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ASSESSMENT OF ROCK MASS STABILITY IN THE HISTORIC AREA OF LEVELS IV-V OF THE "WIELICZKA" SALT MINE

OCENA STABILNOŚCI GÓROTWORU W STREFIE ZABYTKOWEJ POZIOMÓW IV-V W KOPALNI SOLI WIELICZKA

As a result, of more than 700 years of exploitation in the Wieliczka Salt Mine, a network of underground workings spreading over eleven levels was created. All mine workings of significant historic and natural qualities and the majority of functional mine workings designated to be preserved are located on levels I to V. The most precious of them, available to tourists, are located in the central part of the Mine on levels I-III. The Mine is not anticipating to make levels IV, Kołobrzeg and V available for a wider range of visitors, even though there are historically and naturally precious workings in those areas as well. The most valuable of the mine workings come from the eighteenth and nineteenth centuries and were exploited mainly in a bed of fore-shaft salt, Spiza salt and the oldest ones. The characteristic feature of these excavations, distinguish them from the chambers located on the levels I-III, is the room-and-pillar system that had been used there. Mine workings exploited in this system measure up to 100 metres in length, and the unsupported pillars standing between the chambers measuring 4-10 metres in width were remained. The described above levels, including levels of VI-IX are to provide a stable support for the workings located higher up. The remaining part of the mine, with the exception of the function workings, is designated for liquidation by backfilling.

The article presents an assessment of stability of the mine workings, located on levels IV-V, and their impact on the surrounding rock mass and the land surface. The analysis was based on geodetic measurements and numerical calculations for strain state of rock mass surrounding the mine workings, in actual conditions and after partial backfilling, and forecast of the rock stability factor after the end of backfilling. The assessment stability factor in the vicinity of excavations at levels IV-V was based on the results of spatial numerical analysis covering the entire central area of the mine from the surface to level V. Numerical calculations were performed using FLAC programme based on the finite difference method, allowing to observe the mechanisms and processes of destruction and deformation. The calculations were performed for the elastic-plastic medium with the Mohr-Coulomb failure criterium. The choice of this computational model was dictated by a very diverse geological structure of the Wieliczka rock mass and a complex system of excavations.

Keywords: salt mine, backfilling, geomechanical analysis, stabilization of the rock mass

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W Kopalni Soli Wieliczka, po ponad siedemsetletniej eksploatacji, wydobycie soli zostało całkowicie zakończone w roku 1996. W kwietniu 1976 roku kopalnię wpisano na Krajową Listę Zabytków, a we wrzeniu 1978 roku na Listę Światowego Dziedzictwa Kulturowego i Przyrodniczego UNESCO. Pod koniec lat 70 ubiegłego wieku podjęto decyzję, że do stabilizacji górotworu oraz utworzenia mocnego podparcia najważniejszych i najbardziej cennych dla kopalni poziomów, niezbędne jest wypełnianie podsadzką wyrobisk górniczych położonych poniżej, tj. na poziomach VI-IX oraz niezabytkowych rejonów poziomów wyższych. Wszystkie wyrobiska o znaczących walorach zabytkowych i przyrodniczych oraz zdecydowana większość wyrobisk funkcyjnych, przewidzianych do zachowania, zlokalizowane są na poziomach od I do V. Najcenniejsze z nich, udostępnione dla turystów, usytuowane są w centralnej części kopalni na poziomach I-III. Poziomy IV, Kołobrzeg i V stanowić mają stabilną podporę dla wyżej położonych wyrobisk. W artykule przedstawiono ocenę stateczności wyrobisk zlokalizowanych na poziomach IV-V oraz ich wpływ na wyrobiska nadległe, zarówno obecnie, jak i po częściowym podsadzeniu oraz prognozę stanu wytężenia górotworu po zakończeniu podsadzania. Podstawą do oceny wytężenia górotworu w wokół wyrobisk na poziomach IV-V były wyniki przestrzennych analiz numerycznych obejmujących cały centralny rejon kopalni od powierzchni do poziomu V. Obliczenia numeryczne zostały wykonane przy użyciu programu FLAC bazującego na metodzie różnic skończonych umożliwiającego obserwację mechanizmów oraz przebiegu procesów zniszczenia i deformacji. Obliczenia zostały przeprowadzone dla ośrodka sprężysto-plastycznego z warunkiem wytrzymałościowym Coulomba-Mohra. Wybór tego modelu obliczeniowego podyktowany został bardzo zróżnicowaną budową geologiczną górotworu wielickiego oraz skomplikowanym układem wyrobisk.

Słowa kluczowe: kopalnia soli, podsadzanie wyrobisk, analiza geomechaniczna, stabilizacja górotworu

1. Introduction

In 1996, after seven hundred years of operation, mining was completely terminated in the "Wieliczka" Salt Mine. In April 1976 the mine was included on the National List of Monuments and in September 1978 on UNESCO's World Cultural and Natural Heritage.

In the late 1970s it was decided that to stabilize the rock mass and create a strong support of the most important and valuable mine levels, it is necessary to backfill the mine workings located below, i.e. on levels VI – IX and the non-historic areas of higher levels.

