Hybrid-approach for sinkhole occurrence risk mitigation in urban areas

A A Malinowska1 A Guzy1 R Hejmanowski1 P. Ulmaniec2
1 AGH University of Science and Technology. Faculty of Mining Surveying and Environmental Engineering, Al. Mickiewicza 30, 30-059 Cracow, Poland
2 Wieliczka Salt Mine, Park Kingi 1, 32-020 Wieliczka, Poland
e-mail: amalin@agh.edu.pl; pawel.ulmaniec@kopalnia.pl

Abstract. Presented research focused on the development of a novel methodology for sinkhole risk assessment above shallow caverns in a salt mine. The research was carried out for the Wieliczka Salt Mine, which is registered on the UNESCO list and visited by near around 2 million tourists every year. The main assumption of the investigation was to estimate root cause of sinkhole occurrence on the surface. Based on the arch pressure theory the vertical stress in the roof of salt caverns was established. Constructed three-dimensional model of underground mine allowed to determine the stresses between the caverns. Furthermore, the caverns which were hazarded by roof collapse were indicated. Hybrid solution was supported by multicriteria risk analysis based on Analytic Hierarchy Process carried out in Geographical Information System. Spatial analysis led to the identification of caverns potentially influenced by other risk factors. Developed final risk maps were based on four the most significant risk factors leading to sinkhole occurrence. Vulnerability maps developed with support of Analytic Hierarchy Process indicated areas where habitants and infrastructure are exposed to sinkhole occurrence. Merging risk maps with vulnerability maps led to final hazard map, where urban areas susceptible to sinkhole occurrence were shown. In conclusion, the research carried out proved that combined spatial analysis with theoretical solution may pave the way for reliable sinkhole risk assessment above shallow caverns.

1. Introduction

In 1960 a sinkhole over 100 m in diameter occurred as a consequence of collapse of the salt cavern in the Wieliczka Salt Mine. As a result two houses were completely destroyed. The sinkhole was formed within 15 minutes. Similar events take place all over the World, frequently causing danger to urban public space. The problem of sinkhole-prone caverns is extremely complex and despite many years’ investigations has not been satisfactorily solved yet. It is known that old and shallow caves have to be backfilled, though it is not known in what sequence. Moreover, such salt mines as Wieliczka are World’s heritage, therefore their preservation and maintenance for future generations is one of the priorities. On the other hand, security measures must be taken to provide safety for the citizens of Wieliczka with the oldest part of the mine under the town centre.

The course of deformation process in the salt rock mass is influenced by geomechanical properties of various types of salt present in the Wieliczka Salt Mine and also a number of mining and geological factors being potential causes of sinkhole-formation. Studies presented in this paper are focused on determining the most important risk factors responsible for the formation of weaker zones in the rock
mass and, consequently, opening ways to the formation of caving processes. In the past, most of evaluations of the risk of sinkhole formation concentrated on empirical solutions or numerical geomechanical calculations [1-4]. However, those methods turned out not to be fully reliable for a number of reasons:

- strength tests cannot reflect so strongly variable properties of the rock mass composed of several types of salt deposited in strata of various geological origin;
- numerical models can neither account for changing tectonic conditions in the rock mass, nor interrelations between caverns and inter-cavern beams in the mine’s rock mass;
- empirical models simplify the geometrical model of the caverns, without accounting for interrelation of caverns in the rock mass.

Critical approaches to previously applied methods of estimating the sinkhole risk inspired the concepts presented in this paper. It was stated that the sinkhole risk evaluation methods should be principally based on the spatial analysis encompassing the present technical state of caverns, mutual bedding, applied exploitation systems and interrelations between the caverns. Application of Geographical Information System (GIS), as well as Analytic Hierarchy Process (AHP) in order to gather all information regarding geological, mining, hydrological conditions in mine, and factors related to urban development, supported analysis of zones prone to sinkhole occurrence. Presented solution significantly improved sinkhole risk mitigation in Wieliczka town. Geographical Information System also supported safety management of historical UNESCO object.

2. Geological and mining conditions of urban area

Over twenty sinkholes took place during the mine’s life. Sinkholes formed in the study area varied in their range. One of the biggest ones destroyed the Małdrzyk cavern in 1582, and 25 buildings on the surface.

The formation of sinkholes in Wieliczka town can be mainly attributed to:

- bad technical state of roof and pillars;
- poor condition of cavern roof support;
- fires;
- migration of water into the mine;
- loading, caused by development of new buildings or vibration caused by heavy traffic.

