# Extensive Post-Seismic Cover-Collapse Sinkhole Opening During 2020–2021 Petrinja Earthquake Sequence (Croatia): a Unique Local Geological, Geotechnical and Hydrological Setting

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November 22, 2022



**Abstract**

After three foreshocks the day before (M5.0, M4.7 and M4.1, respectively), a strong M6.4 Petrinja earthquake occurred on December 29, 2020, followed by thousands of aftershocks (the strongest was a January 6 M5.0 earthquake). This paper presents a unique multihazard sequence of complex events resulting in numerous cover-collapse sinkhole failures. Although the area heavily impacted by the earthquake was larger than 1,000 km$^2$, all 91 sinkholes appeared within a 4 km$^2$ area surrounding Mečenčani and Borojevići villages located 20–25 km SE of the epicentral area, during the three months following the main earthquake. That area was also previously prone to seldom sinkhole appearances, as evidenced by 45 documented fossil sinkholes. All 91 sinkholes opened as post-seismic events; the first one (the second biggest, 10.8x9.8 m in diameter and 3.6 m deep) started to open six hours after the strongest earthquake. The biggest sinkhole, 25x23 m in diameter and 11.7 m deep, opened seven days after the main earthquake and one day before the strongest aftershock; its total volume is larger than volume of all other 90 new sinkholes combined. The Mečenčani and Borojevići villages surroundings is the only area where a 4–15 m thick sequence of Holocene soil built of unsaturated low plasticity clays with gravel and sand interlayers and lenses covers the heavily karstified carbonate bedrock composed of alternating highly porous Miocene limestones and calcarenites. The unconfined aquifer within a soil is underlain by a well-permeable confined karst aquifer in which the water pressure during wet periods becomes subartesian to artesian, enabling significant erosion and formation of numerous caverns at the soil–limestone contact. Continuous removal of eroded sediment by groundwater flow through karstified systems in carbonates gradually expands cavernous space until a final cover-collapse. The 2020–2021 Petrinja earthquake sequence significantly accelerated these processes, resulting in 91 cover-collapse sinkholes opened during a three-months period, instead of usually one sinkhole opened every few years as reported by local people. It is interesting to note that during the strongest earthquake the water level in the unconfined aquifer was very close to the surface, and in the underlying karst aquifer artesian conditions prevailed.

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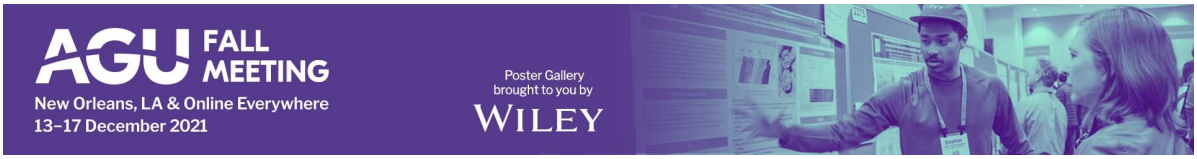

# INTRODUCTION

The Geotechnical Extreme Events Reconnaissance (GEER) of the Petrinja, Croatia M6.4 earthquake of December 29, 2020, followed by numerous aftershocks during the next eleven months, identified 107 new cover-collapse sinkholes occurring over approximately 1 $km^2$ of a terrain (Figures 1 and 2). Cover-collapse sinkholes occurred in the area in the past but were considered relatively rare events. Along with 107 new sinkholes, the GEER efforts identified 49 sinkholes that collapsed before the earthquake. Sinkhole diameters vary from less than 1 to 25 m, with a depth ranging from 0.2 to more than 11 m. Historical sinkholes are often camouflaged with dense vegetation and filled with water, rocks, soil, or even packed with trash. The appearance of sinkholes during the 2020–2021 Petrinja earthquake sequence is considered as the most surprising and relatively rare geotechnical earthquake effect, among other more typical co-seismic and post-seismic events.

The magnitude M6.4 earthquake hit the Sisak–Moslavina county in Central Croatia (Figure 1A, 1B) on December 29, 2020, at about 12:19 PM local time (11:19 AM UTC). Three foreshocks preceded the earthquake, the strongest of which had a magnitude of 5.2 MW and was followed by numerous aftershocks, including 85 with a local magnitude ML ≥ 3.1, until February 22, 2021. The earthquake hypocenter was at 45.422°N 16.255°E, at a depth of 10 km (USGS 2020). The location and depth of the hypocenter suggest that the earthquake occurred within the central portion of the shallow Petrinja strike-slip fault within Internal Dinarides, in the NE marginal part of the Adria Microplate (Figure 1A).