All mine workings of significant historic and natural qualities and the majority of functional mine workings designated for protection are located on levels from I to V. The most precious of them, available to the tourists, are located in the central part of the mine on levels I-III. The Mine is not anticipating to make available, for a wider range of visitors, levels IV, Kołobrzeg and V, although there are historically and naturally precious workings in that area. These levels are to serve as a stable support for higher located workings. The article presents an assessment of the mine workings stability, located on levels IV-V, and their impact on superimposed workings both now and after partial backfilling and forecast the state of rock stability after the end of backfilling.

2. Geological structure and hydrogeological conditions

The rock salt deposit formed as a result of sedimentation of evaporates in the Carpathian foredeep, approximately 13.5 million years ago. It was formed tectonically during the Alpine orogeny As a result of Carpathian Mountains overthrust towards the northern direction (Fig. 1). Jurassic rocky limestones are located in the substratum of Miocene formations characteristic for their significant lithological variations and which can be divided into four layering complexes:

– Skawińskie beds (sub-salt), mainly composed of marl clay with interlayers of siltstones and sandstones

– sulphate and chloride evaporates composed of siltstone – clay sediments with anhydrite, gypsum and rock salt clusters
– Chodenickie beds (over-salt), composed mainly of siltstones and claystones, sandy or bedded with layers of clastic sandstones
– Grabowieckie beds, composed of grey clays and sands.

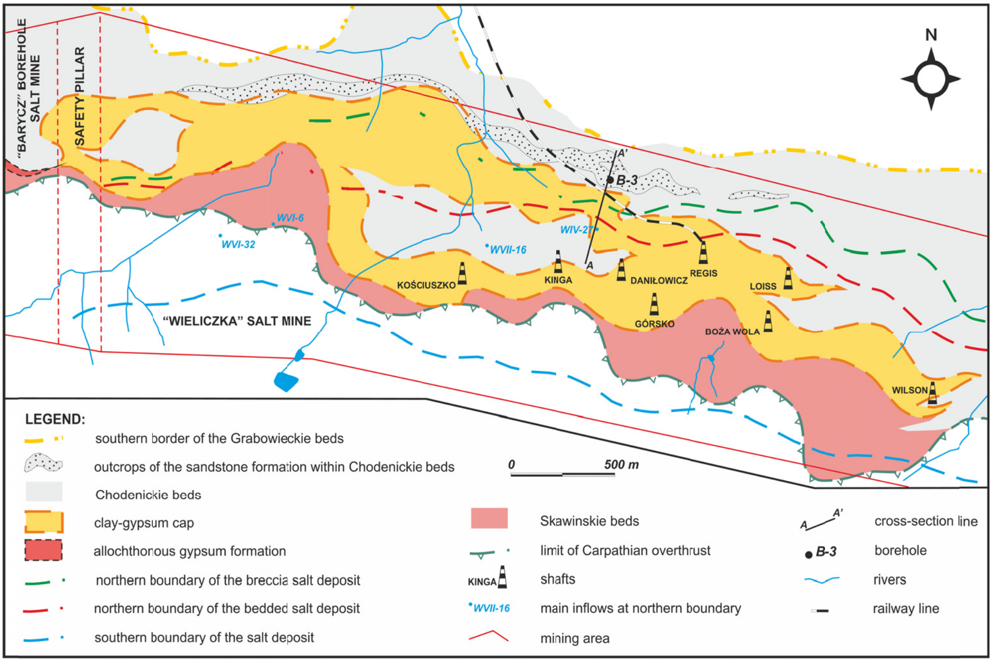
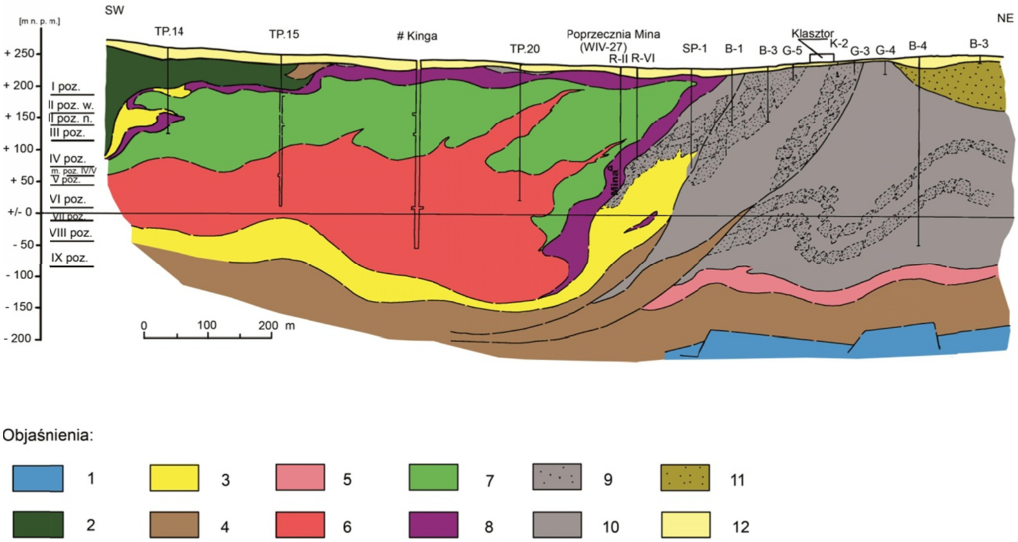


