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Changes of geomechanical state around reconstructed roadways in the historical salt mine

Z. Niedbalski, P. Małkowski & Ł. Bednarek
AGH University of Krakow, Kraków, Poland
niedzbig@agh.edu.pl
0000-0003-0497-0162

Abstract

Underground salt mines in Poland have existed continuously since 13th century. Two of them are preserved as museums, and these were inscribed on the UNESCO heritage list in 1978 and 2013. The underground chambers open to tourists were usually excavated 100–400 years ago. In this long period of time the secondary stress state around roadways was established but salt, as a rheological material, still deforms, which forces the periodic rebuilding of chambers and corridors. Sometimes, excavations need to be reconstructed for other reasons, e.g., changes in technical equipment, their adjustment to current safety requirements, or support repairs. These works generally lead to an increase in roadway cross-sections and to changes in the geomechanical conditions around the workings. Since underground excavations have variable cross-sections, ranging from a few to more than a hundred square meters, all mining works require individual stability analyses.

The analysis of reconstructed underground excavations in one of these historical salt mines was presented in the paper. The analysed chamber and roadways were mined at depths of 180-210 m in the 1st half of 18th century. They need to be rebuilt and widened, due to plans to increase the number of visitors in the mine. The inventory of chambers and roadways, laboratory tests on salt geomechanical parameters, ground monitoring and 2D numerical modelling were carried out to determine the state of stress and the extend of the plastic zone before and after rebuilding. The conducted investigations should enable safe mining operations and ensure the long-term stability of the historical structures in this part of the mine.

Laboratory studies, in-situ mine investigations, and numerical calculations indicate that currently, in the excavation designated for reconstruction, convergence occurs at a rate of approximately 6 mm/year. The largest displacements occur in the salt layers to a depth of about 2 m from the excavation contour and amount to 7 to 17 mm over 7 years. Numerical calculations based on the elasto-plastic Hoek-Brown model have shown that increasing the cross-sectional area of the reconstructed excavation from appr. 12-13 m² to about 24 m² may cause an increase in the excavation closure rate to approximately 10 mm/year and the potential formation of fracture zones in the excavation corners. Therefore, the need to apply a support lining is forecasted.

Keywords

Heritage, Salt mine, Geomechanics, Roadway reconstruction.

1 Introduction

Some underground mines are partially revitalized after mining operations cease and serve as tourist attractions (Rybar and Hroncek 2017; Tost et al. 2021). Such facilities also exist in Poland and include hard coal mines, gold mines, salt mines, and a Neolithic flint mine. The most famous and visited by over 2 million tourists annually, are the historic salt mines located in towns of Bochnia and Wieliczka – near Kraków, southern Poland (Wiewiórka et al. 2008; Dzięgiel 2021; Szydłowski and Flasza 2022). Both mines began their operating in the mid-13th century and are listed on the UNESCO World Heritage List.

Due to the rheological properties of salt, underground workings are subject to continuous deformation (May 2017). In the case of voids not intended for use, they are backfilled. This necessity arises from the potential collapse of the excavations, which would consequently threaten the surface structures of the town located above the mine (Szczerbowski 2020). In the case of maintained chambers, deformation requires periodic reconstruction. Furthermore, the need for reconstruction also arises from the necessity to adapt the excavations to current safety requirements or to increase tourist comfort. Such a case occurred in a salt excavation located at a depth of 180-210 meters, originally excavated in the first half of the 18th century. Renovation works are subject to significant limitations due to the historic nature of the facility and the heritage protection exercised by the conservator of monuments. Among the conservation restrictions affecting the construction technology include the type of support, which should be as similar as possible to the original type, and the need to preserve certain historical elements of the support and equipment.

The aim of this study is to assess the stability of a selected historic section of the excavation planned for reconstruction, which will involve increasing the lateral dimensions and implementing new support. To establish the technical assumptions for the work, geological conditions were analyzed, laboratory tests of the mechanical parameters of salt were conducted, and several years of our own convergence studies from the analyzed area were used, as well as roof layer displacements measured using an extensometersonic probe (Szczerbowski and Niedbalski 2021). Based on the above data, numerical calculations of the predicted extent of the fracture zone were performed to estimate the necessity of applying support.

