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REMEDIATION OF THE EARTHQUAKE - INDUCED COLLAPSE SINKHOLES IN SISAK – MOSLAVINA COUNTY

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Abstract

This paper presents the remediation works of surface openings in the Sisak - Moslavina County, whose activation was triggered by the M6.2 earthquake in December 2020 with an epicenter near Petrinja, Croatia. In addition to the immediate vicinity of residential buildings, openings are recorded near the transport infrastructure, on agricultural and non-agricultural land and in the forests of the municipality of Donji Kukuruzari. The aforementioned surface openings that occurred during and after the main impact were identified as collapse sinkholes. The lack of surface indicators and the sudden increase in the number of sinkholes in the period after the earthquake make this area very dangerous for its inhabitants. As part of the assessment of the condition and categorization of the collapse sinkholes, which preceded the development of a remediation design and remediation works, 143 collapse sinkholes were identified, two of which protrude with a large volume of 943 and 5014 m^3. The paper presents the efforts to categorize the sinkholes to determine the remediation priorities, the development of a remediation design based on the inverse filter method with the use of materials of different grain sizes and geosynthetic materials, along with the remediation work and challenges involved.

Key words

collapse sinkhole, Petrinja earthquake, sinkhole categorization, inverse filter method

1 Introduction

During the strong 6.2 magnitude earthquake that shook Sisak – Moslavina County in Croatia on December 29, 2020, numerous geo-related problems occurred, including landslides, large-scale liquefaction, failure of geotechnical assets etc. In addition, numerous ground openings occurred south of the epicentre, especially in the villages of Mečenčani and Borojevići, leaving the authorities and the engineering community perplexed (Figure 1). Most of the openings occurred on agricultural and non-agricultural land, but some also occurred near buildings and infrastructure. The geology of this limited area is ≈10 km^2 and is characterised by karstic rocks covered by a 5–15 m thick proluvial soil layer deposited in the past by the Sunja River (Pollak, 2021).

Bačić et al. (2021) provide an insight into the formation of these openings and classify them as collapse sinkholes, where failure can develop in a short time, usually without any surface deformation prior to collapse. This type of sinkhole is formed when the soil-like material overlying the soluble karst rock is repeatedly wetted and dried, causing soil particles to dislodge through the channel draining the sinkhole and eventually form a structural arch in the ground. In this case, the aforementioned earthquake caused the arch material to collapse, resulting in sudden and dramatic sinkhole phenomena. For more details on the formation of this type of sinkhole, refer to Bačić et al. (2021) and Šumanovac & Pekaš (2023).