Worldwide, co-seismic or post-seismic sinkhole collapses have been rarely documented in the past in various soils and rocks, and due to different underlying mechanisms related to or enhanced with earthquake shaking. The 2020–2021 Petrinja earthquake sequence represents the second-largest to-date recorded post-seismic occurrence of new sinkholes after those in the Tohoku area following the Miyagi–Oki M7.4 1978 earthquake, while with 107 cover-collapse sinkholes in the area of smaller than 1 $km^2$ (Figures 2, 3 and 4) it could be the number one most dense occurrence of post-seismic sinkholes in the World.

# GEOLOGY, HYDROLOGY, AND GEOMECHANICS

Sinkholes collapsed in clayey soil with sporadic gravel lenses covering cavernous, intensely karstified Middle Miocene carbonates. Although the proposed trace of Petrinja fault as a seismogenic source stretches very close, Mečenčani and Borojevići area is outside of the most active fault segment: epicenters of only a few low-magnitude earthquakes were near the sinkhole area (Figure 1B). Cover-collapse sinkholes found in Mečenčani and Borojevići formed due to the particular combination of heavily karstified limestones covered by relatively thick clayey soil. Therefore, in the approximately 1.000 $km^2$ large area affected by the Petrinja earthquake sequence, only a small area of roughly 1 $km^2$ is prone to cover-collapse sinkholes (Figures 2, 3 and 4). Subhorizontal Badenian deposits (Middle Miocene, $M_4$) are composed of alternating highly porous Lithothamnium limestones and calcarenites that are very susceptible to karstification. Karst phenomena forms including sinkholes/dolines are visible on outcrops in the neighboring hilly area SW of Mečenčani and Borojevići. A 4–15 m thick sequence of Holocene deluvial–proluvial deposits (dpr) built of clays with interlayers and lenses of gravel and sand in lateral and vertical alternations covers the heavily karstified carbonate bedrock. Clayey soil is unconsolidated to overconsolidated and exhibits varying degrees of saturation ranging from a very small value to fully saturated.

During wet periods high water pressure from underlying highly permeable confined karst aquifer caused both gradual underground erosion of non-cohesive fine-grained cover soil (suffosion) and successive failures of cohesive soil. Continuous removal of eroded sediment by groundwater flow through karstified systems in underlying carbonates creates and gradually expands cavernous space. Unlike subsidence that slowly creates depressions with gentle slopes by suffosion in non-cohesive deposits, the collapse of cover cohesive soil deposits is sudden, usually occurring within minutes or hours. Cover-collapse structures usually have steep or even overhanging margins – as most of the studied in the vicinity of Mečenčani and Borojevići – and occur mostly in more competent rocks. The collapse of cover deposits is more common during periods of heavy rainfall, as water significantly increases the total weight of soil and at the same time reduces soil strength and arching stability.

# HISTORICAL SINKHOLES

Mečenčani and Borojevići areas are naturally prone to cover-collapse sinkholes, as indicated by 49 historical sinkholes recorded in the area (grey circles on Figure 2, circles on Figure 3, black circles in Figure 5). Several of these sinkholes were filled up years ago by local farmers and did not reactivate during the studied earthquake series, except for subtle subsidence recorded in a few of them (mostly around 10 cm). Eight out of ten largest sinkholes found in the area are historical ones, having the largest diameter between 10 and 18 m (including major springs in the area, Davidovića vrelo and Pašino vrelo located close to the Sunja river).

Historical sinkholes are generally morphologically very similar to recent ones, including common very steep to sub-vertical walls. However, besides testimonies of local farmers, three major characteristics enabled their recognition:

(1) Lack of freshly opened collapsed margins and irregular cover of fresh soil and grass at their bottoms.

(2) Common old trees are growing, and in places old garbage can be found at their bottoms (Figure 5B).

(3) In the case of sinkholes filled with water, historical sinkholes are characterized by abundant fresh-water macrophytic vegetation, while newly formed sinkholes have no fresh-water plants.

The earthquake sequence with thousands of seismic events significantly boosted natural processes in the area: according to local people, a new cover-collapse sinkhole would be opened in the area once every few years. The stresses caused by the 2020–2021 Petrinja Earthquake Sequence resulted in the opening of as many as 91 cover-collapse sinkholes within only three months, and 16 additional in the next eight months (all 107 new sinkholes are marked by black circles on Figure 2 and rhombs on Figure 3). We speculate that high groundwater levels recorded during the studied period additionally fostered such an intense sinkhole collapsing midst 2020–2021 Petrinja Earthquake Sequence.

# THE LARGEST SINKHOLE

The largest sinkhole, S001 (Figure 6), is characterized by steep walls in brown clay, with sparse 30–60 cm thick lenses of gravel (Figure 6C). The sinkhole is nearly circular, with a diameter of about 24.4 m in March 2021.

