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Numerical modelling of cover-collapse sinkholes caused by the earthquake – a case study

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ABSTRACT

After a MW 6.4 earthquake occurred on December 29, 2020 in Petrinja, Croatia, over 100 cover collapse sinkholes appeared in a small 1 km^2 area in a period of several months after the event. In the beginning of 2021, a geotechnical reconnaissance and a limited geotechnical subsurface investigation was performed. The existing geological and hydrogeological data were analysed, and the geometry of sinkholes was recorded. Two geotechnical boreholes, in-situ geotechnical characterization and standard penetration tests were performed close to the biggest sinkhole, followed by a laboratory testing of physical, index and design properties. All the collected data showed that there was a specific geological setting on this microsite. A typical soil profile for the biggest recorded sinkhole was developed and used for the numerical analyses to examine the possible failure mechanisms and to perform the parametric analyses for determining the effects of depth and geometry of the existing underground caves and soil properties on the cover-collapse sinkhole formation.

Keywords: karst, cover-collapse sinkhole, earthquake, numerical modelling, failure

1 INTRODUCTION

Cover-collapse sinkholes can be found throughout the world in certain geological settings characterized by thick deposits of relatively firm cover soils over weathered karst bedrock that contains well-developed fractures or cavities. The presence of voids and fractures in the bedrock, groundwater circulation, earthquakes or anthropogenic activities such as mining or groundwater pumping are considered as possible causes for their formation. Groundwater oscillations and flow are considered to cause gradual underground erosion and enlargement of cavities, finally leading to the reduction of the arching stability and failure of cohesive cover layers. Cover-collapse sinkholes are characterized by steep, vertical or subvertical side walls. More significantly, such collapse of cover soil materials into the existing underground caves happens suddenly, without any visible features at the ground level prior to the collapse (Drumm & Yang, 2005; Tharp, 1999; Salvati & Sasowsky, 2002).

On December 29, 2020, a strong earthquake (Mw 6.4) occurred close to the city of Petrinja in of Croatia (Figure 1). Typical post-seismic phenomena such as liquefaction, landslides, destruction or damages on buildings, roads, and embankments appeared in the wider area. Unexpectedly, in a much small area (approximately 1 km^2) cover-collapse sinkholes appeared as well. The sinkholes differed in size (diameters from less than 1 m up to 25 m) and depth (from 0.2 m to more than 11 m), but most of them had (sub)vertical side walls and their growth to the final size was very fast (Tomac et al. 2022).

Since more than a 100 cover-collapse sinkholes developed in a small area during several months after the mainshock, this phenomenon received great interest in the scientific and professional community. However, it was not an easy task to organize in-situ investigation immediately after the mainshock, as numerous aftershocks were recorded in the following months, causing many safety and organizational issues. Among others, it was difficult to mobilize the in-situ testing equipment; experts were mainly involved in determining the consequences of the earthquake on the buildings, public water supply, roads and other infrastructural objects etc. Despite all these problems geological, hydrological and geotechnical investigations were conducted in March 2021 in the area with intensive sinkhole development around the villages Mečenčani and Borojevići (Tomac et al. 2021a, 2021b, 2022). In Figure

1 the locations of the earthquake epicentre and the biggest cover-collapse sinkhole are marked, showing their relative distance of about 20 km. The results of field and laboratory investigations will be presented further on in the article just for the location of the biggest cover-collapse sinkhole.

