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Sinkholes induced by the Petrinja M6.2 earthquake and guidelines for their remediation

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Abstract

This paper proposes a remediation solution for the sinkholes appeared as a consequence of a devastating earthquake of 6.2 magnitude which hit Croatia in December 2020. At the time of writing this paper, more than 90 sinkholes in villages Mečenčani and Borojevići opened, all triggered by the main impact as well by the series of aftershocks, leaving both authorities and public, as well the professional – scientific community, in surprise. The sinkholes are identified as the cover collapse sinkholes, a most dangerous type of a sinkhole which collapses without any prior ground surface deformation. Owing to the fact that the conditions for the formation of these phenomena are in geological setting of this sinkhole prone area, characterized by the proluvial deposits underlain by the soluble karstic rock mass, the necessity of appropriate investigation works and remediation techniques is highlighted. Since the sinkholes are presumably well-integrated into the karstic conduit system of the aquifer, part of which is a water supply source Pasha's spring, the remediation techniques should rely on the permeable grained fills with minimized utilization of cement or chemical – based materials.

Key words: cover collapse sinkholes, Petrinja earthquake, karst, investigation works, sinkhole remediation, inverted filter method

1 Introduction

A strong earthquake of 6.2 magnitude hit Banovina region in Croatia on December 29th 2020, with the epicentre near the city of Petrinja. The main impact was preceded by two foreshocks of 4.7 and 5.2 magnitude, and followed by the series of aftershocks with the strongest one having the magnitude of 4.9. The main impact, along with the foreshocks and aftershocks, resulted in seven fatalities and devastating consequences for buildings and infrastructure. The earthquake-linked geotechnical issues at the site manifested as the ground dynamic instabilities, including the activation of many landslides, as well the liquefaction at large scale since several rivers cross the area and the overall geology is characterised by the saturated, poorly graded, sands and silty sands. In addition to these geo-hazards, another phenomena left the inhabitants, authorities, as well the engineering community, completely baffled. In the area south of the epicentre, mainly in villages Mečenčani and Borojevići, more than 90 openings, at the time of writing this paper, appeared on surface. Most of the openings appeared in the fields, such is the largest one having 25 m diameter and 12 m depth, Figure 1a, however some of them appeared in vicinity of buildings and infrastructure, Figure 1b.
The openings are soon identified as sinkholes, whose formation was not indicated by any ground surface deformation or subsidence, making them extremely dangerous. This lack of indicators, with the rapid increase of number of sinkholes in post-earthquake period, where the appearance of the new sinkholes occurs on daily basis, compelled the authorities to mark the region as high risk for its inhabitants.

Figure 1. Some of the sinkholes at the Mečenčani village: the largest sinkhole in field, from [1] (left) and one sinkhole in vicinity of houses (right)

Additionally, most of the formed sinkholes continuously expand, owing mostly to the progressive collapse of vertical and subvertical saturated slopes. The overall geology of the region, limited to the area of ≈10 km^2, is characterized by the karstic rock mass, hidden by the 5 – 15 m of proluvial soil, deposited in the past by the river Sunja passing through the region. The appearance of similar sinkholes in past is reported by the inhabitants, however never on such large scale and all of them being in fields, far away from houses. Inhabitants, mostly involved in agricultural activities, usually buried them when ploughing. Since the coexistence of such features occurred only in this specific sinkhole-prone region and not at large scale, unlike other types of geohazards such as landslides that are much more widespread, sinkhole risk awareness remained low until the recent earthquakes.

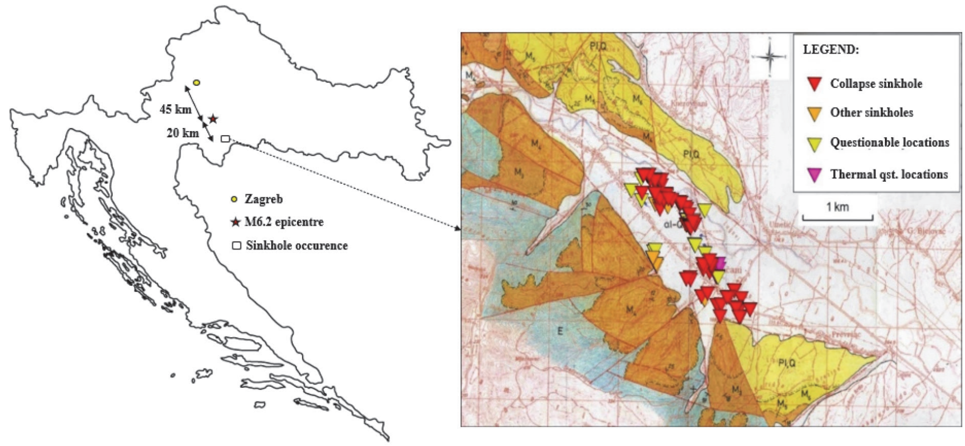

Figure 2. A geological map of the area, with positions of sinkholes, from [2]