Fig. 1. Geological map of the Wieliczka Salt Mine (Brudnik et al., 2010)

Quaternary formations, depositioned over Miocene formations, mainly constitute a several-meter layer of clays and silty sediments with interlayers of sands, gravels and debris of flysch rocks. In the Wieliczka salt deposit within the evaporates, two structural units are distinguished: brecciated deposit and bedded deposit. The brecciated deposit was formed as a result of orogenic movements by tearing and breaking salt layers into irregular blocks and displacement of these blocks along with barren rocks. The salt blocks are located between the so-called zuber, namely non-structural clay mass with slight concentrations of salt. Within the zuber, there are numerous fractures filled with fibrous halite. There are several types of salt that can be distinguished in brecciated deposit, differing in crystal size, the amount of impurities, lamination, interbeddings and compactness. The salt blocks measure from less than 1 cu.m. to over 100,000 cu.m. Generally, the brecciated deposit is located over the bedded deposit. The bedded deposit forms three tectonic slices (folds) which are thrusted over each other. In the area of these folds, salt layers were mainly undulated and overlapped creating a large number of changes in the thickness of the deposits. Also, several types of salt can be distinguished in the bedded deposit, which differ with regard to age, forming conditions, amount of impurities, partings, lamination and durability especially to compression (Gaweł, 1962; Oszczypko et al., 2006; d'Obyrn & Przybyło, 2010; d'Obyrn, 2012).

The geological structure of the salt deposit shaped in such a manner is extremely complex and its duality presented above is an extraordinary phenomenon in Miocene salt formation (Fig. 2).



1 – Jurassic, 2 – Carpathian Flysch formations, 3 – Skawińskie layers + flysch formations (non-separated), 4 – Skawińskie layers, 5 – formations of salt reservoirs of the parautochton, 6 – formations of salt reservoirs of the layered deposit, 7 – formations of salt reservoirs of the breccia deposit, 8 – clay-gypsum cap, 9 – sand formations of the Chodonickie beds, 10 – Chodonickie beds, 11 – Grabowieckie beds, 12 – Quaternary

Fig. 2. Geological cross-section in the area of the St. Kinga Shaft (Brudnik & Szybist, 1995, amended and supplemented Szybist, 2011)

For the purpose of geomechanical analysis and building of a numeric model it seems advisable to use certain simplifications and divide the deposit into subsequent rocks environments:

- Quaternary formations,
- clay – gypsum cap,
- breccia salt deposit,
- bedded salt deposit with separation:
  - spiza and sandy salt layer,
  - the oldest salt layer, green bedded and fore-shaft salt,
  - spiza and sandy salt layer,
- Skawińskie beds.

Quaternary, Tertiary and flysch (cretaceous-Palaeogene) and Jurassic sediment aquifers have been isolated in the area of the Wieliczka deposit. Quaternary aquifer is related to pockets or discontinuous layers of sands and gravels, silty and sandy clays or debris. It is discontinuous horizon with relatively small content, fed by precipitations. This level remains in hydraulic contact with waters, which are present in Tertiary formations. The Chodenice beds (Fig. 2) are most relevant for determining the hydrogeological conditions of the Wieliczka deposit region and mine leakages. Aquifer formations are layers of sandy reservoirs, usually occurring in the form of debris and shattered and tectonically disturbed blocks, pounded into the salt reservoir or gypsum-clay buffer cover, adjacent to the ends of mine workings. Apart from significant misplacements, there are numerous cracks and fractures within sandstones. Waters of these layers feed the largest mine inflows forming consistently along the southern extension of these formations. Hydraulic contacts, circulation routs and feeding conditions of Chodenice beds in the northern foreground of the deposit, are so far poorly recognized. However, the existence of such connections and feeding confirm the underground observations of the latest years and the research results in piezometric holes (d'Obyrn & Brudnik, 2012).

Migration of underground waters in the deposit directly influences the destruction of the rock mass by dissolving salt. However, the increase of humidity in the mine workings causes an increase of rock humidity and a change of geomechanical parameters of the rock. It is especially evident in salt with clay intercalations. The clay minerals swell under the influence of water, which may result in delamination within the chamber ceilings and in extreme cases, lead to loss of stability of the chamber. This is confirmed by the many years of observations of the state of chambers in the Wieliczka rock mass.

3. Mining conditions and the historic and natural qualities of mine workings located on levels IV-V

The mining area of the Wieliczka deposit covers a surface area measuring 5.5 km in length (E-W orientation) and 0.5 to 1.5 km (S-N orientation) in width. The created mine workings formed an underground infrastructure arranged on 9 levels and two inter-levels (Table 1). No less than 2,328 chambers measuring over 9.4 million cu.m. of total volume were exploited and over 245 km of galleries were made.

TABLE 1

Basic data on mining levels

Level	Number of chambers	Depth, [m]
I	126	57.4
IIw (higher)	46	84.3
IIn (lower)	246	103.5
III and interl. Kazanów	378	129.4
IV	512	170.3
V and interl. Kołobrzeg	447	198.8
VI	233	236.5
VII	121	255.2
VIII	66	287.6
IX	2	327.2

Mining operations descend below level III already at the end of the eighteenth century, when the Kloski Chamber, 197 metres below ground level, was exploited. The mine floor of this chamber reached today's level V (Markowski, 1978). The room-and-pillar system introduced in the nineteenth century and the use of explosives significantly increased the mine output. Mine workings exploited in this system measured up to 100 metres in length, and 6-20 metres in width. Unsupported pillars measuring 4-10 metres in width were remained standing between the chambers (Walczy, 2002).