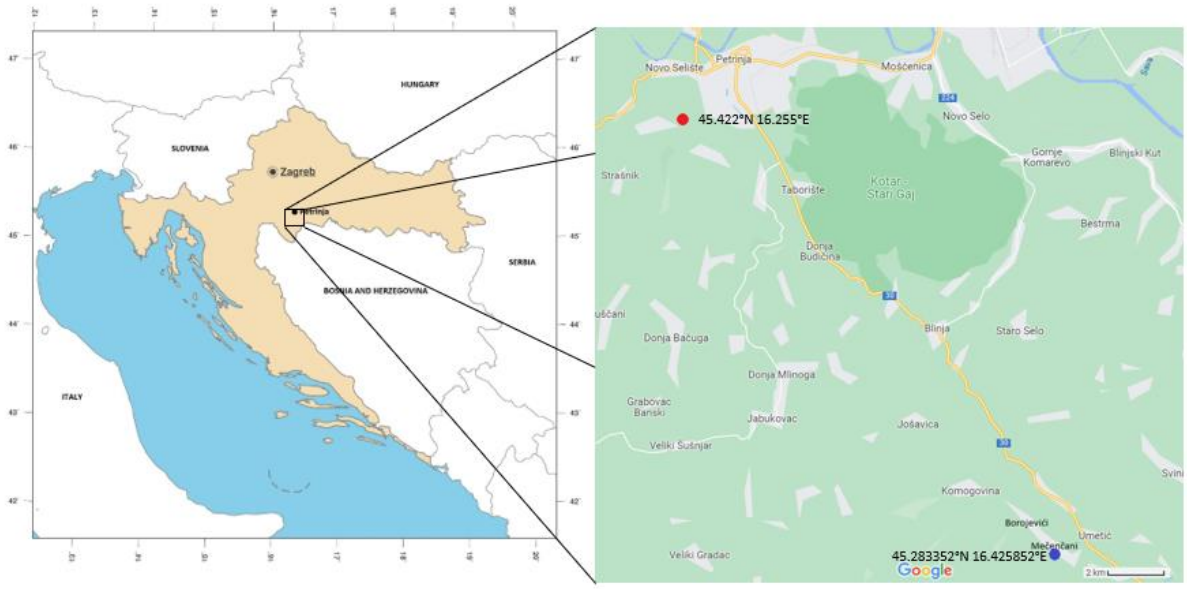


Figure 1. *Map of Croatia with Petrinja municipality (left). Detailed map with earthquake epicenter (red dot) and of the biggest cover-collapse sinkhole (blue dot) position (right)*

The typical soil profile near the biggest recorded sinkhole was used for the numerical analyses. Numerical calculations were performed in PLAXIS 2D to examine possible failure mechanisms and analyse the effects of depth and geometry of natural caves existing in highly karstified limestone bedrock, as well as cover soil properties on the cover-collapse sinkhole formation. Given the limited time and resources for the field work, and poor availability of historical data, especially related to groundwater conditions, the results of numerical calculations that are presented in this paper, can only be considered as preliminary. Their purpose is to improve the understanding of processes leading to sinkhole collapse, enable a better preparation of future investigation and propose some steps needed for the risk assessment in similar geological settings and occurrences. It is not only important for similar future seismic events that are probable in the area, but also in case of constructing buildings, roads, municipal water wells and other facilities or performing agricultural works in that area.

2 FIELD INVESTIGATIONS AND SUBSURFACE PROFILE

A detailed overview of field and laboratory investigations carried out during 2021 is presented by Tomac et al. (2021a, 2021b and 2022). Close to the biggest cover-collapse sinkhole (diameter 25 m, depth around 12 m) in the Mečenčani village (Figure 2), two geotechnical boreholes (B1 and B2), in-situ geotechnical characterization and standard penetration tests were performed, along with laboratory testing of the physical, index and design properties. The obtained results were used to develop the characteristic soil profile and gather input parameters for the numerical analyses.