There is an ongoing investigation work campaign, with the overall aim to identify the condition of subsurface on the location of existing sinkholes, but also to map the subsurface below crucial infrastructure and houses to assess the possibility of occurrence of new sinkholes. Investigations mostly rely on rapid geophysical methods with recent implementation of UAV thermal investigations, where the laser scanning methods are marked as useless since no prior ground surface deformation occurs. This paper contributes to the solution of a problem by presenting the potential remediation methods of these seismic-induced sinkholes, based on the domestic and international experience in remediating such phenomena. The focus is on methods which do not have negative impact on the hydrogeological complex karstic system, as the one that can be found on the location of case study area. In this sinkhole-prone region, the water source Pasha's spring supplies more than 1000 km^2 of area, and it relies on hydrological generosity of the karstic system.

2 The genesis of appeared sinkholes

Generally, the danger posed by sinkholes as karst related phenomenon is well known in the literature, where the sinkholes represent a major hazard causing substantial social and economic losses. By recognizing the necessity to tackle this hazard, geological and geotechnical community continuously organizes, starting from 1984, an international conference on ''sinkholes and the engineering and environmental impacts of karst''. In some regions of United States, the sinkholes are marked as hazard of highest risk. For example in period of 2006 to 2010, the Florida Office of Insurance Regulation [3] reported that insurers had received 24,671 claims for sinkhole damage in Florida between 2006 and 2010 totalling $1.4 billion.

Owing to the various geologic conditions and physical environments where they develop, each sinkhole is unique. However, based on their genesis, three types of sinkholes are usually distinguished, even though some studies of paleokarst [4] reveal that the development of sinkholes in evaporite karst terrains involves a wider range of processes. These sinkhole types include: (1) *solution sinkhole*, which develops as a result of karst rock solution and where the karst is exposed at terrain surface; (2) *cover-subsidence sinkhole*, which manifests as the concave depression on the terrain surface, where the underlaying karst rock mass, characterized by the discontinuities and voids, is filled with the overlaying sand particles, eventually leading to the settlement of the ground surface that is evident and usually no abrupt failure occurs; (3) *cover-collapse sinkholes*, where failure can develop in a short period of time. Since there is usually no, or little, surface deformation prior to collapse, the later type of sinkholes is considered as the most dangerous one and it is exactly this type of sinkhole that appears at the subject location.

According to [5], the cover-collapse sinkholes occur in the soil or other loose material overlying soluble karst bedrock, as shown on Figure 3. When the overlying soil is repeatedly wetted and dried, small amounts of soil are dislodged and carried away by the conduit draining the sinkhole (phase 1). As overlying sediment spalling continues, a structural arch is formed (phase 2) within the covering sediments, leading to progressive enlargement where the soil cavity arch migrates upwards (phase 3). If the overlaying material is stiff and overconsolidated, no visible indications in form of ground surface deformation is apparent. In this particular case, the earthquake of high intensity eventually caused the collapse of the arch material (phase 4), thus creating sudden and dramatic sinkhole phenomena.

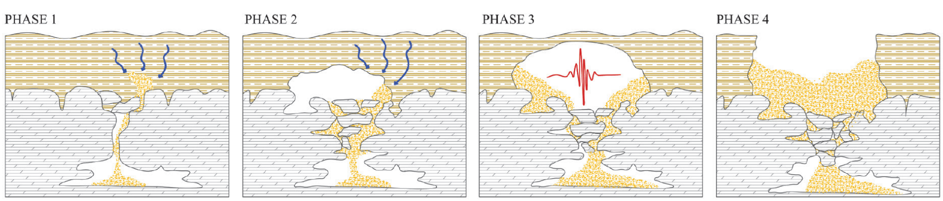

Figure 3. A probable development of the cover collapse sinkhole at the subject location, modified from [6]

Usually, the sinkhole formation triggers vary from natural (e.g. earthquake, heavy rains, droughts) to anthropogenic, which are mostly linked to the uncontrolled water leak into the subsurface, altering the natural water-drainage patterns and causing new waterways to develop. This is also observed in Mečenčani and Borojevići, since in vicinity of some sinkholes there are many human-caused irrigation sources that probably accelerated the karstification process. Thus, the preconditions of sinkhole formation already existed, and the strong intensity earthquake just accelerated the collapse. There are several reported cases in the literature where seismically induced stress changes triggered the collapse of unstable material above the bedrock [7,8].