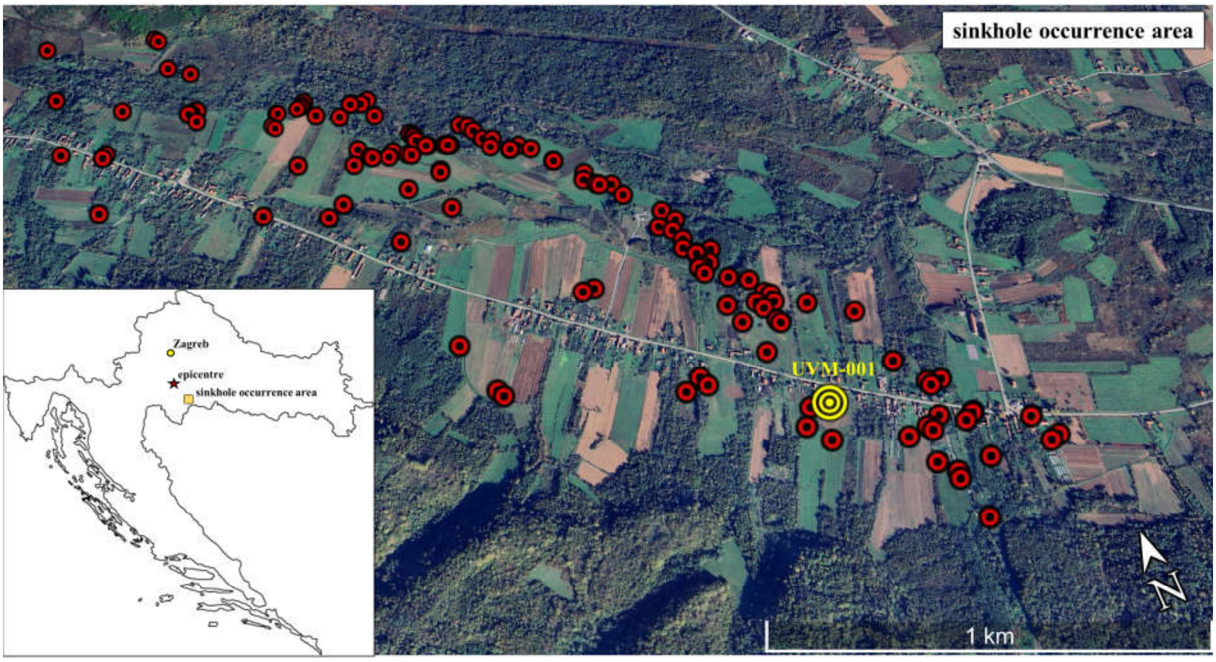


Figure 1. Locations of the occured sinkholes with the position of the largest sinkhole UVM-001

This paper focuses on the rapid assessment activities carried out in sinkhole occurrence area, which led to sinkhole categorization and served as a starting point for the development of the remediation design and the implementation of the remediation measures. While the general assessment methodology is explained, the planning and remediation design and work is demonstrated using the example of the largest collapse sinkhole (UVM-001) with a diameter of 25 m and a depth of 13 m (Figure 2).

Figure 2. Largest sinkhole (UVM-001) occurred as a consequence of the Petrinja 2020 earthquake

2 Sinkhole categorization and remediation methodology

The sinkhole remediation activities financed by the European Union Solidarity Fund required careful planning and implementation. These activities were initiated by the Croatian Waters and the Faculty of Civil Engineering of the University of Zagreb, which prepared a document on the 'Assessment of the current state and categorization of sinkholes in the Sisak – Moslavina County' (FCEZG, 2022). The overall objective of this task was to create an inventory of sinkholes with an appropriate statistical analysis in terms of defined indicators that would serve as a basis for categorising sinkholes according to remediation priorities. However, given the large number of sinkholes, time constraints and the fact that most of these sinkholes are continuously expanding and pose an immediate threat, it was not possible to carry out a comprehensive geotechnical survey campaign.

The general categorization methodology is shown in Figure 3. After the development of the categorization indicators (size, location based on land use pattern, presence of water in the sinkhole, etc.), the field work followed together with the survey campaign. The information thus obtained was subjected to a statistical analysis, followed by the preparation of an inventory of sinkholes with the identification of an optimal remediation method and a preliminary cost estimate. All this forms Phase I, followed by Phase II, in which a remediation design was developed for each sinkhole and the remediation work was carried out.

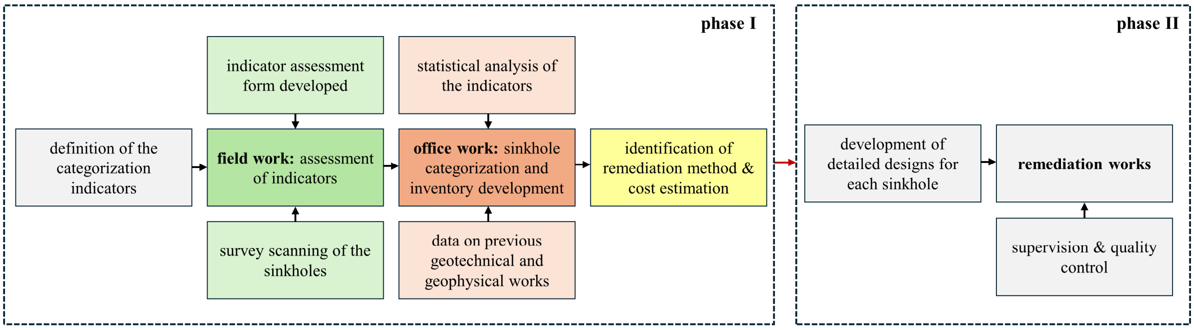


Figure 3. The general methodology for the categorization (phase I) and remediation (phase II) of sinkholes

A total of 143 sinkholes were detected by the end of 2021, two of them with very large volumes of 942.5 and 5014 m^3, while the other sinkholes all have a volume of less than 450 m^3, with most of them between 1 and 50 m^3. Figure 4 provides some statistical data on the sinkholes investigated, showing the volumes of the sinkholes based on the land use pattern and taking into account the size of the opening. The assessment indicates that sinkholes mostly occur in regular shapes, i.e. in the form of a hemisphere or truncated cones. Elongated forms (greater depths and smaller opening areas) also appear, but less often.