2 Geological conditions and salt properties

The historic salt mine is located within folded Miocene formations north of the Flysch Carpathians. The deposit is a tectonically enriched salt series in the northern limb of the Bochnia Anticline. It is overlain by an unconformable layer of clays, silts, loess, and Quaternary sands, often of quicksand character. The Bochnia anticline is composed of nearly vertically dipping layers with an EW strike. The salt in the deposit is not homogeneous and is usually divided into three types: northern salts, central salts, and southern salts with interbedded barren rocks (see Fig. 1). Due to the nature of the salt strata occurrence, mining operations in the analysed area were conducted for about 750 years on a dozen levels at depths ranging from 50-520 m. The section of the excavation designated for reconstruction is located at a depth of approximately 180 to 200 m.

a) b)

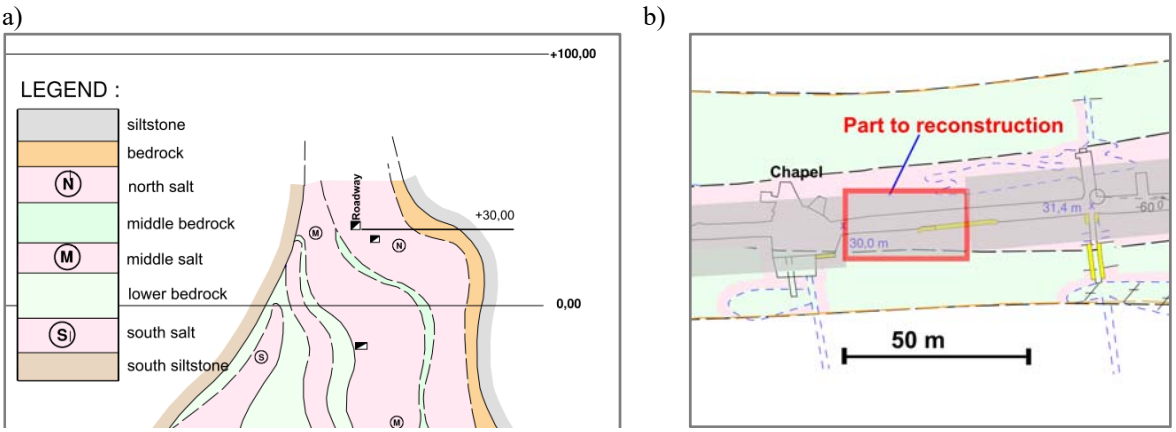


Fig. 1 Geological cross section: a) vertical in distance 115 m from reconstructed roadways part, b) horizontalin reconstructed area.

The salt layer in this area is approximately 24 m wide (see Fig. 1a). In the northern and southern sidewalls, apart from the salt deposit, there are layers of barren rocks composed of anhydrite claystones with a width of 15-20 m. At a further distance, claystones and clay shales occur.

For the assessment of the mechanical properties of the salt, solids were collected and cylindrical specimens were prepared with a diameter of 50 mm and a slenderness ratio of 2:1 for UCS, Young's modulus, and Poisson's ratio testing. Tensile strength was tested on specimens with slenderness 1:2. A total of 36 specimens were tested, and the average values of the parameters are presented in Table 1.

Table 1. Structural and mechanical parameters for rock salt.

	Density [kg/m^3]	**UCS [MPa]**	**Tensile strength [MPa]**	**Poisson ratio [-]**	**Young modulus [GPa]**
Minimum	1925,6	10,08	0,99	0,07	1,58
Maximum	2250,0	30,42	3,41	0,46	3,88
Average	2123,2	21,19	2,14	0,23	2,39
Standard deviation	76,04	5,72	0,59	0,10	0,61
Coefficient of variation [%]	*3,58*	*26,98*	*27,48*	*41,08*	*25,69*

The test results indicate that the salt strength is low, with UCS = 21.2 MPa. Poisson's ratio averages 0.23, and Young's modulus is 2.39 GPa. The coefficient of variation for mechanical parameters is noteworthy, with variations ranging from 25% to 41%. This indicates a significant heterogeneity in the salt's geomechanical parameters. This is due to the numerous interbeds occurring around the analyzed excavation (see Fig. 2).

