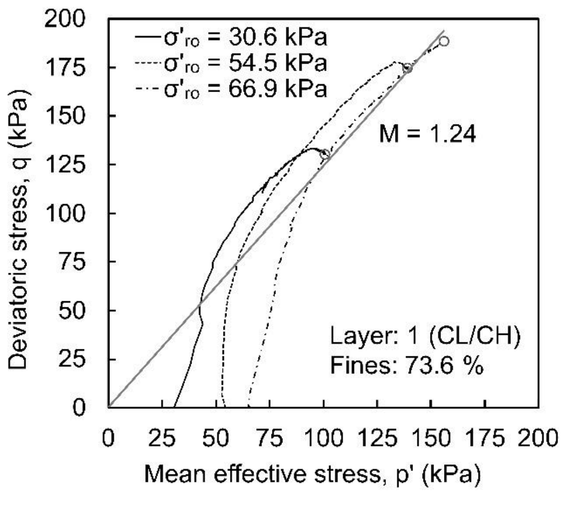
Laboratory testing was conducted at the Faculty of Mining, Geology and Petroleum Engineering of the University of Zagreb and Faculty of Civil Engineering, Architecture and Geodesy of the University of Split. Various geotechnical laboratory tests including specific gravity, moisture content, grain size distribution, Atterberg limits, oedometer test and conventional triaxial tests on saturated specimens, as well as measurement of Soil Water Retention Curve (SWRC) were performed on 31 soil samples.

Plasticity indices and liquid limits for various soil samples collected from boreholes B-1, B-2, B-3, and B-4 indicate that most of the soil samples are in the area of low-plasticity clays (w_L<50%) with few exceptions that fall into the range of high-plasticity clays (w_L>50%).

Oedometer tests were performed in accordance with the ASTM standard [10] on two samples (CL/CH) obtained from the boreholes B-1 and B-2 at the same depth of 3.0 to 3.3 m (layer 1 – CL/CH). Vertical effective preconsolidation stresses were determined based on Casagrande's procedure (σ'_c=230 kPa in B-1; σ'_c=310 kPa in B-2). The corresponding OCR values were computed based on two different GWT levels, one registered during drilling and the other one corresponding to the water level inside the sinkhole. OCR values are according to such a procedure estimated in the range of 3.9 to 4.4 for the B-1 borehole and in the range of 5.0 to 6.2 for the B-2 borehole.

Three series of consolidated isotropically undrained compression (CIUC) tests were also conducted in accordance with ASTM standard [11]. Each series comprised tests at three different cell pressures corresponding to 230, 260 and 300 kPa. Undisturbed samples from boreholes B-1 (depth 4.0–4.3 m, layer 2 – CL) and B-2 (depths 2.0–2.3 m and 3.0–3.3 m, layer 1 – CL/CH) were tested. Deviatoric and mean effective stresses (*q* and *p'*) are shown in Fig. 6. Triaxial test results indicate that all samples were overconsolidated as it was already concluded based on the oedometer test results. Slopes of the critical state lines are very similar giving the critical state friction angles of 30.9°–31.1° for the layer 1 and 30.7° for the layer 2 (Fig. 6).



a)

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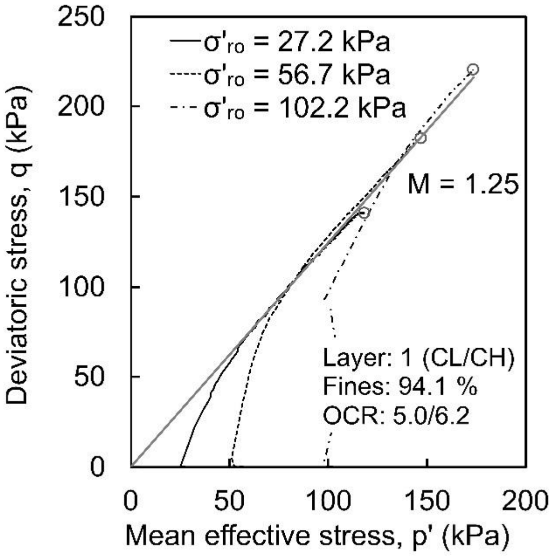