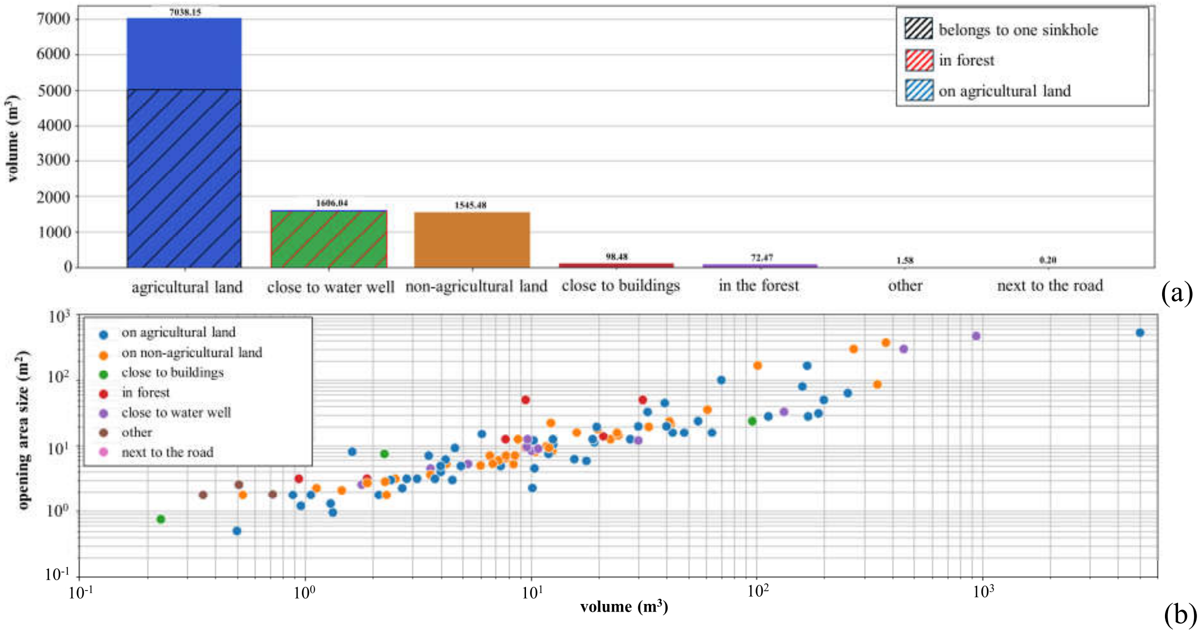


Figure 4. Volumes of the sinkholes based on the land use pattern (a) along with consideration of the opening size (b), modified from FCEZG (2022)

3 Geological and geotechnical conditions on the location of largest sinkhole

A number of scientists and practitioners from the fields of geotechnics, geology and geophysics participated in the data collection in order to gather as much data as possible to determine the causes of the occurrence of collapse sinkholes, but also to assess the risk of new sinkhole occurring, especially in times of increased seismic activity. All this was done in cooperation with the local community and civil defence authorities. Tomac et al. (2023) provide an overview of the geological and hydrogeological conditions of the area, noting that the Sunja River valley is a flat terrain covered by Holocene deluvial–proluvial deposits of low permeability, containing a certain amount of water and forming an aquitard underlain by karstified carbonates. The authors also present geotechnical and geophysical investigations carried out as part of the GEER (Geotechnical Extreme Events Reconnaissance) efforts. Geotechnical boreholes were drilled in predominantly clayey soils to a depth of 8.0 m and did not reach the depth of the bedrock. The clay samples obtained were used to carry out laboratory classification tests and conventional triaxial tests on saturated samples and to measure the soil water retention curve (SWRC). The MASW (Tomac et al., 2023) and HSVR (Ntambakwa et al., 2023) geophysical measurements were able to estimate the Holocene – weathered bedrock - compact bedrock boundaries to some extent. The higher resolution geophysical investigations were carried out by Šumanovac & Pekaš (2023), who conducted extensive geophysical campaigns using two-dimensional electrical tomography. The authors distinguish between two different geological models: GM-1, in which the layer base of the clastic surface deposits consists of lithothamnium limestones and calcarenites, which leads to the formation of underground cavities and collapse sinkholes, and GM-2, in which the layer base consists of clay deposits and no collapse sinkholes occur. Figure 5 shows one of the ERT profiles at the site of the largest sinkhole UVM-001, which shows that there are numerous larger and smaller subsurface voids in the upper parts of the lithothamnian limestones, therefore, the structure can be visually described as grid-like.