The mine workings located on levels IV-V Fig. 3-5 were excavated mainly in a bed of fore-shaft salt and Spiza salt beds and the oldest ones. The fore-shaft salt bed spreads through the whole deposit and measures from ca. 2 to 2.5 metres in thickness. The vast and separated from each other chambers, by means of pillars, measure the same in height. Whereas, the chambers cut out in Spiza salt and the oldest type of salts are in general much higher and more regular in shape, often grouped forming the so-called exploitation fields.

The history of exploiting the bedded deposit in the Wieliczka Salt Mine can be observed in the discussed levels apart from its geological values. Well-preserved excavations from the XIX and early XX century bear numerous traces of the manual notch wedge or groove, and water-spray disolution. At IV level of the mine 9 sites were included to the historic mine workings, and at the Kolobrzeg level , and level V, one chamber site and one gallery site (Jaworski et al., 1984).

In the recent past, intensive backfilling of the lower mine levels is executed by means of hydraulic backfilling. The material used, in this case, is sand with is transported and distributed to the selected sites by means of saturated brine. Backfilling works are performed in two directions: from the top downwards and from the eastern and western peripheral areas of the mine towards the centre, the historic section of the mine. This means a systematic elimination of peripheral mine workings and progressing stabilisation of the rock mass conducted in such a manner that the lower levels serve as a stable support of mine workings on higher levels. Separate backfilling operations include works executed at the northern border of the deposit. Stabilisation of the rock mass in this region is necessary and aimed at preventing cave-ins of chambers, that, if they would occur, would lead to the formation of cracks through which water could potentially penetrate into the mine from the Chodenickie beds.

The volume of backfilling material already injected into the underground mine workings of the Wieliczka Salt Mine, in the period between 1998 and 2013, ranged from 40,000 to 140,000 cu.m. of sand which stabilized, during the past few years, at the level of approximately 100,000 cu.m. per annum. As at 1 January 2014, the volume of the mine workings in the “Wieliczka” Salt Mine (volume of non-eliminated chambers and corridors) amounts to approximately 4,020,000 cubic meters. The targeted volume of mine workings will amount to ca. 1,430,000 cubic meters. Achieving the targeted technical formation will thus require the elimination of approximately 2,590,000 cu.m. of mine working, including ca. 2,000,000 cu.m. by way of backfilling.

4. Analyses of rock mass stability and the condition of mine workings on levels IV-V in the central region of the mine

4.1. Measurements of terrain surface deformation and mine working deformations in the central region of the mine

The salt rock mass affected by mining operations is subject to constant deformation processes, which occur due to:

- convergence of mine workings,
- cave-in processes,
- rock mass dehydration and suffosion.

The main subsidence area is situated on the surface in the area of the central part of the mine forming in the region of the Kościuszko Shaft and settling 44 mm per year on average. It covers an area up to 1,500 m towards the west from the Kościuszko Shaft, the town centre, reaching the area approximately 200 metres westward from the Wilson Shaft. The surface of this trough measures approximately 3.5 square kilometres. The maximum, total depression in the trough centre reaches 1,183 metres (periodic tough 1970-2010). It has been assessed, that the exploitation works conducted in the mine in the twentieth century had caused aggregated settling reaching up to ca. 3 metres (Szewczyk et al., 2011). Based on the analysis of the depression velocity of points conducted in the years 1970-2010, 1984-2010, 2000-2010, 2005-2010 it can be stated, that the process of trough decompression in the area of the town centres has been slightly suppressed. The settling velocity for periods above mentioned is presented in Table 2 below.

TABLE 2

Surface settling velocity in the central region of the mine (Szewczyk et al., 2011)

Region	Surface settling velocity in the years [mm/year]			
	1970-2010	1984-2010	2000-2010	2005-2010
Kościuszko Shaft	44	38	21	20
Kinga Shaft	21	18	17	16
Daniłowicz Shaft	19	15	14	14

The deformation of the surface can also be a result of rock mass dehydration and / or suffusion. Such threats occurred in connection with water penetrating on level IV into the Mina drift, in 1992. This catastrophe caused significant deformations in the northern forefield of the mine where the settlement velocity of the surface reached up to –14 cm/day. After 1993, the terrain subsided at an irregular but decreasing velocity from –25 to –2 mm/year. The maximum subsidence of the terrain was almost 2.5 metres. Stopping the inflow in 2007 initiated the process of restoring natural hydrogeological conditions and natural pressure. Since then, the terrain of the suffosion subsidence in the northern part of the mine forefield continues to systematically uplift. The terrain uplifted by +63 mm by Autumn 2011, and, at the same time, the volume of this uplift reached approximately 2,300 cubic metres. The uplifting phenomenon is observed at all benchmarks in the region of the suffosion subsidence (d'Obyrn & Brudnik, 2011; Maj et al., 2012).

