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GEOMECHANICAL NUMERICAL ANALYSIS AS A GUIDANCE FOR PRESERVATION WORKS OF THE "WIELICZKA" SALT MINE SITE

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Abstract: Salt was excavated at the "Wieliczka" Salt Mine for over 700 years. Underground mining operations terminated in 1996, by which time almost 2,400 chambers and 245 km of galleries had been created underground, situated on 9 levels and a few inter-levels. In 1978, the mine was included in the UNESCO World Heritage List, which stated that parts of the mine with historical value had to be preserved for future generations. In order to preserve the most valuable chambers and galleries, activities aimed at establishing a protection pillar for excavations were conducted in the conservation area on Levels I–V. The need of large scope preserving works created the necessity to conduct a new and truly comprehensive geomechanical analysis. Such an analysis could only be done by means of advanced numerical modelling codes. Three-dimensional calculations were performed by means of FLAC 3D finite difference code. Rock mass stability assessment in the vicinity of excavations was carried out on the basis of the distribution and range of the so called failure zones. This comprehensive geomechanical analysis allows for verification and give the directions for future preservation and closure works in the "Wieliczka" mine.

Key words: *geomechanical analysis, numerical modelling, physico-mechanical rock parameters, "Wieliczka" Salt Mine*

1. INTRODUCTION

The behaviour of historical and functional excavations, especially chambers in the "Wieliczka" Salt Mine, is principally affected by the geological structure of the rock mass and hydrogeological and mining conditions. In rock masses such as rock salt, the rheological and plasticity phenomena are activated as a result of rock mass pressure, which leads to a constantly ongoing deformation process of the rock mass surrounding the excavations, and as a result, their squeezing, loss of functionality and in many cases, their elimination. In 1978, after the mine was included in the first UNESCO cultural and natural heritage list, comprehensive operations were launched to create a strong support (in the form of a pillar) under the most historical, central part of the mine – Levels I to IV and partially Level V, through eliminating (backfilling) excavations located at greater depths (Levels VI–IX). These efforts have continued to the present day. Despite these activities, preserving all the excavations, especially on Levels IV–V, has proved virtually impossible due to continuously deteriorating geomechanical and hydrogeological factors, technical condition of the excavations and associated costs. The scope and directions for further elimination works take into account the major danger for the mine, i.e. the flooding hazard, especially at the northern boundary of the deposit into account. In light of findings from the first comprehensive geomechanical analysis [1], [20], and analysis conducted by the "Wieliczka" Salt Mine and Krakow Saltworks Museum in Wieliczka [15], future actions should primarily focus on preserving the most valuable parts, especially chamber excavations. In addition to geological and mining conditions, an important factor is provided through guidelines from the Polish historical monument protection service, which recommends striving for maximum preservation of the original substance and form of the excavations recognized as historic in conducting mining preservation works and define closure or excessive transformation of the excavations as unacceptable and unjustified.

Work conducted on excavation elimination and securing has so far resulted in the necessity to conduct a new and comprehensive geomechanical analysis, which has been made possible by developments in numerical modelling capabilities [5].

This analysis takes the target technical model of the mine, the geological, hydrogeological and mining conditions into account, to provide more precise knowledge of the physical and mechanical parameters of the Wieliczka rock mass, as well as technical condition of the excavations and the operations conducted so far. This includes creating a protection pillar for excavations in the historic area on Levels I–V. The minimum number of historic chamber excavations and excavations performing technical functions has also been taken into account. This analysis therefore allows for verification and feasibility of the "Wieliczka" mine target model to be achieved, in order to carry out future securing and elimination.

Stability of the rock mass in the "Wieliczka" Salt Mine is determined by geological and mining conditions. In terms of mining factors, both historical conditions resulting from mining activities (post-exploitation voids) and the surface of the backfilled excavations should be taken into account.

2. GEOLOGICAL CONDITIONS

Rock salt deposit in the Wieliczka region is part of the Miocene salt-bearing formation that stretches in a narrow belt within the Carpathian Foredeep, from Upper Silesia towards Kraków and Poland's eastern border. The deposit extends in the east-west axis over a length of about 10 km and its width in the area of the "Wieliczka" mine is of approx. 1.0 km. Within it, three lithostratigraphic modules are distinguished: the Skawina, the Wieliczka (the salt series) and the Chodenice layers. The geological structure of the Wieliczka deposit has been the subject of many studies, both in the regional [16], and local context [13], and the knowledge of its complexity, especially in tectonic terms, is regularly enriched [14], [23].