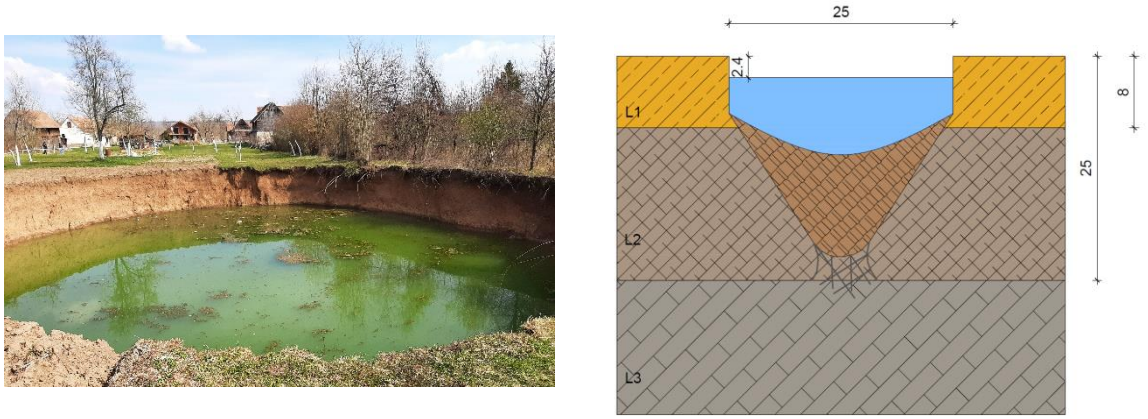


Figure 2. *The biggest cover-collapse sinkhole opened in Mečenčani village (left). Assumed vertical cross-section with borehole positions (right)*

The boreholes were drilled to the depth of 8.0 m (B1) and 7.6 m (B2) by manually driven solid stem auger. Further advancement of the auger was impossible as very stiff marly clay (B1) or increased content of gravel size particles (B2) were found at the bottom of the boreholes. It was assumed that the contact between the soil cover and the weathered limestone was reached at that point. Geophysical explorations showed that bottom limestone can be further divided into two zones: highly weathered (roughly from the depth of 8 to 25 m) and solid (from the depth of 25 m). Presumably that contact line (at the depth of about 25 m) represents also the bottom line of the existing cavern. It was also assumed that the cavern has a funnel shape within the bottom limestone and a semi-circular (arch) shape within the soil cover. The total volume of the initial cavern was calculated on the basis of the observed elevations of crushed materials after the collapse happened (schematically shown in Figure 2 right).

Clayey soil cover is classified as sandy lean and fat clay (CL/CH) to the depth of 4 m, followed by lean clay and lean clay with sand (CL) below the depth of 4 m to the final depth of the boreholes. Sporadic gravel and sand lenses were found in both boreholes. Geological investigations show that the area belongs to heavily karstified Miocene limestone basement rock covered by 4-15 m thick Holocene deluvial-proluvial deposits of clays interlayered with lenses of gravels and sands (Tomac et al. 2022). The ground water table (GWT) was detected in boreholes at depths of 4.7 m (B1) and 4.0 m (B2). Gradually, the GWT stabilized at the depth of 2.4 m in both the boreholes and the adjacent sinkhole.

The hydrological investigation showed that the unconfined aquifer within the soil cover is underlain by a well-permeable confined karst aquifer in which water pressure becomes sub-artesian to artesian in some circumstances. Moreover, these two aquifers are hydraulically connected, thus enabling underground erosion and formation of caves and caverns at the soil-limestone contact. Unfortunately, a GWT observation network is not established in the area, and it is difficult to estimate seasonal GWT fluctuations or pore pressure changes during the earthquake.

The biggest cover-collapse sinkhole was spotted one week after the mainshock. Its initial diameter was approximately 15 m, gradually increasing to a final diameter of 25 m over the next several months. The specific geological setting, circulation of underground water between the two aquifers and the earthquake as a trigger mechanism are considered to be the main factors affecting the intensive cover-collapse sinkhole formation within the investigated area. However, the interaction between the specific geological setting, hydrological conditions, variability of cover soil properties due to GWT oscillations and precipitations, and seismic loading have yet to be investigated.