3 Sinkhole characterization as a basis for remediation activities

Before the selection of an optimal sinkhole remediation method, a sinkhole characterization should be carried out. There are many studies dealing with the methods and techniques for the evaluation of a depth and extent of the subsurface anomaly. The investigation protocols are especially complex in karst, as noted by Bačić et al. [9], where multiple methods and data-gathering techniques should be utilized. The first step should include the analysis of existing data through consideration of existing geological maps and aerial photographs. The borehole drilling campaign should provide an information on the overall stratigraphy of the soil profile, where a CPT tests can be used as reliable alternative considering they are rapid and cheaper. However, considering the discrete nature of both drilling and CPT, the geophysical techniques come to fore since they can give crucial information on the extent of subsurface anomaly as they provide 2D and 3D images of a karst. The wide range of geophysical methods, which are somewhat interpretive, but are useful for providing relatively quickly a significant amount of data, can be used to design the final drilling and CPT program. Still, the most important tool for the investigation of a karst, as a notoriously difficult ground for subsurface imaging, is the knowledge and experience of the engineers conducting the investigation.
An interesting example of usefulness of geophysical methods in ground characterization is given by Bačić et al. [9], for a sinkhole of approximately 3 m in depth and of 10 m^2 aperture area, opened between two lanes of a national highway in Croatia, Figure 4a. This immediately alert the infrastructure managers to detect its origin and extent so that appropriate remediation measures be taken. One resulting refraction profile is shown in Figure 4b, where an area of reduced P- wave velocities is clearly visible between 30th and 45th meter in length and on 6th to 14th meter in depth. This is assigned to a bedrock cavity which caused collapse of surface material, Figure 3b. The overall geology of the site is somewhat similar to the geology of the Mečenčani and Borojevići area. Even though exact cavern dimensions are very difficult to obtain, seismic refraction provided a credible estimation of the approximate size of a cavern, providing the valuable information for the subsequent remediation works.

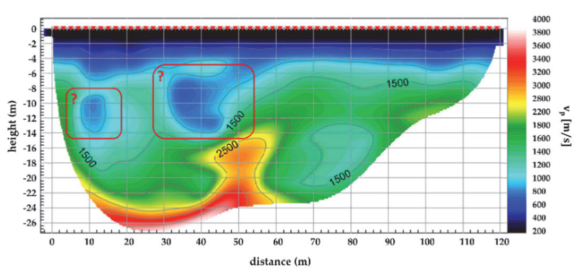

Figure 4. A sinkhole between the Rijeka – Zagreb highway lanes (left) and one seismic refraction profile (right), from [9]

However, the question arises on the identification of potential cover collapse sinkholes, yet not formed, but where the preconditions for their development are present. This is extremely challenging task, in which the topographic and geodetic information are of limited usability, due to lack of surface deformation prior to the collapse. Here, a carefully planned geophysical campaign should be of uppermost importance, with the priority given to the zones where human activity is increased. An UAV with thermal camera can be also useful for the detection of early sinkholes [10]. By no means should the experiences of the local residents from sinkhole – prone area be neglected, since these information may substantially improve the understanding of the past spatial and temporal distribution of non-registered and/or filled sinkholes.

4 Sinkhole remediation techniques

The only guaranteed method of avoiding the negative impact of cover collapse sinkholes for inhabitants, buildings and infrastructure, is to prevent living on a karstic terrain where such phenomena can occur. However, this may be impractical for series of reasons. In high density populated areas, such are the many regions of USA, this would mean relocation of population at large scale. For the area of Mečenčani and Borojevići, affected by the cover collapse sinkhole occurrence, the population density is not so high, but most of inhabitants depend on the family-run farms which benefit from the wide agricultural fields. The history remembers cases where whole villages had to be abandoned [11] due to formation of 157 number of sinkholes triggered by blasting during engineering works. Richardson [12] stresses out some of the preventive measure which may be applied prohibiting or limiting development in the most hazardous karst areas through land use planning and regulations. However, implication of relocation is a multi-layered issue and this is out of the scope of the paper, which focuses on the possible sinkhole remediation techniques. While the collapse sinkhole genesis and the assessment techniques and protocols are well known, the remediation techniques require specific approach, mostly due to complex nature of karst, as an extremely challenging environment from geotechnical engineering point of view. As Nwokebuihe [13] notes, there are no clear-cut methods for sinkhole remediation and every sinkhole is unique and requires peculiar treatment.