S001 collapsed in Mečenčani between the January 4, 2021 afternoon and 1:00 pm local time on January 5, more than 24 hours before the main M4.9 aftershock that took place at 6:01 pm local time on January 6. Landowners noticed the first subtle subsidence of the area on the afternoon of January 4. Two major foreshocks on December 28, M5.2 and M4.7, and the main earthquake of December 29, 2021 M6.4 preceded the S001 collapse by a week. The surface soil collapsed at once into S001, forming a sinkhole about 15 m in diameter, followed by minor adjustments due to failed walls, which remained sub-vertical (Figure 7). Walls were collapsing with an unstable, brittle clay block of approximately 2–3 m widths (Vidić, 2021).

# INFRASTRUCTURE DAMAGE

A few sinkholes caused significant infrastructure damage. Although the two villages' area is predominately agricultural, some homeowners survived dramatic collapses under their houses, in the proximate vicinity, or on their farms. Farmland remained drastically damaged with >100 sporadically placed sinkholes, and some occurred near greenhouses. Cover-collapse sinkhole S015,12.1 m length, 9.4 m width, 3.5 m depth, collapsed between two houses on December 29, 2021, following the mainshock earlier on the same day. Two smaller sinkholes, each approximately 1 m in diameter and 1 m deep, opened six hours after the main earthquake, then combined into a large sinkhole within the next 12 hours. S054 (1.6–2.0 m in diameter, 1.3 m deep) and S055 (1.5 m in diameter, 2.3 m deep) caused significant discomfort and distress to the people residing on the neighboring farm. S054 and S055 are circular sinkholes with small diameters, quite deep, and have vertical walls (Figure 8).

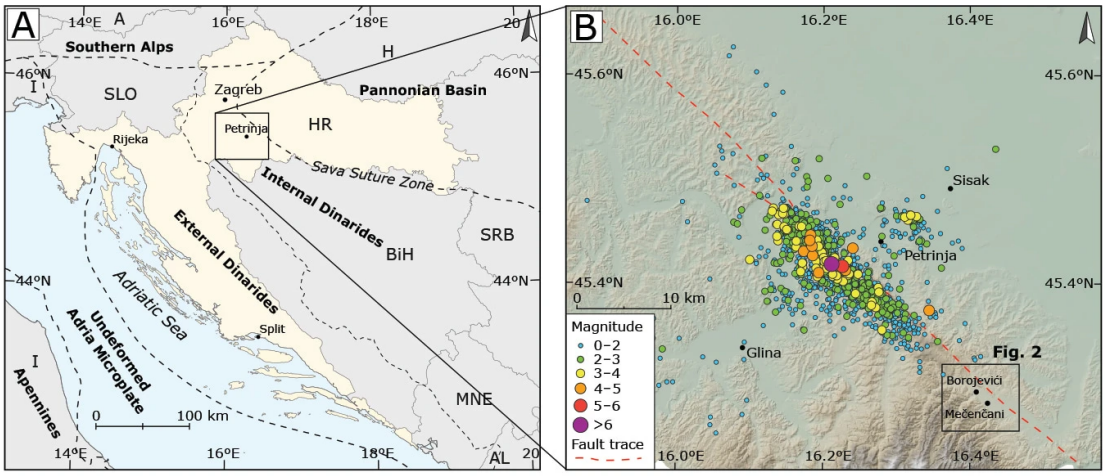


**Figure 1.** A) Location map of the study area along the northern margin of Adria Microplate (Internal Dinarides). B) Epicentres of earthquakes recorded during the first ten days of 2020–2021 Petrinja Earthquake Series (Marijan and Davorka Herak, pers. comm.), trace of seismogenic fault based on InSAR data (Marin Govorčin, pers. comm.) and location of study area.