The velocity of vertical displacements observed at each mine level is an indicator allowing to describe rock mass movement, but primarily permitting to break down levels into complex groups (packets) demonstrating similar subsidence. The average settling velocities (in mm/year) of each level in the mine depending on period are presented in Table 3.

The above table indicates, that levels I-III have been settling for years at a similar velocity, i.e. approximately 14-17 mm/year, whereas, levels VI-VIII are settling significantly slower, i.e. up to few mm/year.

Measurable data regarding processes occurring in mine workings is commonly monitored in salt mining by convergence measurements. The points at which convergence is measured have been stabilized, mainly in the most valuable chambers and gallery workings on levels I to III. The measurements are taken once a year. The average velocity of compression on mine workings, both vertical as well as horizontal, does not exceed 2 mm/year.

TABLE 3

Average settling velocity of each level in the period 1986-2010 in [mm/year]
(Szewczyk et al., 2011)

Level	Average settling velocity of each level [mm/year]							
	1986-1995	1986-2000	1986-2005	1986-2006	1986-2007	1986-2008	1986-2009	1986-2010
Level I	15.1	16.1	15.4	17.7	17.3	17.1	16.2	16.5
Level II w	14.2	14.9	15.5	15.0	14.8	14.4	14.5	14.4
Level II n	15.5	15.1	15.1	15.1	15.0	14.4	14.6	14.4
Level III	14.5	14.8	15.2	15.1	15.0	14.8	14.5	14.2
Level IV	13.2	14.0	14.6	12.6	12.8	12.3	12.6	
Level V	12.2	13.2	14.0	12.2	12.2	11.9	11.7	
Level VI	4.7	5.0	6.8	7.0	7.3	6.6	6.7	
Level VII	3.3	3.2	3.7	4.2	4.7	4.9	3.8	
Level VIII	0.8	0.8	1.5	2.1	2.6	2.3	1.8	

4.2. Numerical analysis of the stability of workings located on levels IV-V

The assessment rock stability in the vicinity of excavations at levels IV-V was based on the results of spatial numerical analysis covering the entire central area of the mine from the surface to level V (Cała et al., 2012). Numerical calculations were performed by means of the Itasca FLAC program (ITASCA, 2009) based on the finite-difference method. The advantage of this program is the possibility to observe the mechanisms and the direction of destructive and deforming processes. The calculations were made for the elasto-plastic environment including the Mohr-Coulomb strength criterion. This model assumes, that the total increase of deformation is composed of an elastic part and a plastic one. The material behaves linearly elastic until the Mohr-Coulomb criterion is fulfilled; however, after exceeding it the material becomes perfectly plastic.

The choice of this computational model was dictated by a very diverse geological structure of the Wieliczka rock mass and complicated system of mine workings. Numerical analysis of rock mass stability in case of individual chambers and caverns excavated in the homogeneous salt layer are performed generaly with use of rheological models (Berest, 2013, Zhu et al., 2015). To evaluate long-term stability of rock salt the phenomenon of dilatancy is also used, in which the volume of rock increases after exceeding dilatancy threshold. The criterion of "dilatation" in the numerical calculations was used by Fachland et al. (2007) and Berest et al. (2008) among the others. To obtain reliable rheological parameters under laboratory conditions for the Wieliczka rock mass is virtually impossible. Viscosity factor η ranges from 0,14×1015 to 5,29×1017 Pas for various types of Wieliczka salt. Comparision and interpretation of these values is very difficult because they were measured under various conditions of stress, and in different periods of time. Whereas, application of the inverse analysis to obtain parameters for the rheological model on the basis of excavations convergence was possible only for single chambers, not for such an expanded mine model (d'Obyrn, 2011). The problem of numerical modelling in such complicated salt rock mass conditions has been discussed in many earlier publications (d'Obyrn & Hydzik-Wiśniewska, 2013; d'Obyrn, 2011).

The numerical analyses of the rock mass included the region of the current Tourist Route and a majority of mine workings on levels I-V which are planned to be maintained in compliance with the targeted technical model of the mine. The analysis included range of following coordinates: X (–86250, –85150) and Y (21650, 22350). Two mutually overlapping areas of analysis were separated, with dimension each of 700×700 m (total area measuring 1100×700 m). Each model was created with about 2.5 million of tetrahedral elements. The dimensions of the elements were smaller in the vicinity of excavations (about 1 m), and larger, up to approx. 30 m on the edges of the model. Fig. 3-5 is presents mapping of the individual levels, along with marked cross-sections.

For the construction of the numerical model five types of rock, forming six defaulting on a juxtaposed layers were selected (parameters given in Table 4).