Zhou and Beck [14] conclude that the selection of specific method, or combination of methods, used to remediate sinkholes depends on many factors such as the subsurface conditions (or geological model), accessibility for remediation equipment, the land-use after remediation, as well the available funding. Foremost, when considering the remediation of the sinkholes in karst, an engineer should be aware of the sensitivity of karstic groundwater systems. Two aspects of cover collapse sinkhole remediation should be addressed:

- treatment of the voids and fractures within the bedrock, as well the treatment of the sinkhole 'throat', as a column (channel) connecting the bedrock anomaly with surface opening, and the through which the material collapsed;
- filling of a surface opening with appropriate material, after the throat has been plugged.

One of the often-used techniques is the compaction grouting. The method requires drilling holes into the substrate and then pumping and filling the voids with grout mixture, followed by the plugging of a throat as well the stabilization of the soil above the bedrock. However, there are many downsides of using this technique, especially when it comes to karst. The grouting procedure may be hazardous since grouting can actually trigger the sinkhole to activate and cause further damage. Further, strong argument against the grouting methods is their potential influence on the karst groundwater flows, since there is practically no guarantee that the method won't interfere with the non-uniform, unpredictable, flows in karst aquifers, in which water moves primarily through conduits formed and enlarged by bedrock dissolution along pre-existing openings. To check if the sinkhole is well-integrated into the karstic conduit system of the aquifer, a dye-trace studies, such as given by Hunt et al. [15] can be conducted prior to the remediation to identify the path, velocity, and destination of groundwater in a karst setting. Therefore, any technique which involves cement or chemical – based materials should be avoided or at least minimised when remediating a karst surrounding. Finally, engineers generally disfavour the grouting methods due to lack of existing methodologies to evaluate or to analyse the remediation. Considering all the drawbacks of the compaction grouting in karst, the only reliable solution would include plugging of a throat and filling of the surface opening.
To plug the sinkhole throat, it should be firstly exposed, if possible, and cleaned up for any fine-grained particles. Excavation and throat plugging is the simplest way to remediate an existing sinkhole, especially in rural areas, where there is enough space to expose the throat by simple excavation. Zhou and Beck [14] suggest a plug of rock or stones, concrete blocks or grout of 1.5 times the width of the throat. If the sinkhole does not have an obvious throat, but consists of many discrete fractures, these can be blocked by dental infill grout, where the pockets are filled with high/low slump flowable fill to plug and cap the fractures, or bridge bedrock voids. However, an issue of using cement-based material remains. Rather than using a cement – based material, many engineers prefer the graded-filter technique, in which the hole is filled with a layer of boulders, followed by the layer of smaller rocks, and, finally, a layer of gravel. This technique is called inverted filter filling, Figure 5. A graded-filter material allows the continuation of the natural drainage of water.