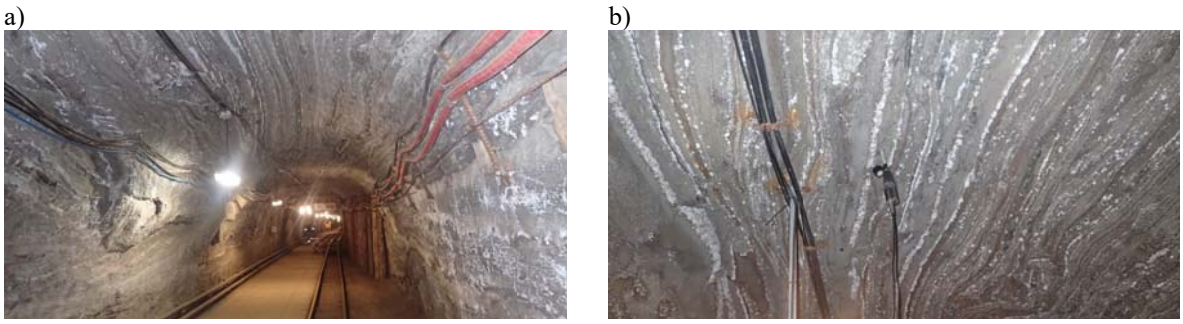


Fig. 2 General view in area planned to reconstruction a) full cross section roadway, b) roof of roadway.

To assess the phenomena occurring in the cross-section of the excavation planned for reconstruction, convergence studies were conducted between 2020 and 2025. These studies included measuring the excavation height and width at two different levels using a rangefinder. The original dimensions and the locations of the measured values are shown in Fig. 3a. The results indicate (see Fig. 3b) that over the long period of time, the nature of changes is close to linear, and the contour closure of the excavation is small, amounting to approximately 6 mm/year in each measured cross-section.

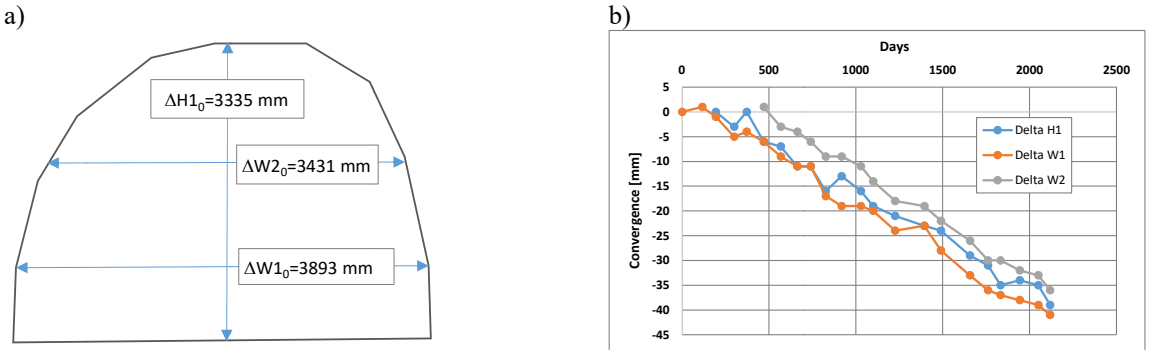


Fig. 3 Convergence measurement a) location of points measurement, b) graphs with changes of value of convergence.