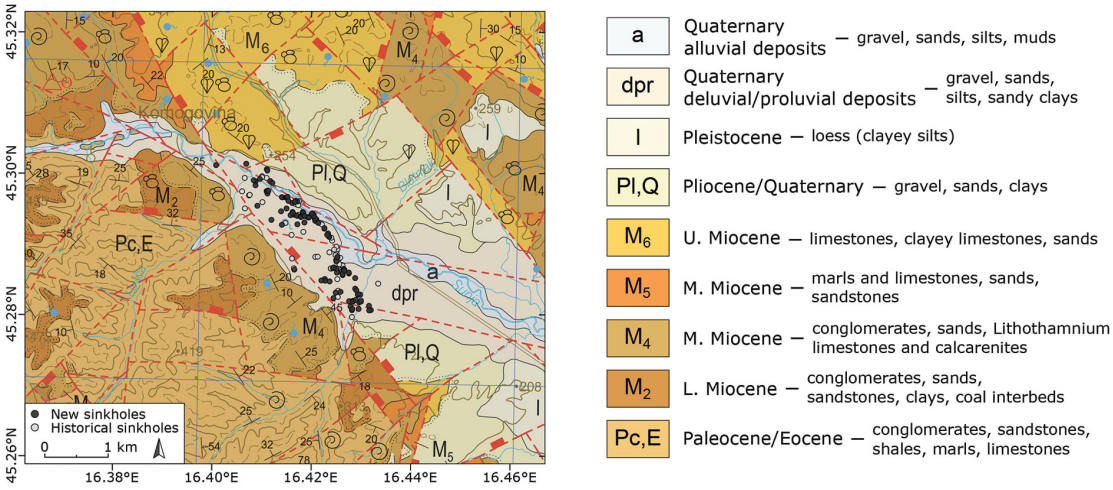


**Figure 2.** Part of the Basic Geological Map of the Republic of Croatia 1:100k, Bosanski Novi Sheet (Šikić, 2014) showing locations of 49 historical cover-collapse sinkholes (grey circles) and 107 new sinkholes collapsed during the 2020–2021 Petrinja Earthquake Series (black circles).

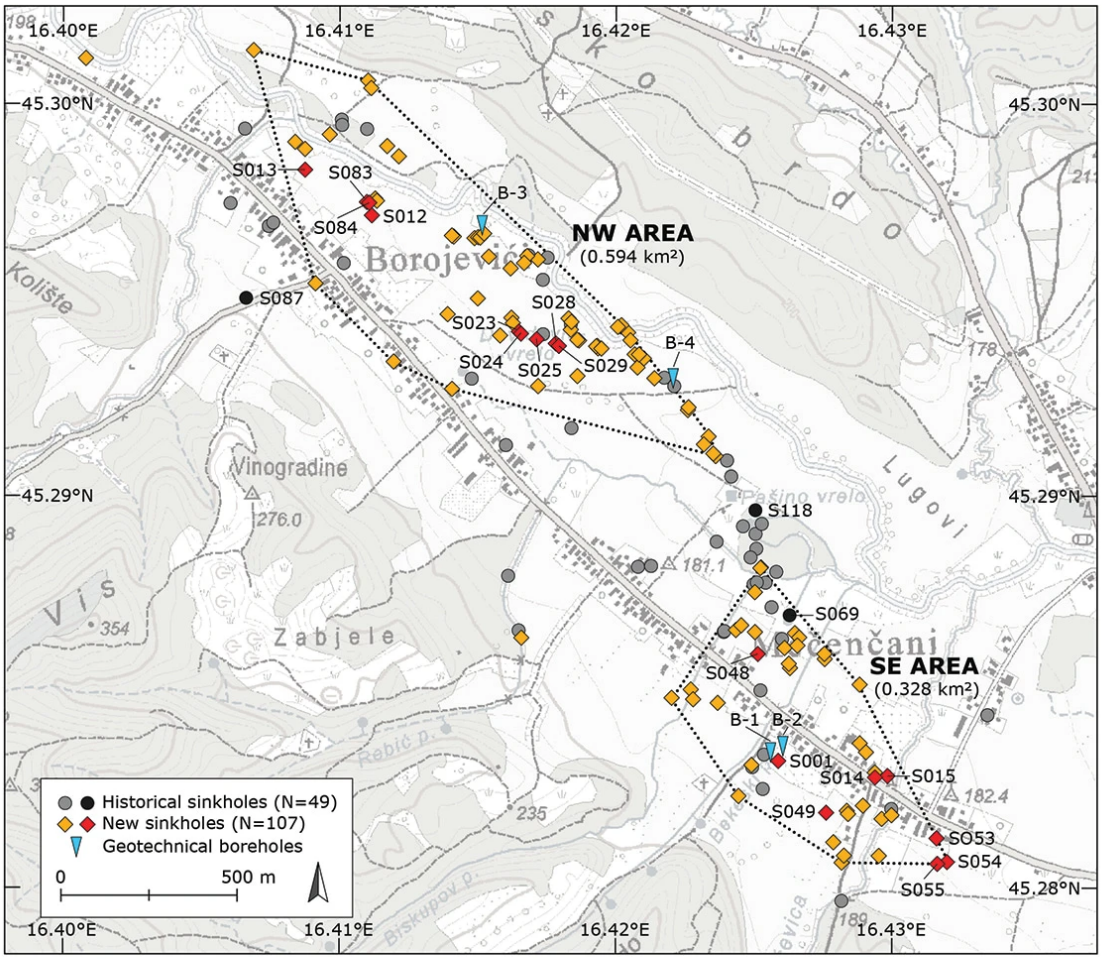


**Figure 3.** Topographic map of the Borojevići and Mečenčani area showing two areas with locations of 49 historical cover-collapse sinkholes (circles) and 107 new sinkholes collapsed during the 2020–2021 Petrinja Earthquake Series (rhombs).