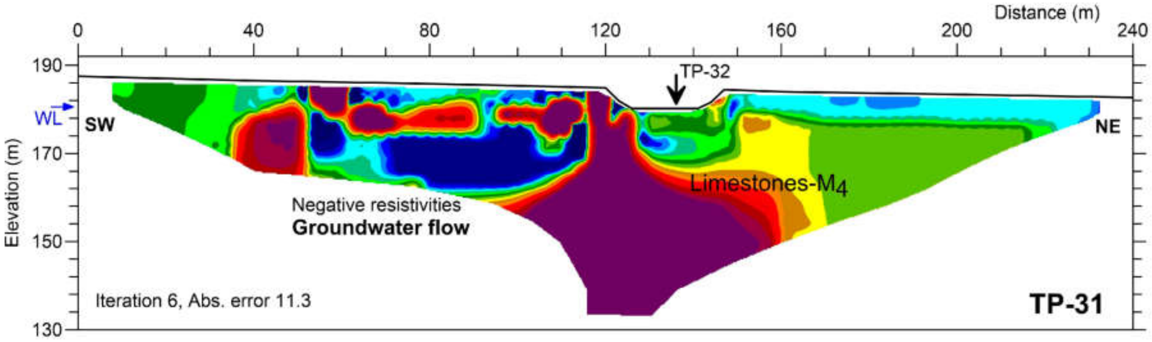


Figure 5. Electrical resistivity profile on the location of UVM-001 (Šumanovac & Pekaš, 2023)

4 Design and Remediation works

4.1 Remediation design: Inverse filter method

Categorization (FCEZG, 2023) proposed remediation of 102 sinkholes, while a detailed design was developed for each collapse sinkhole in order to take local characteristics into account. The inverse filter method proposed by Bačić et al. (2021) was considered as the optimal remediation method, as it is environmentally friendly and allows the continuation of natural water drainage. This is particularly important given the complex underground water flow and the proximity of the Pašino vrelo water well.

The remediation layout is given in Figure 6. The method consists of backfilling a sinkhole, including blocking the sinkhole throat with boulders, followed by the installation of upper granular layers with high permeability, each with finer particles than the one below. The backfill material consists of 300 -

500 mm and 500 – 800 mm boulders (Type 1), followed by 32 – 250 mm crushed stone (Type 2), over which 16 - 32 mm material (Type 3) is placed. The Type 2 and Type 3 materials are placed in 50 cm thick layers and compacted to 40 MPa.