In the same area, roof strata displacement measurements have been conducted since 2018 using a magnetic extensometer (see Fig. 4a). Observations were conducted to a depth of 6.8 m of the roof, at a total of 18 levels. Twenty two readings were taken manually, usually every three months. The measurement accuracy is 0.02 mm (Szczerbowski and Niedbalski 2021). The highest values of displacements of roof layers were recorded directly at the excavation contour, amounting to approximately 17 mm at the end of 2025 (see Fig. 4b). Assuming uniform closure of the excavation along the excavation contour, this value is similar to the results obtained from convergence

measurements, where after 6 years, the displacement in the roof-floor line is 40 mm, i.e., approximately 20 mm for the roof and 20 mm for the floor. As the sensors move further from the excavation contour, the displacements decrease significantly, to 7 mm at the second meter of the roof and to approximately 3 mm at the 4th meter of the roof. The highest point is stabilized and the remaining measurements are referenced to it. However, it is possible that a roof package thicker than 6.8 m also moves as a result of tectonic stresses (Toboła and Bezkorowajny 2006). However, the displacement values at a distance of 6.8 m from the contour are in fact insignificant, because at a roof depth of approximately 6.0 m, displacements after 7 years do not exceed 1.0 mm. Although local irregularities are visible in some measurement series, e.g., the first control measurement after 92 days, it can generally be concluded that changes occur with high repeatability.



Fig. 4 Extensometer measurement a) magnetic anchorsgeneral view, b) sonic probe with box reader, c) graphs with changes of value of displacement roof layers.

3 Reconstruction plan of roadways and numerical calculation

3.1 Reconstruction plan

In the analysed excavation, modifications are planned to enhance safety and increase the number of tourists visiting the historic salt mine. As part of these works, a double-track railway is planned on selected sections, which will require an increase in the cross-section from the current $H \times W$ of approximately 3.3 m × 4.0 m (see Fig. 5a) to dimensions in the excavation $H \times W$ of 4.0 m × 6.0 m (see Fig. 5b). On sections without support, the cross-section will almost double from the current approximately 12–13 m^2 to about 24.0 m^2.

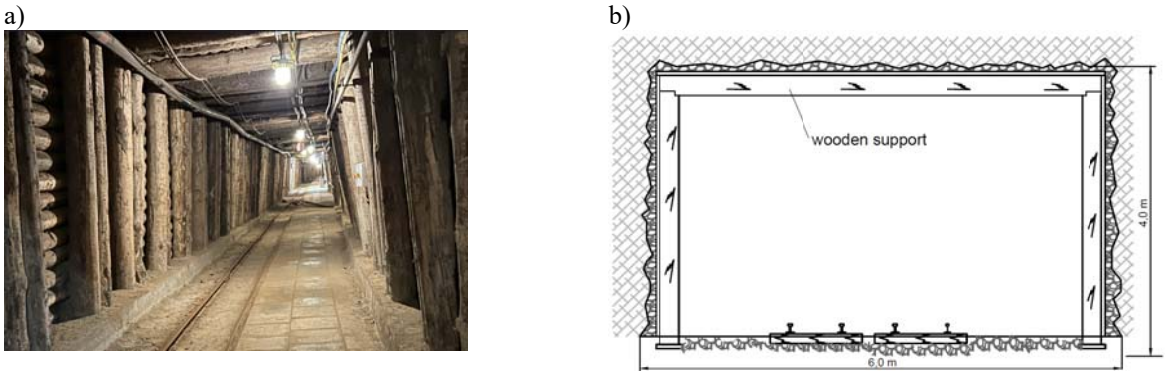


Fig. 5 Roadway a) current view with support, b) new dimensions.

On sections where there was no support previously, wooden lining is planned in accordance with the requirements of the monument conservator. In case of expected fracture zones, anchors are anticipated.

3.2 Numerical calculation predicted cracks zones and displacements

To forecast the extent of fracture zones and the convergence values of excavations, numerical calculations were performed using the RS2 Rocscience program and the Coulomb–Mohr criterion (Hoek et al. 2002). The elastic-plastic rock properties was assumed and the following boundary conditions: fixed nodes on the horizontal lower edge of the model and movable restrains on the vertical edges and the horizontal upper edge of the model.