Boundary conditions were adopted in the form of lock slide in directions perpendicular to the planes of the side and bottom. After setting the model boundary conditions it was solved

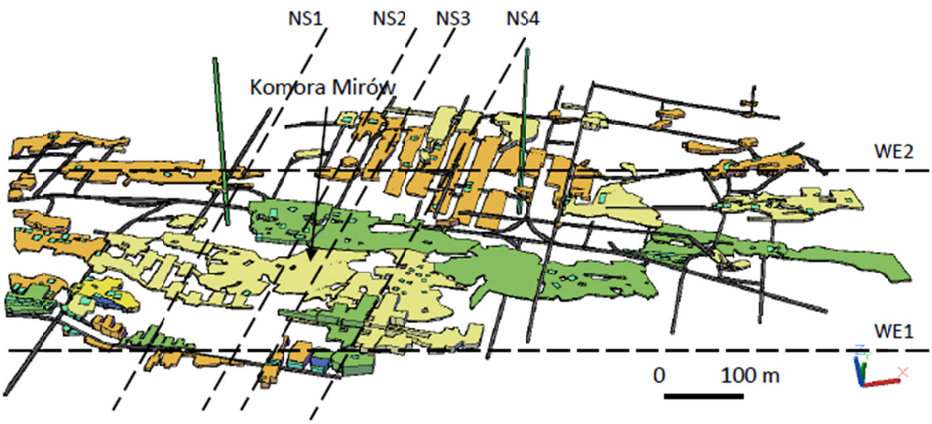


Fig. 3. Geometry of the excavation level IV (Cała et al., 2012)

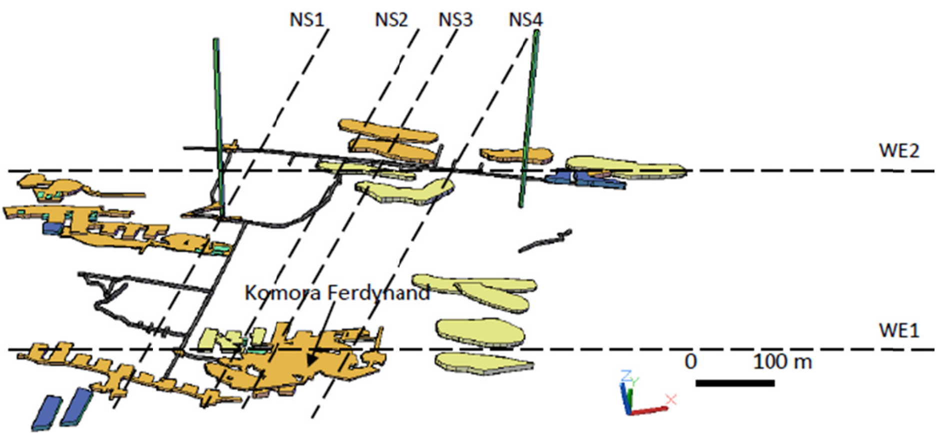


Fig. 4. Geometry of the excavation Kołobrzeg level (Cała et al., 2012)

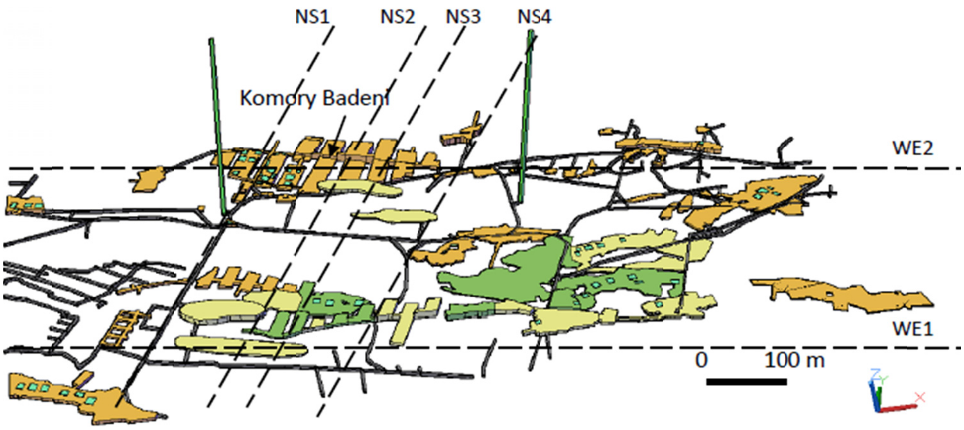


Fig. 5. Geometry of the excavation level V (Cała et al., 2012)

firstly with the assumption of no exploitation (in order to obtain the original state of stress), and then the velocity and displacement vectors were reseted.

Calculations were performed for 3 variants: the first one examines how non-backfilled mine workings interact with one another, and in which areas of the mine the stress concentrations occur; the second one analyses the current state taking under consideration the level of backfilling of currently eliminated mine workings; whereas, the third variant accounts for backfilling all the mine workings that are planned to be eliminated. The backfill material was included in the model with parameters shown in Table 4. Contact between backfilling and the rock mass was assumed with following strength parameters: cohezion $c = 0$ kPa, and friction angle $\varphi = 25°$. The objective of variant 3 was to examine the impact of backfilling a large number of mine workings on the state of the rock mass.