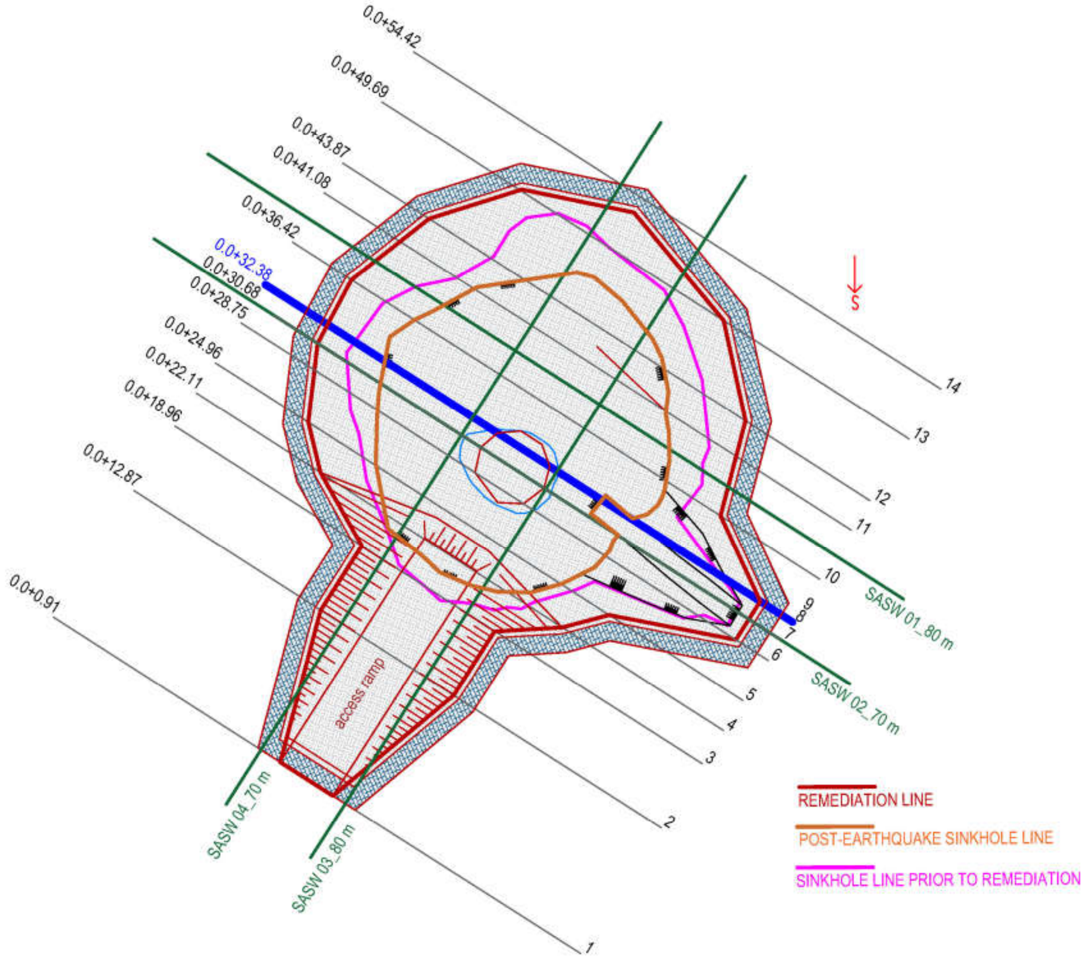


Figure 6. A layout of the remediation solution for UVM-001, modified from Brodska Posavina (2023)

After the initial excavation and reprofiling of the slopes, due to removal of loose slope material and to achieve sufficient compaction of the backfill material, the excavation area is lined with a geocomposite consisting of a non-woven geotextile with a mass of 300 g/m^2 (to prevent the penetration of fine soil particles into the backfill material during the water seepage) and biaxial geogrids with a tensile strength of 30/30 kN/m (to allow interlocking with the backfill material, increasing both the stiffness of the backfill and the contact shear strength along the slope). The geocomposite is placed in the surface trench and anchored to the ground with U-segments of reinforcing steel. The geogrids were also positioned at predefined heights to enable interlocking with the backfill material.

After backfilling the surface opening, the top layer of clay is installed in four 25 cm thick layers at a thickness of 1.0 m (on agricultural fields) or 0.5 m (on non-agricultural fields) and the surface is then weeded. The separating geotextile is laid on type 3 – clay cap boundary. The characteristic cross-section (blue line from Figure 6) is given on Figure 7.

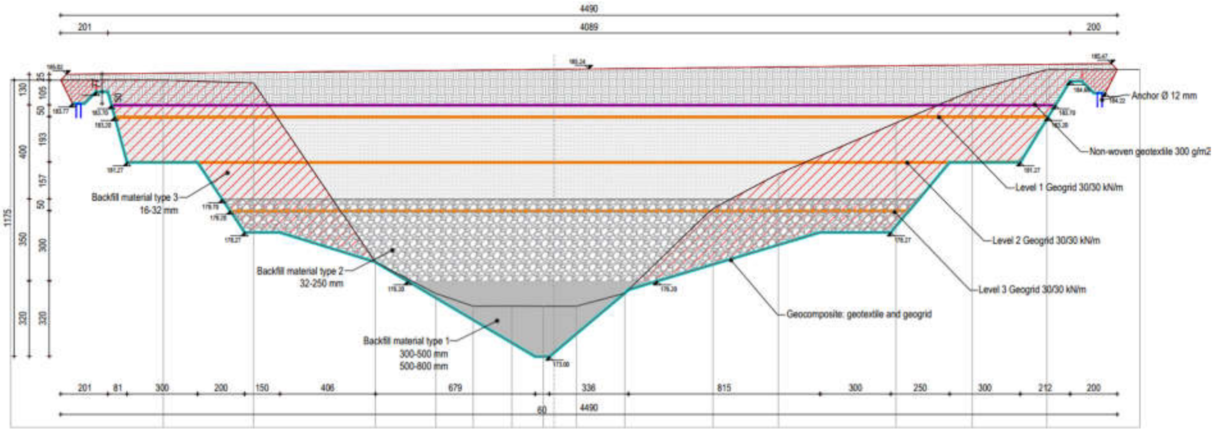


Figure 7. A cross-section of the remediation solution for UVM-001, modified from Brodska Posavina (2023)

4.2 Remediation works: phases and challenges

Due to its size (almost 50% of the volume of all the collapse sinkholes in the area) and complexity, the majority of the remediation work was focused on the largest collapse sinkhole, UVM-001. In order to carry out the planned work, the contractor started a trial water pumping operation to verify that the work could be carried out in dry conditions. It was found that water ingress was quite low due to the low permeability soil deposits. However, during this work, cracks appeared in the bottom of the sinkhole slopes and eventually slope sliding occurred, most likely due to the residual water in the soil reducing the shear strength and the loss of external water pressure, Figure 8. Slope sliding-induced sinkhole enlargement is depicted on Figure 6, compared to its initial size recorded just after the earthquake.