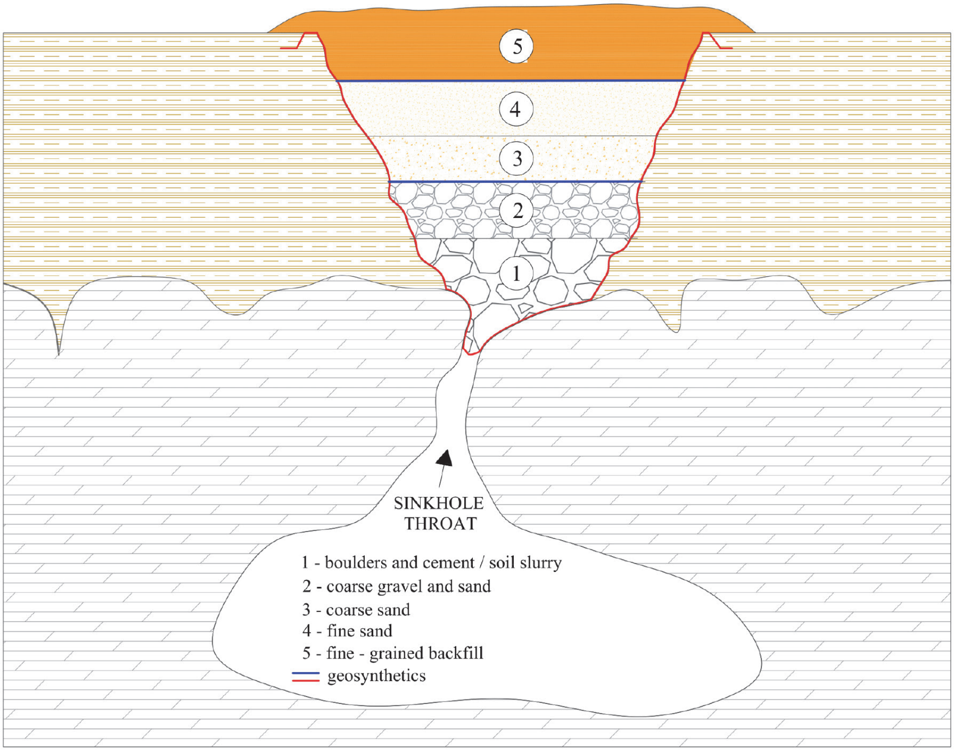

Figure 5. Remediation of a sinkhole by using inverted filter filling technique

The technique comprises the backfilling of a sinkhole including blocking of the throat of the sinkhole with rockfill and/or boulders, Figure 6a, possibly in combination with sandy or gravel material with addition of 3 % to 5 % cement and water, followed by the installation of upper layers, each having finer particles than the one below him. If the filling material is compacted, as suggested by some authors, it would be necessary to provide a proper geometry and angle of the slopes. However, such slope re-profiliation and compaction require additional efforts, and if the sinkhole has loose sides, access by heavy machinery could also trigger a wider collapse. Some of the finer layers can be also stabilized with 3 % to 5 % cement. Even though a sinkhole provides a convenient place to deposit trash, this should be avoided since any contaminants disposed of in sinkholes may end up in caves, springs, and water wells in the area of the sinkhole.

Geosynthetics can be also used to improve the effectiveness of the remediation solutions, and it was successfully used in some previous works [14, 16]. Geotextiles or geogrids are sometimes used to line the base and walls of the sinkhole and to retain the material above the throat of the sinkhole, Figure 6b. They can also support layers within the lower and top selected fill layers [14], to improve to improve load distribution on softer overburden material left in place on shallow overburden strata.

Figure 6. Bulldozing chunk rock into the throat of a large subsidence sinkhole, from [17] (left); installation of the geotextile to line the base and walls of the sinkhole, from [18] (right)

After the surface opening is filled, it is recommended to cap the sinkhole by a clay layer about 0.2–0.5 m below the planed surface to further prevent water percolation, as well to seed the area to reduce soil erosion. Controlling the surface drainage is critical to proper sinkhole remediation, so additional measures can be applied, such as making the surface impermeable with geomembranes.

Another technique can be used if the building is to be constructed atop of a sinkhole, and this includes underpinning the building by driven or drilled steel, wood, or concrete piles, for which the adequate design should be made. This method is not directly linked to remediation of a sinkhole but rather relies on the transfer of loads to the identified bearing layers of bedrock.

5 Conclusions

More than 90 cover collapse sinkholes appeared in area of villages Mečenčani and Borojevići in Croatia, after the strong earthquake of 6.2 magnitude and series of aftershocks which hit the region during December 2020. Being the most dangerous type of sinkholes, since no prior indication of any ground surface deformation or subsidence before the collapse, a necessity arose for proper investigations to determine the depth and extent of karst subsurface phenomena which caused the collapse of overlying material. The subsurface characterization campaign should rely mostly on geophysical investigations, supplemented with borehole drilling or alternatively CPT tests. Based on investigation works, a proper remediation technique should be selected. Since cement or chemical-based material should not be used in karstic terrain either for void filling or for stabilization, due to possible interference with the non-uniform, unpredictable, flows in karst aquifers, a remediation should incorporate implementation of so-called inverted filter filling technique. This technique utilizes rockfill and/or boulders to plug the throat of the sinkhole, followed by the backfilling of a sinkhole using graded-filter materials which allow the continuation of the natural drainage of water. To improve the effectiveness of remediation, incorporation of geosynthetics is recommended to line the base and walls of the sinkhole and to retain the material above the throat of the sinkhole, as well to support layers within the lower and top selected fill layers. Considering the unpredictable nature of this hazard, a careful selection of investigation and remediation techniques is of upmost importance.

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