TABLE 4

Mechanical parameters of for the different rock types and filling sand (Cała et al., 2012)

Layers (ordinates layer)	**Rocks**	**Compressive strength, *Rc* [MPa]**	**Tensile strenght *Rr* [MPa]**	**bulk density, [kg/m³]**	**Young's modulus *E* [GPa]**	**Poisson's ratio, *v* [-]**	**cohesion, c [MPa]**	**friction angle, *φ* [°]**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Quaternary formations and locally Chodenice beds (Surface – 230 m a.s.l.)	clay, silty sediments, with inserts sand, gravel and debris flysch	—	—	2000	0.07	0.2	0.2	30
Cap (230 – 210 m a.s.l.)	Clay – gypsum cap	15	1.0	2250	0.75	0.30	0.85	35
Breccia salt deposit (210 – 100 m a.s.l.)	Marl – clay breccia salt deposit and zubrer	23	1.5	2150	1.0	0.25	1.27	35

1	2	3	4	5	6	7	8	9
Sulphate and chloride evaporates (bedded salt deposit) (100 – 0 m a.s.l.)	Spiza salt with sands (100 – 70 m a.s.l.)	35	2.0	2200	1.5	0.35	1.84	40
	The oldest salt layer; green bedded and fore-shaft salt, (70 – 40 m a.s.l.)	36	2.0	2150	2.0	0.35	1.84	40
	Spiza salt (40 – 0 m a.s.l.)	35	2.0	2200	1.5	0.35	1.84	40
Sand backfilling		-	0	1960	0,036	0.20	0.01	25

For the purpose of executing an overall assessment of rock mass stability in the surroundings of the mine workings of the "Wieliczka" Salt Mine, the assessment of rock mass stability (or failure) was conducted. The "stability factor" (Cała et al., 2012) is understood as the ratio between the maximum stress resulting from the Mohr-Coulomb hypothesis and the average stress in an element. In the case, when the value of the "stability factor" will amount to less than 1 – the environment is destroyed. The higher its value the more stable is the rock mass.

In respect to the first variant, the chambers on levels IV, Kołobrzeg and V have the greatest impact on the state of rock stability. This effect is the greatest in the southern and central part of the analysed area. It is also possible to observe large failure zones in the area of the Mirów Chamber (Fig. 6a) which is vast. Also, the significant impact of level IV mine workings on the Piłsudski Chamber becomes apparent (Fig. 6b). Failure zones are noticed between chambers on levels Kołobrzeg, IV and III, the greatest occurring in the area of the Ferdynand Chamber on the interlevel Kołobrzeg. Whereas in the northern section of the analysed area, it is possible to notice significant rock failure zones in the environ of the Badenia chambers on level V (Fig. 6d).

Changes were noticed (Fig. 7) after analysing the impact of the current degree of backfilling of mine workings on overall rock mass stress field, with special reference to the areas of chambers where, in a non-backfilled state, failure zones were observed. In the presented examples of the first variant, a small decrease of failure zone was observed between chambers on levels IV, Kołobrzeg and V. Also, no major changes occurred in the failure state in pillars of the Badenia

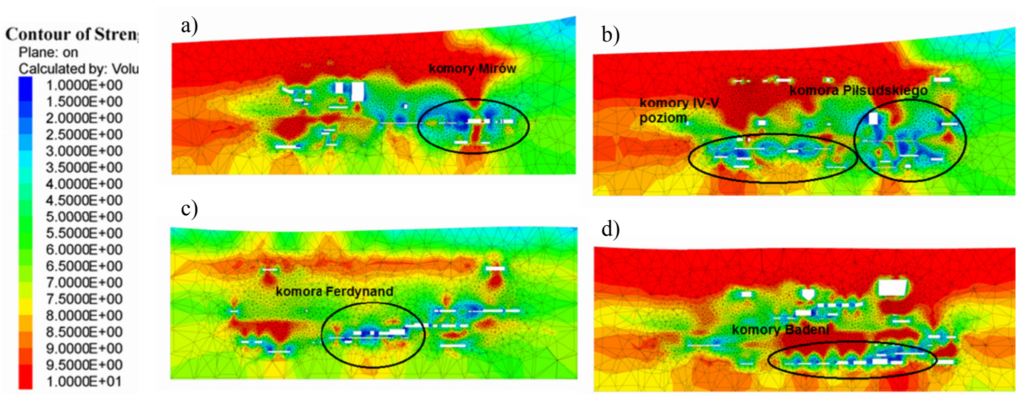


Fig. 6. Failure zones for the original model in the regions of : a) Mirów Chamber (cross-section NS3), b) Piłsudski Chamber (cross-section NS4), c) Ferdynand Chamber (cross-section WE1), d) Badenia chambers (cross-section WE2) (Cała et al., 2012)

chambers (Fig. 7d). New failure zones that appeared in this variant, resulted mainly from the additional load of backfill in chambers above, which were located directly over the non-backfilled chamber mine workings.

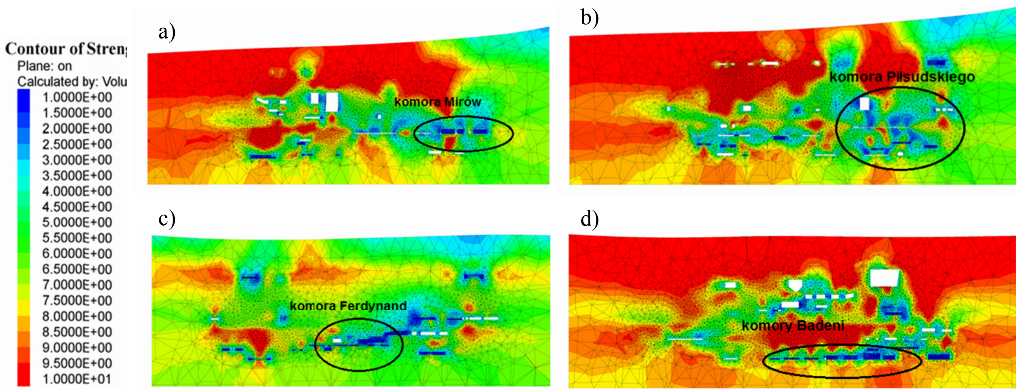


Fig. 7. Failure zones for the current state of backfilling in the regions of: a) Mirów Chamber (cross-section NS3), b) Piłsudski Chamber (cross-section NS4), c) Ferdynand Chamber (cross-section WE1), d) Badenia chambers (cross-section WE2) (Cała et al., 2012)