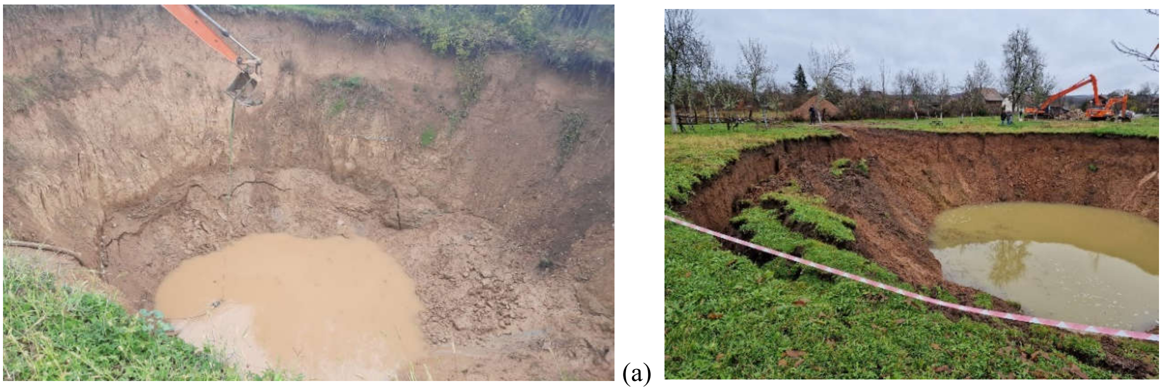

(a) (b)

Figure 8. Trial pumping of sinkhole water (a) and the consequent collapse of the sinkhole slopes (b)

Work on the largest sinkhole began with the slope reprofiling (Figure 9a) in May 2023 and was completed in July 2023. However, it should be noted that the preparatory work started earlier, as the access road for the heavy machinery had to be built, as well the temporary disposal areas for the backfill material and geosynthetics. In addition, the underground telecommunications cable that runs along the site had to be relocated. After the geocomposite was installed (Figure 9b), backfilling began with Type 1 material (boulders), followed by Type 2 and Type 3 material (Figure 10).

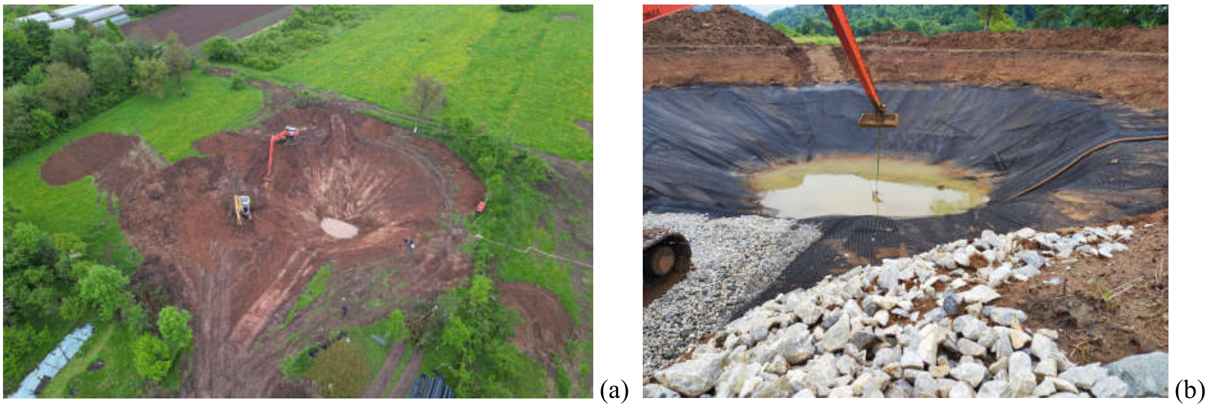

(a) (b)

Figure 9. Reprofilling of the sinkhole slopes (a) and installed geocomposite on the excavation area (b)