The Skawina layers are formed of green-grey marl with rich foraminifer fauna, sandstones and mudstones. They overlie strongly dislocated formations of the older substrate, mostly Upper Jurassic limestone. The thickness of these formations is highly variable and ranges from approximately 50 m in the western part of the deposit to 350 m in the east.

The Wieliczka deposit contains several layers of rock salt with variable thicknesses, structures and NaCl content. Rock salt layers are separated by claystone, siltstone and sandstone formations as well as gypsum and anhydrite which represent the sulphate facies.

The Chodenice layers occur in the form of dark-grey claystone, shale and mudstone containing gypsum as well as anhydrite, limestone and dolomite clusters. Within the complex of Chodenice layers, the presence of sandy, conglomerate and clastic formations can also be observed.

Within the deposit, two major parts are distinguished: the brecciated deposit and layered bed. In the brecciated deposit, salt formations are strongly dislocated, while in the layered bed, despite tectonic movements the continuity and succession of layers have been generally preserved. The thickness of the salt-bearing layer is approximately 350 m.

The layered bed is formed of three tectonic slices thrust over one another. Within these thrust slices, the salt layers are subject to continuous deformation, i.e. folding and local superimposition, leading to significant changes in their thickness. As a result of these processes, the rigid gangue surrounding the deposit is highly fissured. The bed is formed of layers of the oldest, layered green, shaft and spiza, salts. These salts vary in age, and were formed in ~~a~~ slightly different sedimentation conditions, and also contain different impurities. The gangue in the deposit has formed as laminated mudstone transforming into claystone and sandstone.

The oldest salts form a complex of layers with a thickness of approximately 12 m. They are characterized by varying grain size, variable amounts of terrigenous material and numerous veins of silty-clay and gypsum-anhydrite. The impurities in the salt make up to 50% of its volume. The oldest salts display the greatest variation of strength, particularly compressive strength.

A higher stratigraphic module is formed of layered green salts. These are distributed throughout the deposit in the form of 3–5 layers with the thickness between tens of centimetres and 2 meters, separated by gangue. The size of the crystals in those is variable, but large-crystal salt with crystals between a few to a dozen centimetres in size prevails.

Another stratigraphic module is formed by shaft salt, characterized by the constancy of structure and is present throughout the area. The fine- to medium-crystal salt layer, with a thickness of approximately 1.5 m, is often tectonically thickened due to the susceptibility of shaft salt to plastic deformation. This layer is formed from crystals up to a few millimetres in size.

Above the shaft salt layer, spiza salts occur, approximately 30 m thick, with a variable granular structure, which has a content of terrigenous material. The grain structure is predominant here, with a large admixture of quartz and other terrigenous material (up to 20%). The degree of contamination with sand increases towards the roof of the salt spiza layer, which in places becomes sandy salt (so called "Makowica") or unevenly overlying and distributed sandstone with a halite binder in the roof part of the complex. In the lower part of the layer, a pure variety of the spiza salt (the so called "eagle salt") is usually found. The entire complex of spiza salt is interspersed with mudstone-sandstone anhydrite inserts, with an average thickness of approximately 0.1 m. In the spiza salt layer, a central mudstone-sandstone-anhydrite insert with a thickness of 2–5 meters occurs.