According to the data, the excavation was assumed to be located at a maximum depth of 210 m. The primary stress values were assumed to be p_z= 4.83 MPa, and due to the specific nature of the salt, p_x=

$p_y = p_z$. The parameters used in the calculations are presented in Table 2. Due to the high geological variability of the rock mass in the analyzed area, parameter values 50-60% lower than those resulting from laboratory tests were used in the calculations. Conducted calibrations indicate good correlation of calculation results with measurements.

Table 2 Rock parameters using in numerical calculations.

Parameter	Salt	Interlayer siltstone	South and north siltstone
Density [kg/m^3]	2120,0	2400,0	2300,0
Young modulus [MPa]	1500,0	1700,0	1250,0
Poisson ratio [-]	0,23	0,25	0,25
Cohesion [MPa]	1,68	2,00	1,65
Internal friction angle [^{O}]	30,0	25,0	25,0
Tensile strength [MPa]	2,07	1,25	1,00

The calculations were carried out in three phases (see Fig. 6): before the start of mining works, after excavation without support, and after increasing the transverse dimensions. The article presents the results for the current situation (see Fig. 6b) and after the planned reconstruction (see Fig. 6c). Fig. 7 shows the calculation results covering the immediate surroundings of the excavation for principal stresses along with the predicted fracture zone and displacement maps.

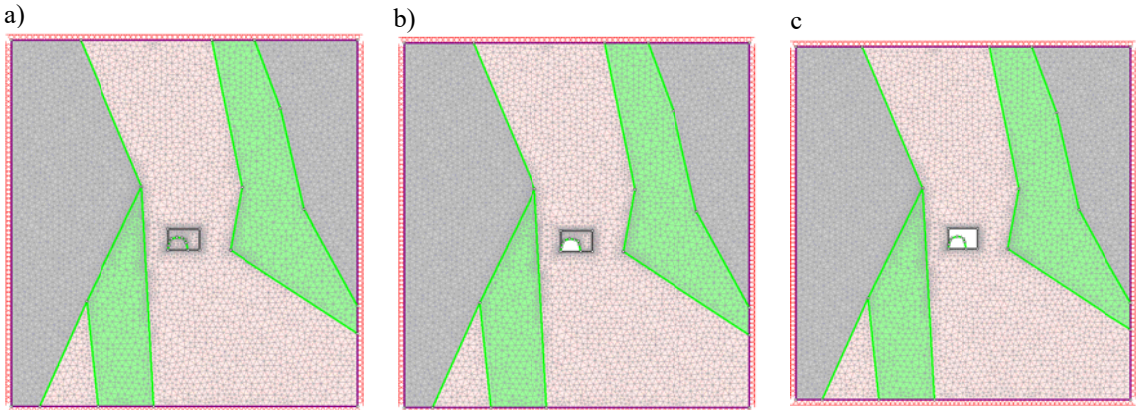


Fig. 6 Numerical models a) before excavation, b) current situations c) situation after reconstruction.