The target model assumes, that all the chambers designated for elimination will be backfilled. The analysis of such a variant confirmed the observations made of the current variant. Loading the rock mass with backfill has significantly affects the formation of failure zones. In the case of a majority of the chambers this impact is local, whereas, in certain parts of the mine, regions evolve of a significant degree of failure that cover several mine levels. Zones of failure including levels V, Kołobrzeg and IV reaching at certain points to level IIw, may develop in regions of the backfilled part of the Kazanów Chamber (Fig. 8a).

In general, the greatest predispositions for failure zone occurrence are the areas between the Kinga and Daniłowicz shafts stretching towards the south. This is associated with the large surface of mine workings on levels IV, Kołobrzeg and V. The results of numerical analysis prove that chambers on levels IV, Kołobrzeg and V have the greatest impact on mine workings on levels from I to III. Increased failure may occur locally in chamber ceilings above which backfilling

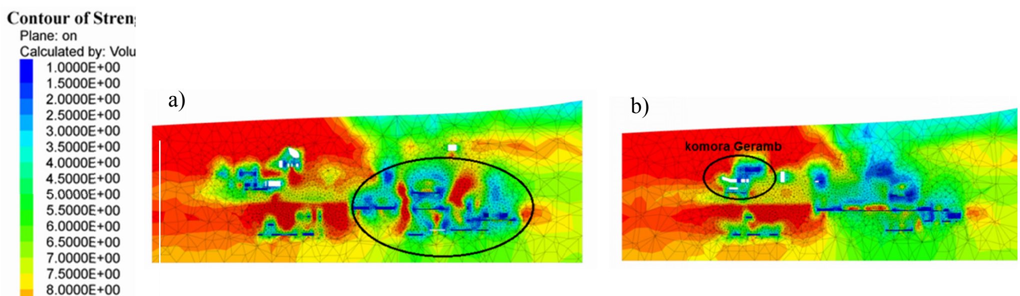


Fig. 8. Failure zones for the targeted backfilling state in the regions of: a) Kazanów Chamber (cross-section NS1), b) Geramb Chamber (cross-section NS2) (Cała et al., 2012)

works are in progress. Such an example would be the Geramb Chamber, above which the Franciszek and Drozdowice chambers are backfilled (Fig. 8b) .

5. Conclusions and summery

Mine workings situated on levels IV, Kołobrzeg, and V are also part of the zone included in the heritage conservator supervision and some of them are distinguished by considerable historical and natural qualities. Moreover, there are many functional workings located on these levels which are crucial for dewatering, communication, transportation, and ventilation. Mine workings situated within these levels were excavated mainly by way of a room-and-pillar system within the deposits of shaft salt, Spiza salt, and the oldest salt and are characteristic for their large surface area.

In the last years, intensive backfilling of the lower mine levels is being gradually conducted (V-VIII) in all areas of the mine by filling empty spaces with hydraulic backfill. It should be stated, after analysing rock mass movements, that periodic measurements of displacements on the surface demonstrate steady subsidence with a tendency to hamper the displacement process. Only in the area of the former Mina inflow slight surface upheavals are being noted during the last years. The rock mass movement in the area of the mine's two main shafts is characteristic for its compressive strain increases in the central parts of the mine workings, i.e. between levels IV and VI, has been stable for a while now. As it results from the analyses of benchmark displacements on individual levels, the whole complex of higher levels together with the surface behaves like a single solid, settling over the lower levels (which contain the largest concentration of modular exploitation excavations). In the area of level IV and V the vertical movement is receding. The movement of lower levels is minimal and is the result most probably of compression of leaching chambers situated there. The hazard to the surface and the historical part of the mine occurs due to the compressing of mine workings in the central and partially in the lower levels. This points to the necessity to, first of all, backfill those levels as the ones that are hazardous to higher levels and the surface. Differences between stress concentrations in the area of the fourth level should also be noted which may affect the destruction of chambers within the limits of the brecciated deposit.

The performed numerical analysis confirmed that mine workings of level IV, Kołobrzeg, and level V have the largest influence on rock mass stability factor. This results from their considerable horizontal dimensions and large density. In the long run they qualify for backfilling. However, it should be taken into account that below them there are the chambers of levels VI-IX and these should be backfilled first because backfilling puts additional load on rock ledges between the levels. The backfilling sequence should also consider water/flooding hazards, technology and work organization.

Numerical modelling showed a very disadvantageous effect of chamber backfilling above the existing mine workings. That is why currently the Mine does not conduct chamber backfillings above the historical chambers. It is crucial to reinforce the chamber that is to remain with additional supports, if backfilling or waterproof liquidation of a chamber situated above historical chambers be necessary.

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