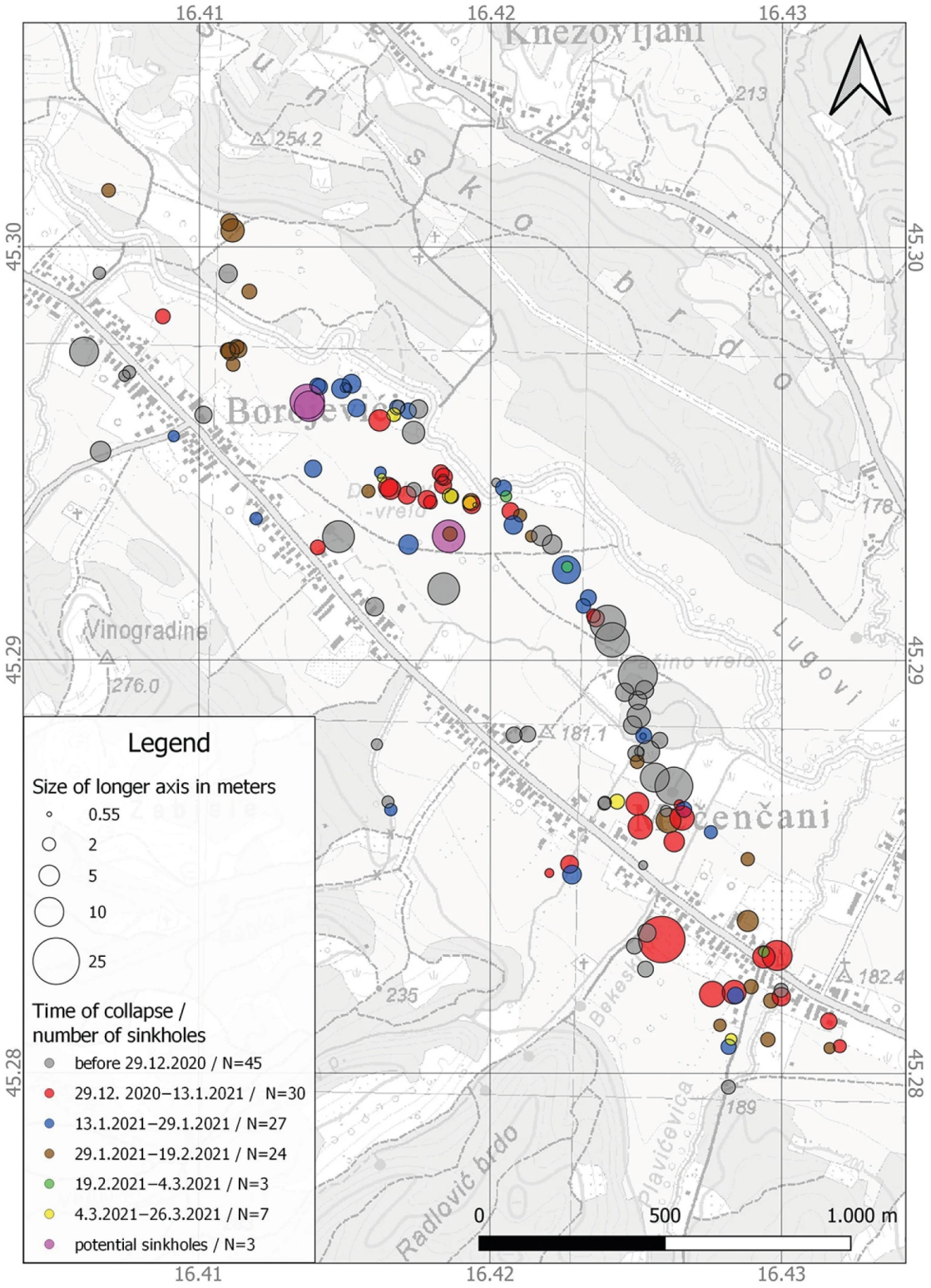


**Figure 4.** Spatio-temporal map of cover-collapse sinkholes and their longer diameter on the topographic map.

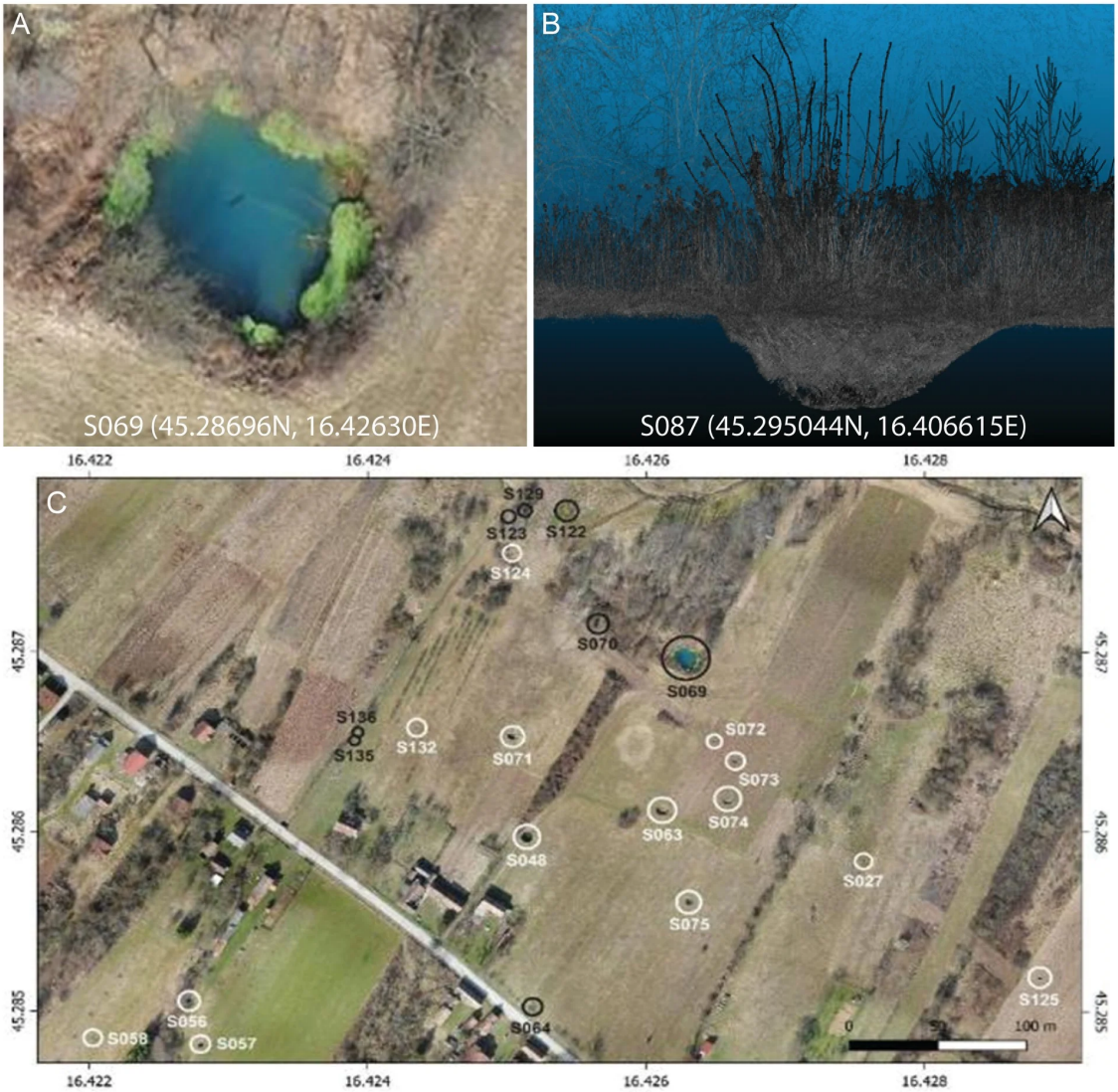


**Figure 5.** Historical cover-collapse sinkholes A) S069 areal photogrametry, circled black in C), B) lidar image cross-section of S087 and C) areal photogrametry where black circles denote historical and white circles post-seismic sinkholes.