3 NUMERICAL ANALYSES

Numerical calculations were performed in PLAXIS 2D on two models (Figure 3). Model 1 represents the idealized circular shape of a cavern, half of which is placed into the cover soil and the other half into the bottom limestone. Only the biggest circular cavern (Figure 3 left) is intentionally made different for comparison with Model 2 (Figure 3 right). Model 1 was used to perform a parametric study for different depth/diameter (h/D) and cohesion/vertical stress ratios. Model 2 represents the assumed shape of a real cavern existing in the underground prior to the formation of the biggest cover-collapse sinkhole. The

circular cavern with the largest diameter (see Figure 3 left) has the identical volume and depth as the assumed real cavern (see Figure 3 right).

Numerical analyses were performed in PLAXIS 2D using the axisymmetric model. The Hardening Soil (HS) model was used for the cover soil material (L1-layer 1) and the Mohr-Coulombs (MC) model for the bedrock limestone materials (L2-layer 2 and L3-layer 3). The groundwater level was defined at 2.4 m below the ground surface (as observed during field investigations, see Figure 2) i.e., a simple hydrostatic pore pressure distribution was assigned in all calculations.

Data collected from the laboratory and field work were used to create the numerical model. Input parameters for numerical calculations are summarized in Table 1. They were partly obtained by laboratory testing of samples from boreholes B1 and B2, and partly from the previously published data or archives made available by construction companies.

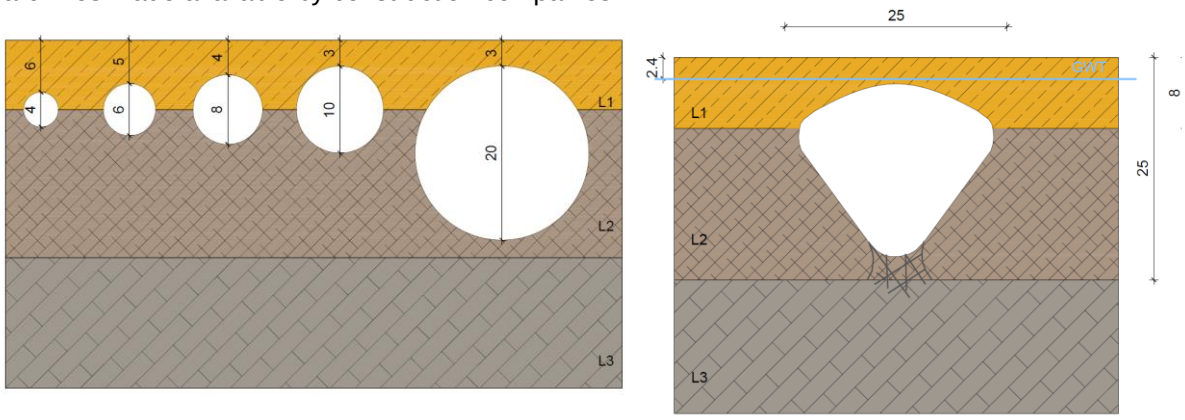


Figure 3. *Model 1 – idealized circular cavern (left). Model 2 – assumed real cavern (right)*

In all calculations, only half of a model was used for the mesh generation, the dimensions of a model were much larger than the opening, and the mesh was locally refined close to the opening. In the first phase the initial stress state was obtained without the underground cavity; this cavity was created in the second phase of the calculations. The plastic calculation was then performed until a stable roof was obtained providing the soil strength parameters by back calculation. It was followed by safety calculations until the cavern roof failure was reached. In the following sections, only some selected results will be shown for both numerical models.

Table 1. *Input parameters for the numerical models.*

Layer/Input data	**c [kPa]**	**φ [°]**	**E_s [kPa]**	**E_{oed} [kPa]**	**E_{ur} [kPa]**	**ν_{ur} [-]**
L1 - cover soil (HS)	80	30	8×10^4	8×10^4	24×10^4	0.3
L2 - weathered limestone (MC)	1300	35	1.6×10^5	-	-	0.3
L3 - solid limestone (MC)	2500	40	7×10^6	-	-	0.25

