GIS-BASED APPROACH FOR SINKHOLE OCCURRENCE RISK MITIGATION IN URBAN AREAS FOR HISTORIC WIELICZKA SALT MINE

Agnieszka Malinowska  
AGH University of Science and Technology, Cracow, Poland, amalin@agh.edu.pl

Ryszard Hejmanowski  
AGH University of Science and Technology, Cracow, Poland, hejman@agh.edu.pl

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In 1969 a sinkhole over 100 m in diameter occurred as a consequence of a goal in the salt cavern Schmidt in Wieliczka salt mine. As a result two houses were completely destroyed [1]. The sinkhole was formed within 15 minutes. Similar events take place all over the World, frequently causing serious catastrophes. 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 workings 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 center.

The course of deformation process in the salt rock mass is influenced by geomechanical properties of various types of salt present in the Salt Mine “Wieliczka” 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 [2,3]. 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 salt deposit 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) in order to gather all information about geological, mining and hydrological conditions in mine, supported analysis of zones prone to sinkhole occurrence. Presented solution significantly improved sinkhole risk mitigation in Wieliczka town.


gis-based approach for sinkhole occurrence risk mitigation in urban areas for historic Wieliczka salt mine

Geological conditions and mining of study 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 cavern Małdrzyk 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 support,
– fires,
– migration of water flows to the mine.

All caverns, which caused sinkholes in the mine of Wieliczka were exploited 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.

It was proved on the basis on many year World’s investigations and observations, that other factors which can be also significantly attributed to the formation of sinkholes are:

Height of caverns

World’s studies and Polish experience [2–6] revealed that the height of caverns is one of the most important factors responsible for sinkholes. The height of caverns in the Salt Mine “Wieliczka” ranged between 4 and 50 metres.

Thickness of roof beam

The thickness of the roof beam is understood as a difference of the terrain surface datum and workings’ roof datum. The thicknesses of the roof beam in the study area vary depending on the depth (the roof beam for caverns on the first level ranges between 23 and 300 meters). Quaternary sediments

Quaternary strata can be a factor increasing the probability of occurrence of a sinkhole through the possible filtration of water to cavern workings when the continuity of the strata has been disrupted. In the Quaternary strata in the Wieliczka area they are thick with inserts and water-bearing lens. Water infiltrates fractures formed as a result of rock mass relaxation, and along vertical workings.

Type of caverns

Salt exploitation mode is directly connected with the type of salt and way it was deposited. Salt exploitation in the Wieliczka area was carried out with various methods. Generally 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 and variable thickness of salt cover insulating against the water fluxes.
Fig. 1. Working chambers in Wieliczka salt mine – 3D perspective

Fig. 2. Database content in Geographical Information System (GIS)

Fig. 3. Salt cavern in unfavorable spatial distribution
Interrelation of caverns is the most complex issue, requiring advanced IT for analyzing spatial interrelations between caverns. The most hazardous are complexes of caverns at neighbouring horizons, especially when the size of the caverns is considerable (Fig. 1). Afore-mentioned factors will be the criterion of final selection of sinkhole-prone caverns.

**Fig. 4. Analysis of geological and hydrological conditions for level I of the mine**

**Fig. 5. Map of sinkhole hazard occurrence**

- Water leakage
- 75%
- 50%
- 25%
- 5%

**Legend**
- Sallow salt caverns prone to collapse
- Zones prone to sinkhole occurrence on the surface
- Salt cavern prone to collapse in deeper mining level
Sinkhole occurrence risk assessment

At the first stage structure of the geological, mining and hydrological database was designed. Currently, Geographical Information Systems (GIS) are commonly used tool for data integration and risks analysis [7–11]. In the data base information was gathered regarding: shape of mining working and their technical condition, geological layers and their strength, hydrological conditions like watered layers and observed water leakages, terrain surface shape and development of Wieliczka town (Fig.2).

Rock mass deformation was analyzed in the area of shallowest salt caverns using the generalized Knothe's geometrical-integral model [12]. The results of those calculations enabled finding the distributions caused by the convergence of cavern workings in deeper horizons of the mine.

Basing on the Ryncarz theory, which is theoretical approach, the vertical stresses in the area of walls of shallow caverns were calculated [3]. That solution enable us to separate caverns for which such stresses were regarded as critical. Depending on the risk of exceeding critical values, cavern prone to collapse were established. Depending on the depth which could be reached by the cracks sinkhole-prone zones were found for all salt mine. Unfavorable spatial location of mining cavern and Ryncarz theory was basis for that analysis (Fig.3).

As a final results four area being under sinkhole risk were established for Wieliczka Salt Mine.

The next step was to confront the theoretical results with mining, geological and hydrological risk factors, which were discussed in the previous chapter. The spatial analyses were mainly based on dependences stemming from the Boolean logics (Fig.4).

As a result of performed analysis, 15 caverns were selected as potential sinkhole risk for the terrain surface (Fig.5). This analysis enabled accounting for such factors as:
- local walls collapse,
- flaking, splitting of walls,
- wetting of workings,
- change of cracks opening,
- bad technical state of cavern,
- increasing stresses around cavern
- closeness of top of crackings roof to the surface,
- unfavorable mutual position of cavern,
- thickness of top beam of selected caverns on the background of Quaternary and Miocene water-bearing horizons,
- occurrence of water and brine reservoirs in the zones of selected caverns,
- presence of zones hazarded with water flux.

An author's method for assessing the risk of discontinuous deformations on terrain surface through the modelling of vertical stresses on the basis of theoretical state and advanced GIS analysis were presented in the paper. For caverns potentially hazarded with stresses over the boundary values, the cracks zone was established. Finally, four zones prone to salt cavern roof collapse in the mine was selected (Fig.3).

Supplementing theoretical analyses by results of additional studies of mining and geological factors, eventually sinkhole-prone caverns in the rock masses were selected. Geological, hydrological and mining condition information collected in GIS database support the final inference about risk of sinkhole occurrence. The final stage of the studies was providing spatial analyses, from which caverns hazarded by the influence of other risk factors could be distinguished.

Abstract

The article presents the results of the definition of a new methodology for assessing the risk of flooding a shallow slotted mine, which was carried out on the square above the Wieliczka Salt Mine, which is a world heritage.

Vertical stresses are estimated on the basis of the theoretical state of rock mass deformation in the area of test chambers. In addition, the risk for chambers indicated in the zone was calculated based on the theory of arc crush pressure. The final stage of the study was spatial analysis, which led to the identification of chambers, potentially subjected to the influence of other risk factors. The results of the study proved that a combined spatial analysis with a theoretical solution can lead to a reliable risk assessment methodology in mining.

Keywords: evaluation, stress, pressure, deformation, geomechanical properties, collapse, mine workings, modeling.

References