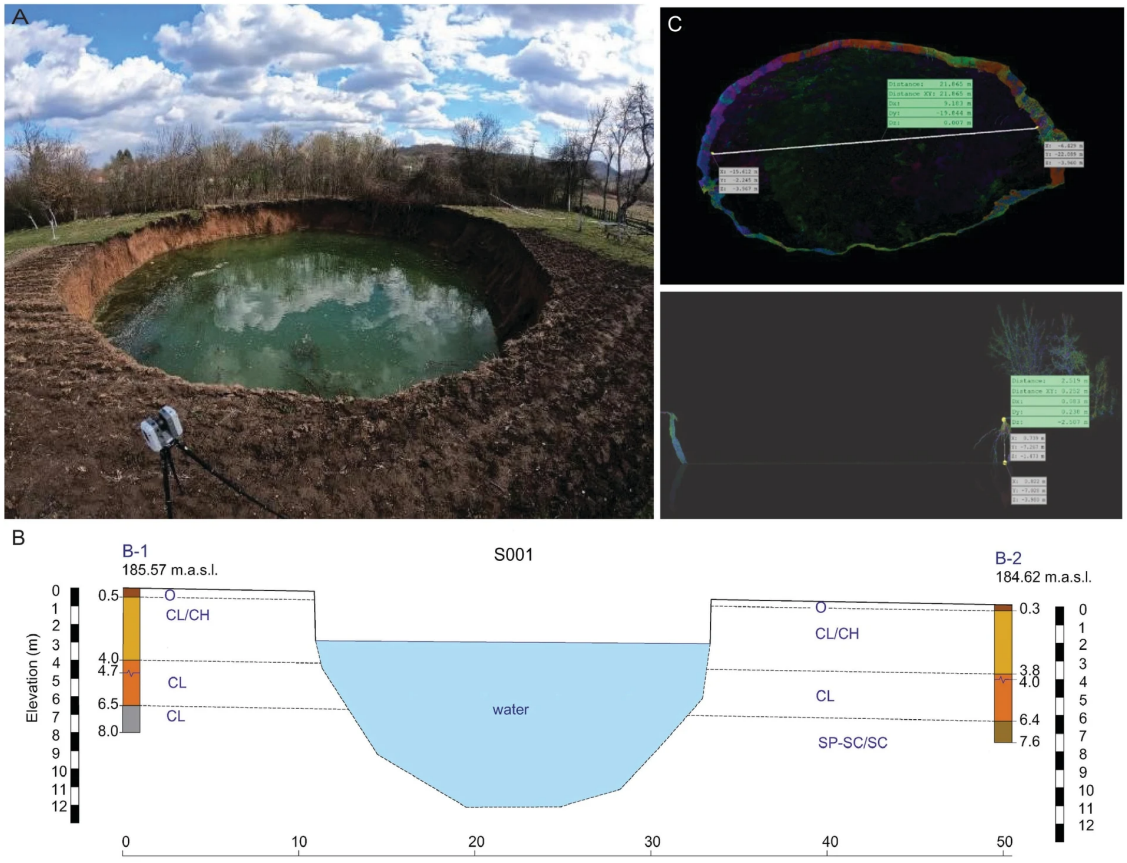


**Figure 6.** The largest sinkhole S001, that is 24.4 m in diameter, and >11 m deep filled with water, A) photogrametry, B) lidar image with dimensions and C) geotechnical soil classification, borehole profiles and water levels.


**Figure 7.** A sequence of events during S001 walls widening as brittle clay collapse on January 6, 2021.


S014 Position
S014 images (45.282822N, 16.429389E)
S053 bundle image
(45.281270N, 16.431618E)
S055 lidar scan bundle view (45.280618N, 16.431644E)
S054 lidar scan bundle view and lidar point cloud cross-section image (45.280665N, 16.431996E)
S015 (45.282859N, 16.429841E)
S015 (45.282859N, 16.429841E)
S015 (45.282859N, 16.429841E)

**Figure 8.**

# CONCLUSIONS AND DISCUSSION

An extensive formation of numerous cover-collapse sinkholes occurred in the aftermath of the December 29, 2020, M6.4 earthquake, and its 2020–2021 sequence in Petrinja, Croatia. The total number of registered new sinkholes increased to 107, as of November 2021, appearing within two small areas of less than 1 $km^2$, combined, surrounding Mečenčani and Borojevići villages, 20 km SE of the mainshock epicenter (Figure 1). Out of 156 registered sinkholes, 49 already existed in the area prior to the earthquake (Figures 2, 3).

Data collected from different sources, such as interviews, media, field observations, and aerial photographs, indicate that all cover-collapse sinkholes opened due to the 2020–2021 Petrinja earthquake sequence may be considered post-seismic structures. Sinkholes collapsed in clayey soil with sporadic gravel lenses covering cavernous, intensely karstified Middle Miocene carbonates.

## Acknowledgments

The work has been supported by the GEER Association, which is based in part on work supported by the National Science Foundation through the Geotechnical Engineering Program under US NSF Grant No. CMMI-1266418. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Furthermore, this work has been supported in part by the Croatian Science Foundation under the project “Experimental and numerical investigations of mechanisms in unsaturated geomaterials” (UIP-2017-05-3429). It has also been partially supported through project KK.01.1.1.02.0027, a project co-financed by the Croatian Government and the European Union through the European Regional Development Fund - the Competitiveness and Cohesion Operational Programme, as well as a project on inventory of cover-collapse sinkholes for the Ministry of Physical Planning, Construction and State Assets of the Republic of Croatia.