The results of numerical calculations for Model 1 are presented in more detail only for the largest circular opening, thus enabling the comparison with the results for the real cavern. Vertical displacements for the plastic calculation and both models are shown in Figure 4 and for safety calculation in Figure 5. Figure 6 shows the unstable zone in the cavern roof. By comparing the results for Model 1 and 2, with the same volume of the cavern, but a different shape (circular vs non-circular), it can be concluded that vertical displacements are much higher for the non-circular cavern due to different stress distributions. Stable and unstable zones are divided by an almost vertical line which largely corresponds to the observed vertical walls of the cover-collapse sinkholes in the field. Moreover, for the non-circular cavern the tension cut-off mode of failure prevails, as it is expected in brittle cohesive materials, such as over-consolidated clays found close to the modelled cover-collapse sinkhole.

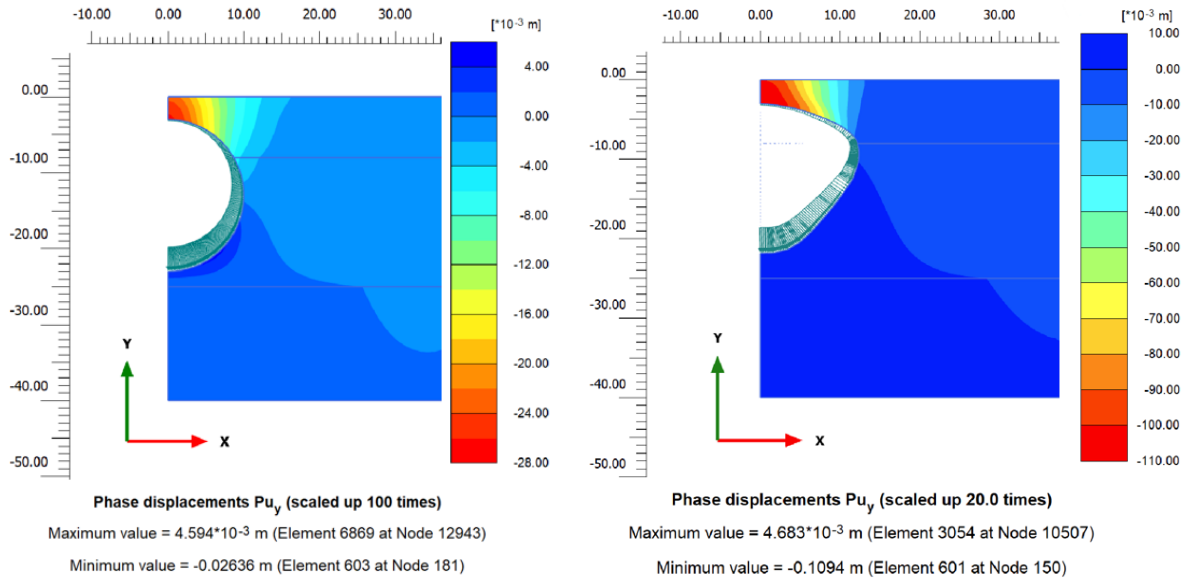


Figure 4. *Plastic calculation – vertical displacements: Model 1 (left), Model 2 (right).*