In the upper part of the Wieliczka layer profile, above the layered part of the salt deposit, the brecciated deposit, formed of a conglomerate of marly claystone and zubry (marly claystones with suspended grains of crystalline halite) with laminated green salt blocks and, to a lesser degree, blocks of coarse-grain salt (so-called "stained-glass salt") distributed among them in an irregular manner is found. In the brecciated deposit, dark grey and grey marly claystone, zubry and salt lumps dominate. Dark-grey marly claystone with low cohesion, characterized by irregular cracks and slickensides is found. Within them, numerous gaps filled with fibrous salt occur. As a whole, the claystone complex has virtually no cohesiveness, although its individual fragments can be regarded as solid rock. When decompressed due to mining activities, it crumbles into small pieces, causing collapsing. In the solid salt layer, typical green, laminated, green coarse-grain and dolomitic salt can be observed. Solid laminated green salt contains 1–2 cm crystals, which form thin layers often divided by thin laminae of clay or fine-grain free flowing white salt. Green salt also occurs in the form of thicker lenses of up to 10 cm in thickness. Solid coarse-grain salt is characterized by large crystals surrounded by clay. This layer also contains silty-clay veins of up to tens of centimetres thick. Due to the low level of impurities, only the typical green salt has been mined. The solid green salt blocks vary in size from approximately 1 m^3 to over 100,000 m^3. The blocks are often irregular in shape with rounded edges, often with preserved fragments of the roof and floor surface of the original layer.

On the surface of the Miocene rocks of evaporate series, the most recent Quaternary layer occurs, with very variable thickness and lithology. The Quaternary profile is dominated by clay and silt deposits with sand and gravel inserts.

When constructing physical and then numerical models, it appears that the best possible simplification in mapping such a complex geological structure consists in distinguishing a few layers of rock with parent rock material dominant in the layer. In the numerical model constructed, the following rock layers were distinguished:

- Quaternary formations (clay, silty sediments with sand, gravel and flysch debris inserts);
- deposit lagging (the gypsum-clay cap);
- the brecciated deposit (marly claystone, zubry, salt blocks);
- the layered bed:
  - spiza and sandy salt layer,
  - oldest salt layer (green layered and shaft salt),
  - spiza and sandy salt layer;
- Skawina layers (marly claystone, mudstone and sandstone).

Particular attention should be paid to the separate layer of the brecciated deposit. In the numerical model, parameters of marly claystone and zubry are assigned to this layer. This is due to the fact that salt lumps have been depleted and only thin layers were left around the chambers, which only affects local stability, without influencing the global strength of the rock mass.

It was also assumed that the boundaries of the layers, distinguished for the purposes of numerical modelling should not intersect mine levels, but be located between them instead.

3. MINING CONDITIONS

The current mining structure of the "Wieliczka" Salt Mine is the result of centuries (over 700 years) of exploitation of salt deposits carried out using various extraction techniques. The oldest excavations in the so-called brecciated deposit was created using the dry method, by manual digging. Later, both the brecciated deposit and layered bed were mined with the use of mining machinery and explosives. In the latest stage of the mining operations, the main extraction method consisted of leaching salt with water. As a result, post-exploitation voids of various shapes and dimensions have been created, forming a maze of intersecting or adjacent excavations. The particular method of mining the Wieliczka salt deposit has led to the creation of large-size chamber excavations with the surface of several hundred square meters and the height of up to several dozens of meters. No less than 2,381 chambers with a total volume of more than 9.4 million m^3 have been exploited and more than 245 km of galleries have been created. Currently, excavations cover an area of approx. 5.5 km in the east-west axis and 1.5 km in the north-south one and a depth of approximately 327 m below the surface.

4. CONSTRUCTION OF THE NUMERICAL MODEL

The numerical analysis of such a complex mining structure is a very complex task. The most important issue concerns the selection of the size of the calculation model, the density of mesh nodes and the elements discretizing the area covered by the analysis. The numerical model should be precise enough to allow for mapping the geometry of the excavations, but also performing calculations within a reasonable deadline. Given the excavation dimensions (between several and several dozens of meters) and the approximate dimensions of the area of the mining operations (5.5 × 1.5 × 0.3 km), it is not presently possible to create a numerical model of the entire mine and carry out numerical calculations for it. Therefore, in order to achieve the required mapping accuracy, the exploitation area was divided into two sub-areas, which overlap in the section adapted to the location of the excavations in relation to one another. The numerical analysis of the rock mass surrounding the "Wieliczka" Salt Mine covered the scope of coordinates *X* (–86,250, –85,150) and *Y* (21,650, 22,350). Two overlapping areas were distinguished in the analysis, each measuring 700 × 700 m (Fig. 1) within the following ranges of coordinates:

- Model I – *X* (–86,250, –85,550) and *Y* (21,650, 22,350),
- Model II – *X* (–85,850, –85,150) and *Y* (21,650, 22,350).