All caverns, which caused sinkholes in the Wieliczka Salt Mine were done in typical green salt blocks. Collapse of the roof parts of the salt crust and the lack of overburden above the caverns resulted in the migration of the empty void towards the surface and formation of a sinkhole. On the basis on many year world’s investigations and observations, it was proved that other factors which can be also significantly attributed to the formation of sinkholes are:

- Height of caverns:
  World’s studies and Polish experience [1-6] revealed that the height of caverns is one of the most important factors responsible for sinkholes. The height of caverns in the Wieliczka Salt Mine ranged between 4 and 50 metres.

- Thickness of roof beam:
  The thickness of the roof beam is understood as a difference between terrain altitude and depth of cavern roof. The thicknesses of the roof beam in the area of investigation varied depending on the cavern location depth (the roof beam for caverns on the first level ranges between 23 and 300 meters).

- Quaternary sediments:
  Quaternary strata are considered as a risk factor increasing the probability of occurrence of a sinkhole. The filtration of water to salt cavern increases when fractures occur in the rock mass strata. Quaternary strata in the Wieliczka area are thick with inserts and water-bearing lens. Water infiltrates through fractures, which are formed as a result of rock mass deterioration [7].

- Type of caverns:
Salt mining method is related to the type of salt and the way it was deposited. Mining in the Wieliczka area was carried out with various methods. Basically, caverns can be divided into: made in a block of salt, in salt bed, leached, and hole ones. Most sinkhole-prone caverns are the shallowest ones of irregular shape.

- Spatial distribution of salt caverns:
  Spatial distribution of caverns is the most complex issue, requiring advanced three-dimensional spatial analysis. The most hazardous are complexes of caverns located close to each other, particularly when the size of the caverns is considerable (figure 1).

![Figure 1. Underground salt caverns and shafts located below Wieliczka town - 3D perspective. Spatial distribution of salt cavern located close to each other.](image)

Afore-mentioned factors will be the criteria of final selection of sinkhole-prone caverns and development of final risk map.

When risk map is strictly related to mining and geological risk factors, vulnerability map is related to factors like:
- urban development (housing, public buildings);
- land use (build-up residential areas, areas ready for new development, green areas, industrial zones);
- geotechnical conditions (characteristics of shallow geotechnical conditions, where ground is stable or unstable. That factor should be taken into consideration when new buildings or infrastructure is planned to be built).

Based on these three factors vulnerability map was developed.

3. Sinkhole risk mitigation in urban areas
The first stage of the investigation was to design the architecture of functional database. Currently, Geographical Information Systems (GIS) are commonly used for spatial and attribute data integration and risks analysis [8-12]. Moreover, Analytic Hierarchy Process (AHP) is a multicriteria method commonly applied in order to resolve complex problems, which are burden with uncertainty [13-15]. Combination of GIS and AHP is a powerful tool supporting facing the problems related to geohazards. In the database information was gathered regarding geological, mining, hydrological condition, and urban development in the study area. The information about following risk factors was gathered in the database: shape of caverns and their technical condition, characteristic of geological strata and their geomechanical properties, hydrological conditions like watered layers and observed water leakages, digital terrain model, land development, landuse, and geotechnical conditions (figure 2).
Figure 2. Database content in Geographical Information System (GIS). Salt caverns and observed water leakages located at different depths.

Based on collected data, further spatial analysis were carried out. Research was divided into a few steps (figure 3a). First step was to select risk and vulnerability risk factors. Furthermore, a raster maps were created for every factors. Then, based on AHP, the risk and vulnerability maps were developed. Final step of the research was to merge both the vulnerability and the risk map. A final sinkhole susceptibility map was created based on combination of information about vulnerable zones and hazarded areas'.
Figure 3. (a) Flow chart of the research; (b) Salt cavern in unfavourable spatial distribution located at different depths. Applying Ryncarz method for every salt cavern probability of roof collapse was estimated.

In the next chapters steps of the research will be explained in the details.

3.1. Risk map development

For salt rock deposits a novel approach has been developed in order to assess probability of sinkhole occurrence on the surface. Presented approach was based on combining four risk factors with the use of the AHP method. Every risk factor was unify to the values from 0 to 100, where 0 meant low risk and 100 meant high risk.

First factor related to the selection of cavern prone to collapse was based on the Ryncarz theory. That theory was applied in order to simulate the vertical stresses in the roof of salt caverns [3]. That solution enabled us to separate caverns, for which vertical stresses were regarded as critical ones. Depending on the risk of exceeding critical values, cavern prone to collapse were chosen. Moreover, depending on the zones in the rock masses, which are influenced by cracking roof of salt caverns areas prone to sinkhole occurrence were found (figure 4 a).