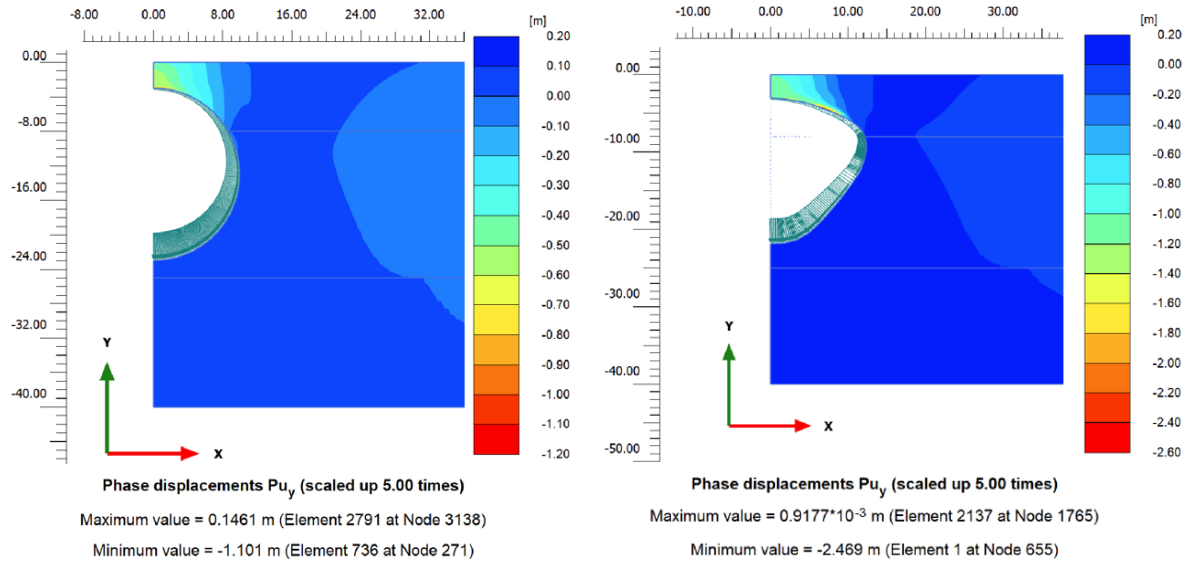


Figure 5. *Safety calculation – vertical displacements: Model 1 (left), Model 2 (right).*

The summary of numerical results for the parametric analyses for five different h/D values (see Figure 3 left) and various cohesions of cover soil in relation to vertical stress are shown in Figure 7 by expressing the safety factor. This diagram is obtained for precisely determined geometries of the problem (h/D) and specific parameters (in this case cohesion varied from 20-80 kPa, and unit weight kept constant). However, the diagram shows the increase of safety for higher h/D and cohesion, and lower vertical loading, as expected. According to the research by Nam et al. (2018), it is advisable to use Fs=2 as a threshold value. If the factor of safety is less than 2, than sinkhole collapse can be achieved. In contrast, for a factor of safety larger than 2, sinkhole collapse is not probable.