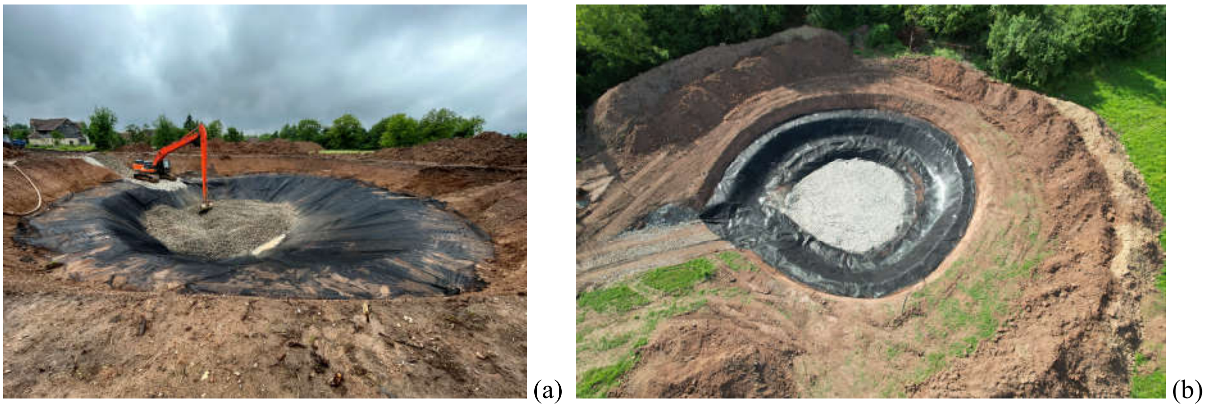

(a) (b)

Figure 10. Backfilling works using long reach excavator (a) and aerial view of material type 2 placed and compacted (b)

During the backfilling work, several heavy rainfall events occurred, which prolonged and made the remediation work more difficult. However, the combination of the compaction of the backfill material and the installation of geogrids (Figure 11a) provided a solid foundation for the work of the heavy machinery (Figure 11b). This can be also considered as a large-scale load test which verified design solutions since no problems occurred regarding excessive deformation or settlements of backfill material Finally, a clay cap was installed (Figure 12a).

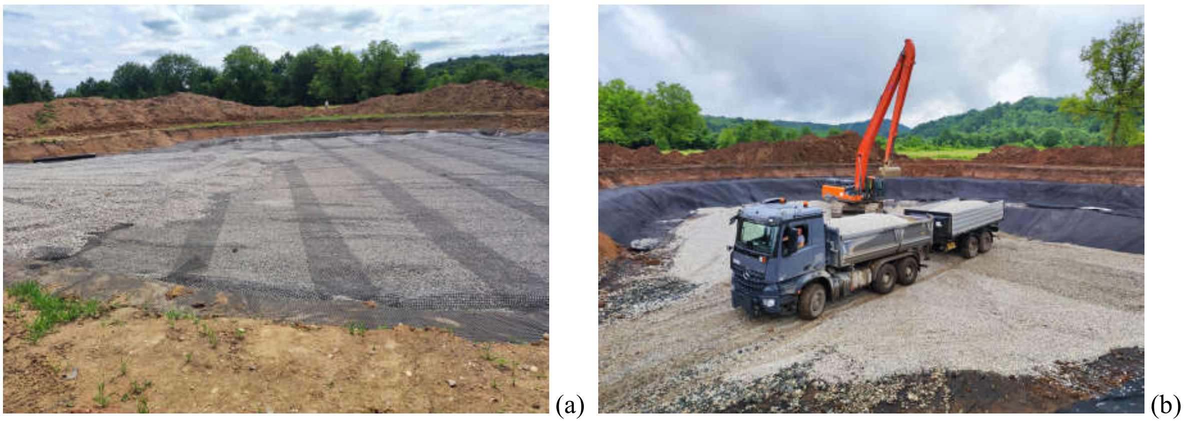

(a) (b)

Figure 11. Installed biaxial geogrids (a) and heavy machinery inside the sinkhole (b)