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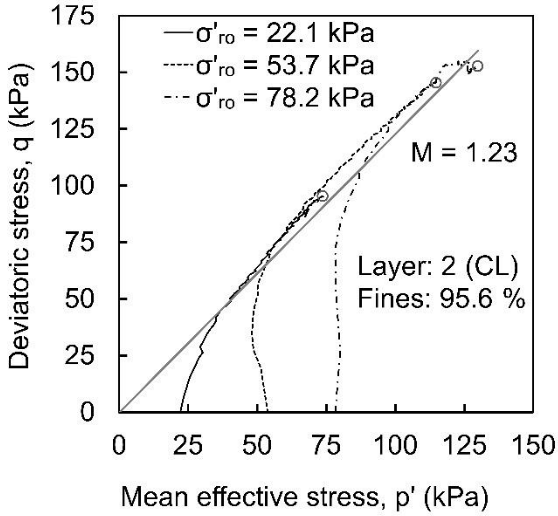

c)

Figure 6. Triaxial (CIUC) test results a) borehole B-2 (2.0–2.3 m) – layer 1; b) borehole B-2 (3.0–3.3 m) – layer 1 and c) borehole B-1 (4.0–4.3 m) – layer 2 (modified from [1])

As it was also recognized that repeated cycles of saturation and desaturation may play a role in effective stress distribution within the clay cover layer, and thus affect shear and tensile strength and possibly contributing to a sinkhole collapse, soil water retention curves (SWRC) were also obtained. Laboratory tests were carried out in accordance with ASTM D6836-16 [12] by using the "chilled mirror hygrometer" or chilled mirror dew point method and WP4C potentiometer [13] suitable for making suction measurements in the range of 0.1 to 300 MPa. Undisturbed samples from boreholes B-1 (depth 2.00–2.15 m, layer 1 – CL/CH) and B-2 (depth 5.00–5.15 m, layer 2 – CL) were tested.

Closed form equation of SWCC proposed by van Genuchten [14] was used herein to fit the experimental data. Van Genuchten's equation in terms of effective degree of saturation (S_{eff}) is given by

$$S_{eff} = \frac{1}{[1+(a\psi)^n]^m} \tag{1}$$

$$S_{eff} = \frac{S(\psi)-S_r}{1-S_r} \tag{2}$$

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where S_{eff} is the effective degree of saturation according to Equation (2), ψ is suction (kPa), a (kPa^{-1}), n, m are fitting parameters, S(ψ) is degree of saturation corresponding to a given suction value while S_r is residual saturation.

The experimental data obtained from suction measurements in WP4C apparatus including drying and wetting paths are shown in Figs. 7 and 8. Van Genuchten curves [14], which were fitted to the experimental data with the parameters according to Table 1, are also shown.

Table 1 – Parameters of van Genuchten model for SWRC drying curve

Specimen	a (1/kPa)	m	n	S_r (%)
B-1 (2.00–2.15 m)	0.00950	0.390	1.250	7.483
B-2 (5.00–5.15 m)	0.00027	1.200	0.630	6.034

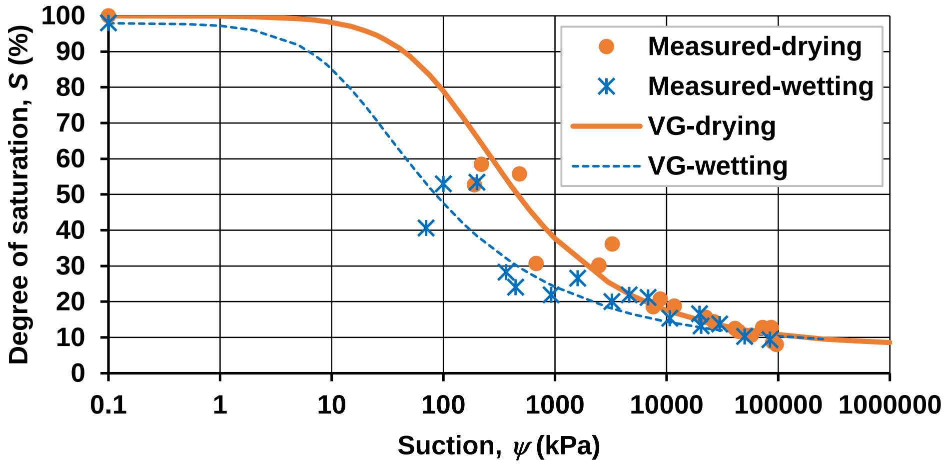

Figure 7. Experimental data and fitted van Genuchten (VG) curve for specimen B-1 (2.00–2.15 m).