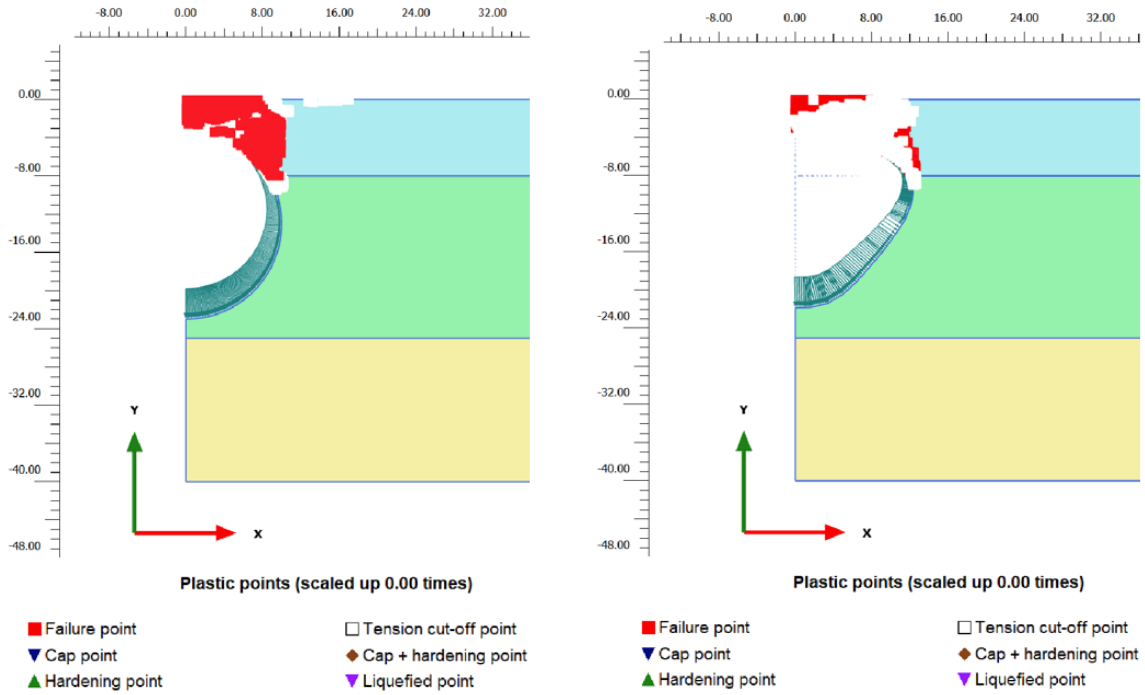


Figure 6. *Safety calculation – failure points: Model 1 (left), Model 2 (right).*

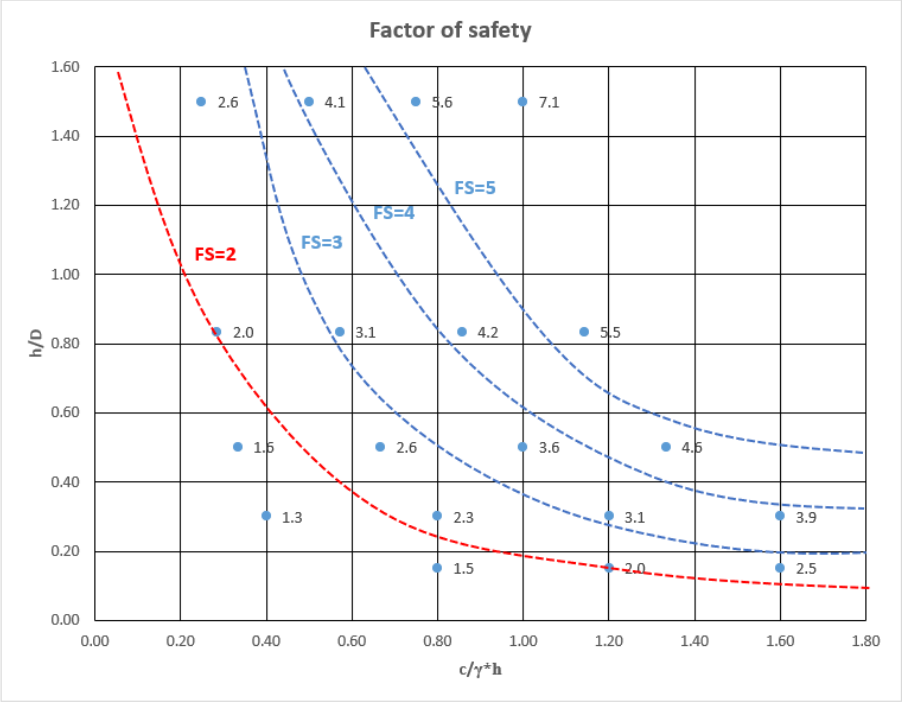


Figure 7. *Safety chart.*

4 CONCLUSIONS

In karst terrains, where highly karstified bedrock limestone is underlying the relatively thick competent soils, sudden cover-collapse sinkholes may develop in certain circumstances. These circumstances could be of natural origin, such as heavy rains or earthquakes. Equally, sinkholes may be triggered by anthropogenic causes, such as increased pumping of underground water, agricultural activities, or additional loading due to the construction works.

Cover-collapse sinkholes develop suddenly, without visible features on the surface. Because of that material damage can be significant. Cover-collapse is related to the arching (in)stability of cover soils, so that it is advisable to estimate their thickness and properties, as well as the size and depth of cavities in underlying limestone bedrock in order to perform risk assessments.