The second factor was related to unfavourable spatial location of mining cavern. Based on spatial analysis areas where underground fissure may occur, influencing cavern stability, were selected (figures 3b, figure 4 b)

Figure 4. Selection of caverns prone to collapse expressed by probability – Factor 1 (F1) a), map of probability of cavern collapse due to their unfavorable location – Factor 2 (F2) b).
The next step was to evaluate hydrological risk factors, which could contribute to sinkhole development. For every area, where a water leakage was observed, a buffer zone was created. The radius of the buffer zone was 20 meters. In that area water leakage could initiate salt leaching and contribute to reducing the stability of the salt excavation (figure 5 a). Moreover, geological and hydrological conditions were analysed taking into consideration a rock mass strength and their permeability.

The last analysed risk factor was ground vibration caused by heavy traffic. An estimation of possible rock masses stability disturbances due to heavy traffic was investigated. For significant city roads a map of intensity of possible vibration was created (figure 5 b).

Figure 5. Underground water leakages analysis – Factor 3 (F3) a), loading and vibration analysis due to heavy traffic Factor 4 (F4) b).

Finally, multicriteria analysis were provided for all above discussed factors (figure 6).

Figure 6. Weights for risk factors estimated based on AHP pairwise matrix comparison.

Based on weighted risk factors final risk map was generated (figure 7).
3.2. Vulnerability map development

Similar approach was established for the vulnerability map development. Three factors were taken into consideration:

- land development;
- landuse;
- ground geotechnical conditions;

First vulnerability factor was related to land development. Location of buildings and their type was taken into consideration (factor 5, \(F_5\)). Next factor was related to landuse. Area where new buildings may be developed were highlighted (factor 6, \(F_6\)). Last factor was associated with technical condition of ground according to its stability (factor 7, \(F_7\)). If the ground conditions are unstable, then damages to buildings may occur with high probability. Moreover, when a new buildings are constructed, additional buildings reinforcements are needed. For that three vulnerability factors based on AHP method weights describing their importance were assigned (figure 8).

![Figure 7. Risk map of probability of sinkhole occurrence.](image)

![Figure 8. Weights for vulnerability factors estimated based on AHP pairwise matrix comparison.](image)
Based on weighted risk factors final vulnerability map was generated (figure 9).

The final map indicating urban areas susceptible to sinkhole occurrence was established as merging both the risk and the vulnerability map. Only a few areas in the city were significantly hazarded (figure 10). Probability of severe damages to buildings covered around 4% of all urbanised area. Medium risk was estimated for around 15% of all the city. The rest of urbanised area should not undergo sinkhole treads (figure 11).
Figure 11. Graph representing percentage of the areas with high, medium and low hazard for the urban areas caused by sinkhole occurrence.

As a result of performed analysis the mining company and the local authorities may incorporated additional monitoring systems in the areas with high hazard of sinkhole occurrence.

4. Results discussion
Based on the obtained computation results, it can be stated only small part of Wieliczka town is substantially susceptible to sinkhole occurrence on the surface. Probability of severe damages to buildings covers around 4% of all urbanised area. Medium risk was estimated for around 15% of all the town. The rest of urbanised area should not undergo sinkhole threats (figure 10, figure 11).

Although the highest probability of sinkhole occurrence is predicted in a relatively small area, it covers, however, Wieliczka downtown, which is characterised by dense building, as well as highest density of population. In addition, these areas are rich in important objects of surface infrastructure and monuments. Nonetheless, it should be noted, the areas of the town center are located directly above salt caverns. These caverns belongs to the oldest and shallowest mining operations. For this reason, they are already a priority in the case of carrying out the monitoring and protection works by mine’s measuring department.

In the second area with highest probability of sinkhole occurrence, which is located east to the center of Wieliczka town, only one risk factor prevails. This factor is coupled with transportation. It can imply vibrations contributing to the weakening of the strength of the surface rock layers overlying salt caverns. However, it should be recognized the sinkhole threat in this region in the context of the existing infrastructure and inhabitants is relatively small. It is due to the negligible influence of other factors that were taken into account when establishing the final map of sinkhole risk occurrence.

In other regions of the study area, the main risk factor regarding sinkhole occurrence is the unfavourable mutual position of salt caverns. The obtained computation results indicate that a relatively large number of caverns may be prone to unfavourable deformation forces caused by deeper localized salt caverns. In addition, in areas where water leakages are observed, the incidental threat may be greater. The reason for that is migration of water in rock layers. As a results of water migration, deformation processes may accelerate, especially in the case of small thickness of rock layers separating adjacent salt caverns.

5. Conclusion
The assessment of sinkhole related hazard is a crucial issue encountered in a number of active and closed mines. Sinkholes occurring on the surface generate a special risk in urbanized areas. The
Wieliczka Salt Mine is world heritage object. Moreover, area above that sallow salt mine is inhabited by 23 thousand of people. Especially, in areas similar to mentioned above aware of risk of sinkhole plays a pivotal role. That is why, an author’s made and attempt to develop reliable method for mapping susceptibility of sinkhole occurrence in urban areas.