# AUTHOR INFORMATION

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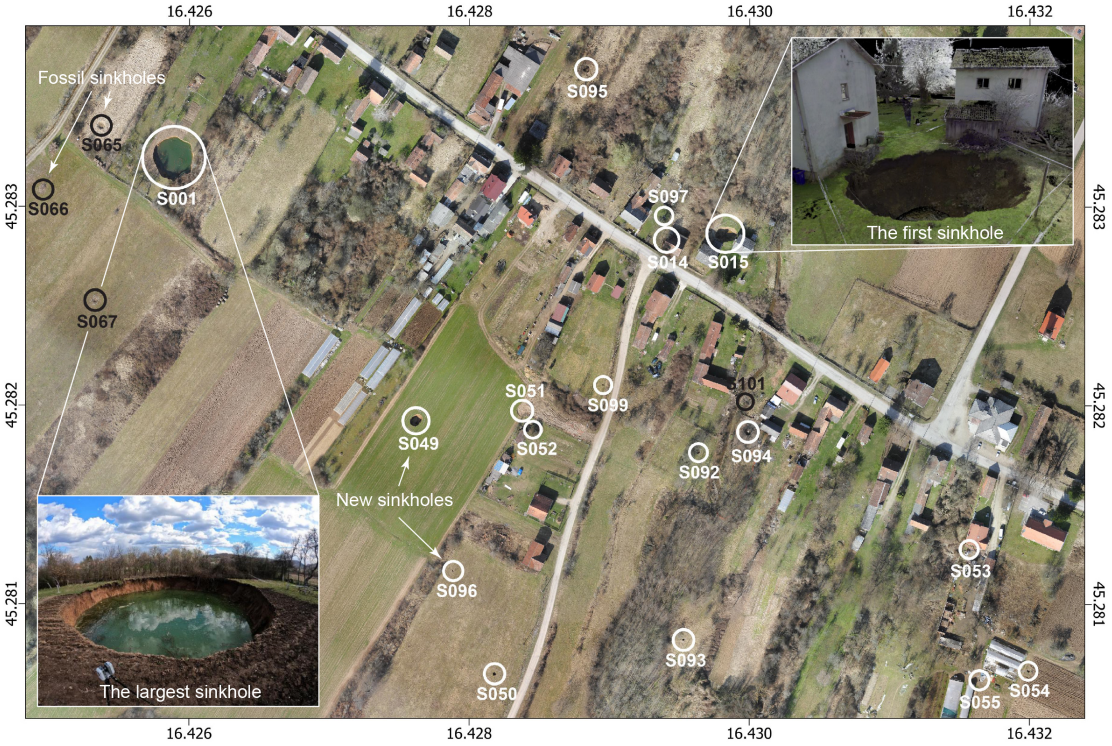
# ABSTRACT

After three foreshocks the day before (M5.0, M4.7 and M4.1, respectively), a strong M6.4 Petrinja earthquake occurred on December 29, 2020, followed by thousands of aftershocks (the strongest was a January 6 M5.0 earthquake). This paper presents a unique multihazard sequence of complex events resulting in numerous cover-collapse sinkhole failures. Although the area heavily impacted by the earthquake was larger than 1,000 km$^2$, all 91 sinkholes appeared within a 4 km$^2$ area surrounding Mečenčani and Borojevići villages located 20–25 km SE of the epicentral area, during the three months following the main earthquake. That area was also previously prone to seldom sinkhole appearances, as evidenced by 45 documented fossil sinkholes. All 91 sinkholes opened as post-seismic events; the first one (the second biggest, 10.8x9.8 m in diameter and 3.6 m deep) started to open six hours after the strongest earthquake. The biggest sinkhole, 25x23 m in diameter and 11.7 m deep, opened seven days after the main earthquake and one day before the strongest aftershock; its total volume is larger than volume of all other 90 new sinkholes combined. The Mečenčani and Borojevići villages surroundings is the only area where a 4–15 m thick sequence of Holocene soil built of unsaturated low plasticity clays with gravel and sand interlayers and lenses covers the heavily karstified carbonate bedrock composed of alternating highly porous Miocene limestones and calcarenites. The unconfined aquifer within a soil is underlain by a well-permeable confined karst aquifer in which the water pressure during wet periods becomes subartesian to artesian, enabling significant erosion and formation of numerous caverns at the soil–limestone contact. Continuous removal of eroded sediment by groundwater flow through karstified systems in carbonates gradually expands cavernous space until a final cover-collapse. The 2020–2021 Petrinja earthquake sequence significantly accelerated these processes, resulting in 91 cover-collapse sinkholes opened during a three-months period, instead of usually one sinkhole opened every few years as reported by local people. It is interesting to note that during the strongest earthquake the water level in the unconfined aquifer was very close to the surface, and in the underlying karst aquifer artesian conditions prevailed.

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