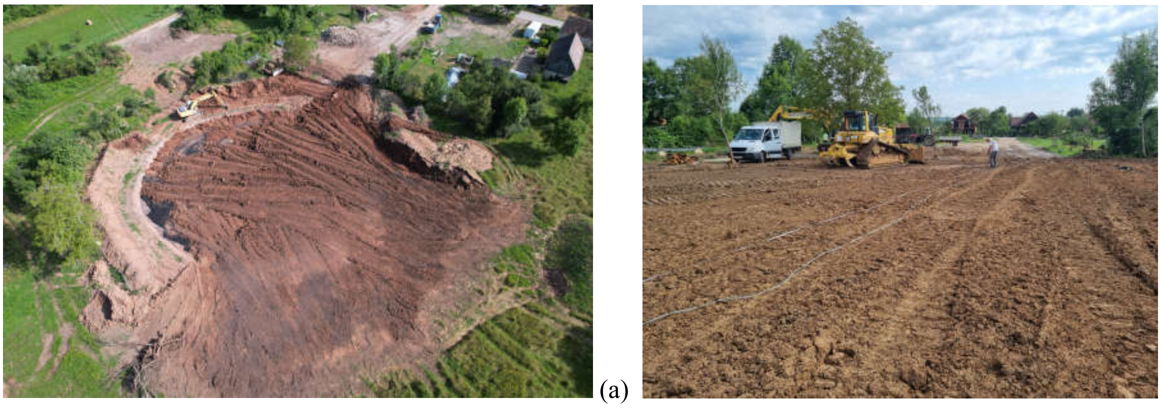
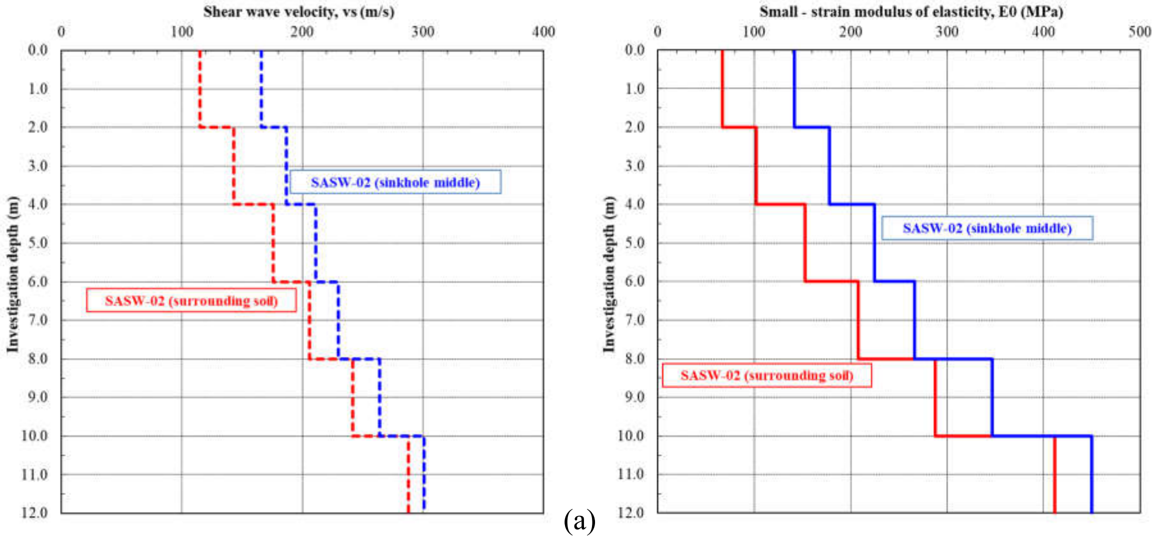

(a) (b)

Figure 12. Installation of final layer of clay cap (a) and the terrain surface after the remediation works with SASW control quality work being conducted (right)

Continuous supervision and control quality works have been carried out during the sinkhole remediation, which was particularly important given the many remediation phases and the large number of details. All the materials installed complied with the criteria set by the design. Quality control works were also carried out, including the plate load test to check the compaction of each layer and the geophysical method of spectral analysis of surface waves (SASW) to determine the stiffness over the entire backfill depth at the end of the work. Results of the one SASW profile, named SASW-02 (Figure 6), are shown in Figure 13. The required small – strain stiffness is higher than required by the design. It can be also seen that the backfill material (blue lines) exhibits larger shear wave velocities and small - strain stiffnesses than the surrounding soil (red lines) which is characterized by overconsolidated clayey materials. The monitoring network consisting of survey points was installed to measure the long-term settlement of the backfill material and this monitoring work will continue in the near future.



(a) (b)

Figure 13. Excerpt from results of one SASW profile showing shear wave velocities (a) and small – strain stiffnesses (b) of the backfill material and the overconsolidated surrounding clayey material (CFCE, 2023)

5 Conclusion

In Sisak–Moslavina County, during and shortly after the strong earthquake of December 2020, numerous collapse sinkholes appeared, leaving the authorities and the engineering community perplexed. Numerous investigations were carried out to determine their origin and assess the risk of new sinkholes occurring. The comprehensive efforts presented in this paper served to categorize sinkholes in order to identify remediation prioritizations. A detailed design for 102 sinkholes was developed, taking into account the specifics of the microsite, using the inverse filter method design solution, which consists of backfilling the sinkhole with materials of different grain sizes and incorporating geosynthetic materials. The remediation of sinkholes was a major challenge both in the categorization and design phase, as well during the remediation work, monitoring and quality control. All of these challenges required continuous collaboration between investors, designers, contractors and supervisors to successfully complete this project. In the end, the implementation of the remediation measures not only fulfilled the technical requirements set before the project itself, but also increased the level of safety for the population, agricultural land and infrastructure in this part of the Sisak – Moslavina County.

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