The proposed research methodology is based on multistage algorithm. This algorithm enables the selection of threatened areas due to geological and mining factors, as well as related to the development and land use of the surface. Based on AHP method and advanced GIS analysis significant risk and vulnerability factors were chosen. The analyses carried out revealed that the most significant vulnerability factors were: buildings location and a type of building. The most crucial risk factor was shallow salt caverns in unfavourable mutual location. AHP method supported weighted linear combination of all selected risk factors. As a final result of the investigation areas prone to sinkhole occurrence and urban vulnerable areas were mapped. Achieved results proved that less than 20% of the urbanised area is highly or partly vulnerable to sinkhole occurrence. Those areas should be under monitoring of ground movements. What is more, technical conditions of existing buildings and infrastructure should be also established. In addition, landuse on hazarded areas should be developed under restrictive control of ground stability.

However, the presented methodic has its limitations. In the case of underground exploitation of mineral resources, full recognition of geological and mining conditions is often not able to carry out. Hence, only limited parametrisation of these conditions is possible. For this reason, values of parameters such as: the height of salt cavern, the thickness of rock layers, the location and volume of water leakages are characterized by considerable uncertainty. In addition, the use of AHP method allows for solving complex decision problems, however, due to the significant subjectivity of individual scales of assessing given decision parameters, the obtained results of calculations may be randomness and uncertain. Therefore, when carrying out the research using this method, knowledge and empirical experience in the field of solving particular research issue are highly recommended. Nevertheless, the obtained computation results indicate the ease and universality of the application of presented research methodology. Thus, it can be used as an effective tool to support activities aimed at assessing, managing and prediction of sinkhole occurrence on the surface induced by underground exploitation of mineral resources.

6. References
[1] Malinowska A A, Misa R and Tajduś K 2018 Geomechanical modeling of subsidence related strains causing earth fissures Acta Geod Geomater 15 pp 197–204
[2] Delle Rose M, Federico A and Parise M 2004 Sinkhole genesis and evolution in Apulia, and their interrelations with the anthropogenic environment Nat Hazard Earth Sys 4 pp 747–755
[3] Ryncarz T 1978 Analysis of the impact of filling ventricle excavations at levels I-III of the Wieliczka Salt Mine on surface deformation and stability of lower-lying cavern subject to protection (Cracow: AGH University of Science and Technology) (in Polish)
[4] Ryncarz T 1993 Outline of rock mass physics (Katowice: Silesian Technical Publisher) (in Polish)
[5] Brudnik K 2010 The complex hydrogeology of the unique Wieliczka Salt Mine Polish Geological Review 58 pp 787–796 (in Polish)
[6] Wieworka W and o’Byrn K 2012 Selection of backfilling technology works in the Ksawer caverns complex of the Wieliczka Salt Mine AGH Journal of Mining and Geoengineering 36 pp 107–115 (in Polish)
[7] Kleczkowski A 1993 Groundwater in the vicinity of Cracow – potential and threats Archives of the Faculty of Hydrogeology and Geological Engineering of AGH University of Science and Technology pp 35–38 (in Polish)
[8] Malinowska A A 2010 A fuzzy inference-based approach for building damage risk assessment on mining terraining Eng Struct 33 pp 163–170
[9] Mancini F, Stecchi F and Gabbianelli G 2009 GIS-based assessment of risk due to salt mining activities at Tuzla (Bosnia and Herzegovina) Eng Geol 109 pp 170–182

[10] Hejmanowski R and Malinowska A A 2010 Building damage risk assessment on mining terrains in Poland with GIS application Int J Rock Mech Min 47 pp 238–345

[11] Thierry P, Prunier-Leparmentier A M, Lembezat C and Vanoudheusden E 2009 3D geological modelling at urban scale and mapping of ground movement susceptibility from gypsum dissolution: The Paris example (France) Eng Geol 105 pp 51–64

[12] Yilmaz I 2007 GIS based susceptibility mapping of karst depression in gypsum: a case study from Sivas basin (Turkey) Eng Geol 90 pp 89–103

[13] Saaty T L 1980 The analytic hierarchy process (New York: McGraw-Hill)

[14] Malinowska A A and Dziarek K 2014 Modelling of cave-in occurrence using AHP and GIS Nat Hazard Earth Sys 14 pp 1945–1951

[15] Malinowska A A and Matonóg A 2016 Spatial analysis of mining-geological factors connected with discontinuous deformation occurrence Acta Geodyn Geomater 14 pp 159–172

Acknowledgments
This research has been financed by the National Science Centre, Poland, grant No.UMO2014/15/B/ST10/04892.