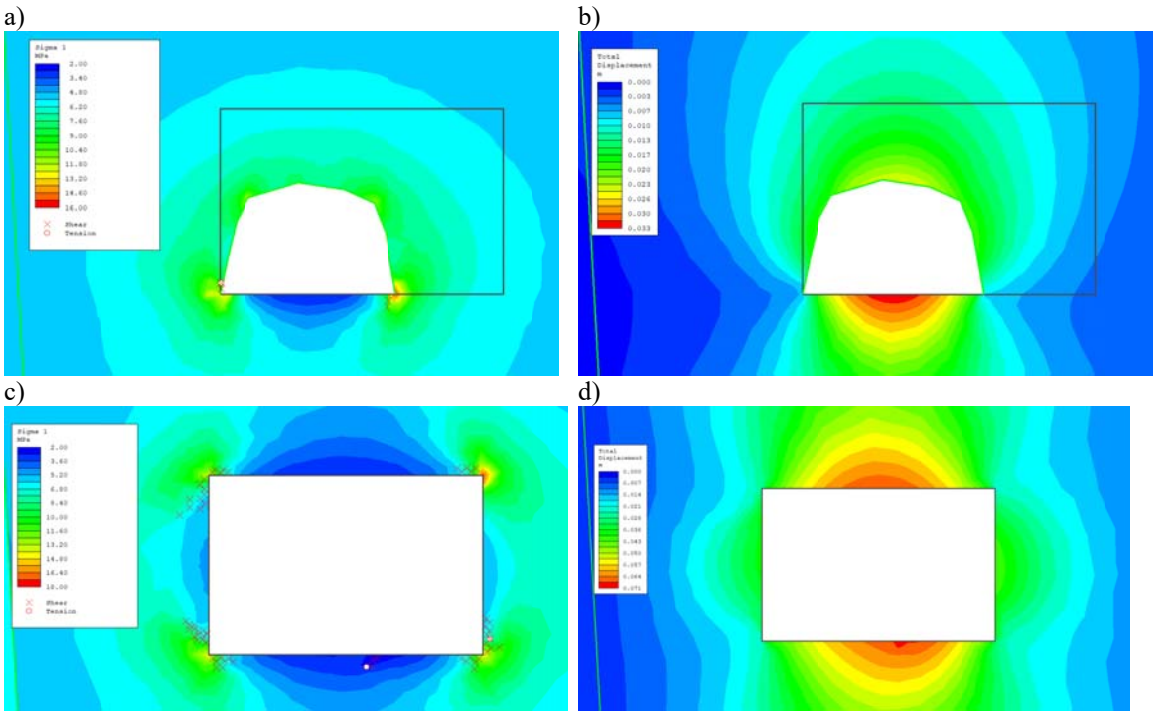


Fig. 7 Results of numerical calculations a) main stress σ_1 with yielded element for current situations, a) displacement for current situations c) main stress σ_1 with yielded element after reconstruction, a) displacement after reconstruction.

The calculation results indicate that in the current state around the excavation, the principal stresses σ_1 reach approximately 15 MPa in the corners near the floor, with a negligible crack zone in the corners (see Fig. 7a). Displacements at the floor are approximately 33 mm, and at the roof approximately

26 mm (see Fig. 7b). These values correspond approximately to the actual convergence measurement period of approximately 10 years. Widening the excavation causes a slight shear crack zone in the corners and an increase in the predicted displacements to approximately 71 mm in the floor and approximately 67 mm in the roof. It is estimated that the predicted convergence increase will be greater than the current one by approximately 5-6 mm/year, and the displacement values determined in the calculations will occur over a period of 10-15 years. In view of the above values, the use of wooden support for the reconstructed section of the excavation is predicted. Apart from purely historical reasons, due to the deformability of the wood over a long period of time, it can be assumed that it will safely protect the excavation.

4 Summary

Historic underground structures maintained for tourist purposes require a special approach. This is due to their long period operational life, the restrictions imposed by the monument conservator, and the number of visitors who must be provided with the highest level of safety. In the case of the Bochnia Salt Mine, field observations have been conducted for many years to assess and, if necessary, forecast phenomena that may occur around the underground excavations.

Laboratory and mine tests, as well as numerical calculations, indicate that convergence is currently occurring at a rate of approximately 6 mm/year in the excavation designated for reconstruction. The largest displacements occur in salt layers up to a depth of approximately 2 m from the excavation contour, ranging from 7 to 17 mm over a 7-year period. Numerical calculations based on the Coulomb-Mohr elastic-plastic rock parameters indicate that increasing the cross-section of the excavation being rebuilt from approximately 12-13 m^2 to approximately 24 m^2 couldincrease the excavation's compression rate to approximately 10 mm/year and potentially create fracture zones in the excavation's corners. Therefore, it is necessary to apply wooden support, which should fully ensure the stability of the roadway and safety for hundreds of thousands of tourists annually.

Acknowledgement

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