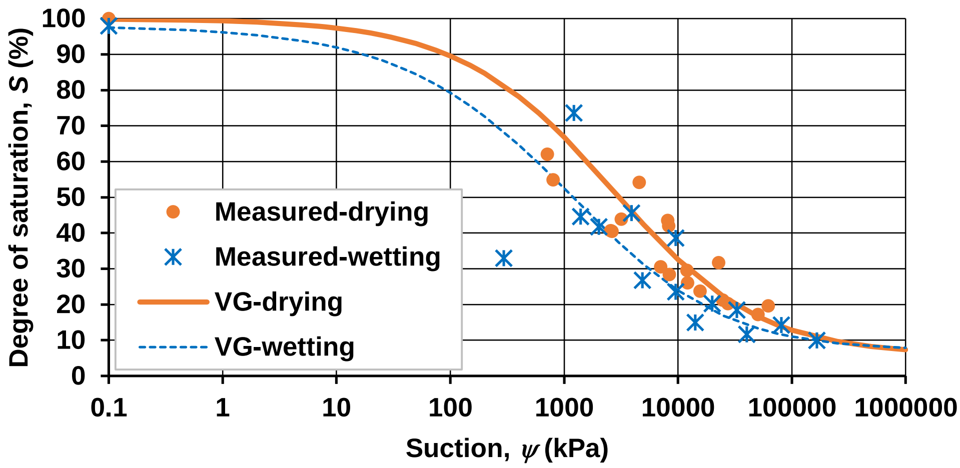

Figure 8. Experimental data and fitted van Genuchten (VG) curve for specimen B-2 (5.00–5.15 m).

The differences in SWRCs shown in figures 7 and 8 are consistent with differences in their grain size distributions. The sample from the borehole B-1 (layer 1, CL/CH) contains 53.6% fines, 43.8% sand-

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sized particles and 2.6% gravel-size particles, and the sample from the borehole B-2 (layer 2, CL) contains 71.7% fines, 28.3% sand-sized particles and no gravel-size particles.

The presented results of the field and laboratory investigations provide essential geomechanical information necessary to understand the associated sinkhole failure at that specific location and to help in better preparation and performance of future investigations geared towards providing the clarification of failure mechanism in this type of geological settings.

4. Discussion and conclusions

This paper provides an overview of geotechnical, geological and geophysical investigation of soil in the area of Mečenčani and Borojevići villages, Croatia. The area was subjected to a M_L 6.2 earthquake on December 29, 2020, followed by numerous aftershocks. The motivation for better characterizing soil in this area is an extensive sinkhole collapse phenomena, that occurred post-seismically over the period of 12 months after the main shock. The sinkhole collapse area is relatively small and characterized with karst overlain by 4 m to 15 m thick deposit of clays with gravel lenses.

So far, no detailed analytical or computational modelling of the sinkhole collapse associated with Petrinja 2020 earthquake sequence has been conducted. Nevertheless, based on the results of in situ and laboratory geotechnical tests as well as geophysical tests a hypothesis can be formulated as to how sinkhole cover collapse might have occurred.

The pre-existing historical sinkholes indicate susceptibility of this region to a sinkhole formation. This is further corrobated by the presence of limestone in subsurface as well as karst topography visible in surrounding area. Thus, the initial process of a sinkhole formation by gradual expansion of large cavities on the contact between the soil and underlying karstified carbonates was ongoing at the time when the earthquake hit. Nevertheless, the cavity covers appear to have been relatively stable prior to the earthquake (cover-collapse sinkholes opened in the area of Mečenčani and Borojevići on average every few years in the decades before the 2020 Petrinja earthquake), but they started to collapse after the earthquake.

Clearly there are two factors that played important role in the process including the interplay between the groundwater located in the karst aquifer and the groundwater located in the overlaying clay aquitard, and the effect of the earthquake. Specifically, a decrease in suction and corresponding increase in pore water pressure decreases the effective stress in the clay layers, thus decreasing the shear and tensile strength of the clay and increasing the probability of the sinkhole collapse. Furthermore, the observed collapse pattern that is characterized by vertical walls would be expected in a brittle cohesive material such as the overconsolidated clay encountered at this site.

The role of the earthquake sequence is in that it may have simply accelerated the process of the sinkhole formation through the dynamic loading imposed to already partially formed underground arch like structures. That might have lead to further slimming of the arches, but according to available data there are no evidences of the instant, co-seismic collapse. Future computational and analytical modelling efforts are expected to shed more light on the sinkhole collapse scenario provided corresponding hydrogeological data are available.

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