On December 29, 2020, a strong earthquake (Mw 6.4) occurred in Croatia. Besides the typical post-seismic phenomena such as liquefaction, landslides, damages on buildings, roads and embankments, surprisingly over 100 cover-collapse sinkholes appeared in a small area. A few months later (March 2021) geological, hydrological and geotechnical investigations were conducted showing that the investigated area is characterized by a high susceptibility to cover-collapse sinkhole formation.

The results of the investigation were used for the development of a characteristic soil profile at the location of the biggest cover-collapse sinkhole and input parameters necessary for the numerical modelling. Numerical calculations were performed in PLAXIS 2D. Two models were developed: Model 1 for the idealized circular cavern and Model 2 for the assumed real cavern. Given the limited time and resources for the field work, and poor availability of historical data, (especially related to groundwater conditions), the results of numerical calculations can only be considered preliminary. In this phase only static analyses were performed, and a simple hydrostatic pore pressure distribution was assigned in all calculations. Other scenarios should be modelled in future as well.

Plastic and safety calculations were performed in PLAXIS 2D. By back analysis for the case of a collapsed sinkhole, and calculated volume of pre-existing cavern, the cohesion of cover soil was estimated. It was observed that in all models stable and unstable zones are divided by almost a vertical line, which largely corresponds to the observed shapes of the cover-collapse sinkholes in the field. In the analyses of the non-circular i.e. real cavern, the tension cut-off mode of failure prevails, as it is expected in brittle cohesive materials, such as over-consolidated clays found close to the modelled cover-collapse sinkhole.

Safety calculations were performed for various geometries (depth and diameter of caves) and cohesions of cover soil in relation to vertical stresses resulting in a safety chart. Once established, the safety chart represents a very useful, easy-to-use tool for the preliminary risk assessment, even at the local administrative level. It is not only important for future seismic events but also in case of constructing buildings, roads and other facilities or performing agricultural works in the area prone to cover-collapse sinkhole failures.

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REFERENCES

Drumm, E.C., Yang; M.Z. (2005). Preliminary Screening of Residual Soil Stability in Karst Terrain. Environmental & Engineering Geoscience, XI(1), 29-42.

Nam, B.H., Shamet, R., Soliman, M., Wang, D. & Yun, H-B. (2018). Development of a sinkhole risk evaluation program. Final Report, FDOT, 147 pgs.

Salvati, R., Sasowsky, I.D. (2002). Development of collapse sinkholes in areas of groundwater discharge. Journal of Hydrology, 264, 1-11.

Tharp, T.M. (1999). Mechanics of upward propagation of cover-collapse sinkholes. Engineering Geology 52, 13-33.

Tomac, I., Kovacevic Zelic, B., Peric, D., Domitrovic, D., Stambuk Cvitanovic, N., Vucenovic, H., Parlov, J., Stipcevic, J., Matesc, D., Matos, B., & Vlahovic, I. (2022). Geotechnical reconnaissance of an extensive cover-collapse sinkhole phenomena of 2020–2021 Petrinja earthquake sequence (Central Croatia). Earthquake Spectra, 0 (0), 1–34, doi:10.1177/87552930221115759

Tomac, I., Salkovic, I., Kovacevic Zelic, B., Domitrovic, D., Vucenovic, H., & Hrzenjak, P. (2021a). Complementary Geotechnical and Geophysical Investigation Works. In: Tomac, I. and Zlatović, S. (eds.): Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake and Associated Seismic Sequence – A report of the NSF-Sponsored Geotechnical Extreme Event Reconnaissance Association, pp. 164–196. Retrieved February 25, 2023, from http://www.geerassociation.org

Tomac, I., Vlahovic, I., Parlov, J., Matos, B., Matesic, D., Kosovic, I., Pavicic, I., Frangen, T., Terzic, J., Pavelic, D., Pham, N. (2021b). Cover-collapse sinkholes. In: Tomac I and Zlatović S (eds.): Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake and Associated Seismic Sequence – A report of the NSF-Sponsored Geotechnical Extreme Event Reconnaissance Association. 52–99. Retrieved February 25, 2023, from http://www.geerassociation.org