Each of the areas of analysis had a height in the range between 0 m "AMSL" and the ground surface and included mine levels from I to V inclusive.

Thanks to this, the size and scope of numerical models were selected in a manner allowing for calculations of stress and strain state along the current tourist route, including the analysis for future preservation of all 396 chambers to be performed.

In addition to geological conditions, mapping of the shape of the chambers plays an important role in the construction of a calculation model. Geometry of the "Wieliczka" Salt Mine chambers is very complex, varying in shape depending on exploitation technology used. In the brecciated deposit, excavations often have a considerable height, and in the horizontal section, they are oval in shape, adapted to the form of salt lumps and are inclined to the north, in line with the general direction in which the lumps are located in the rock mass. This is illustrated, e.g., by the Staszic chamber located at the Kazanow inter-level (Fig. 2).

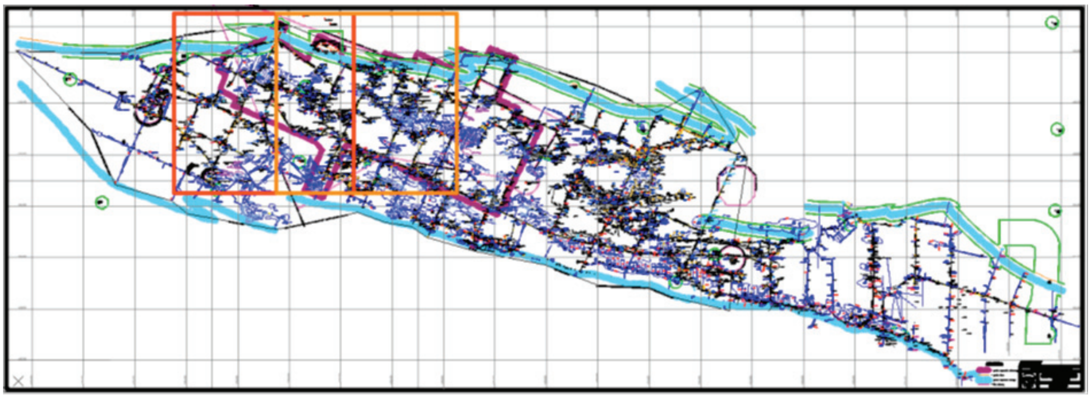

Fig. 1. The size and scope of numerical models and the map of Level III of the mine (Model I – red, Model II – orange)

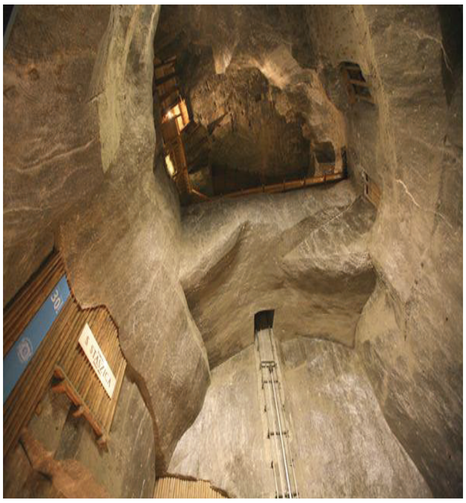

Fig. 2. Example of a chamber created in the brecciated deposit – the Staszic Chamber is 36 m high

In the layered bed, chambers were dug out in shaft salt, spiza and oldest salt layers. The shaft salt layer is present throughout the deposit and has a thickness of approx. 2–2.5 meters, and this is the height of the chambers in this layer. Most of them are extensive and divided by pillars. In contrast, chambers dug out in spiza and the oldest salts are generally much higher, they have a more regular shape, and are often grouped together in the so-called exploitation fields. Spatial mapping of so many different shaped excavations is a very complex issue. While it is possible to create accurate models of each chamber, an analysis of the entire mine or a substantial portion of it requires introduction of some simplifications. Due to the complex shape of each chamber as well as a large number of excavations to be included in the model and aforementioned limitation in the number of components and grid nodes in the numerical model some of the chamber shapes need to be simplified. Such changes have a limited influence on the calculation results but greatly facilitate the solution of the problem.

The analyses of the shapes of the chambers in the shaft, spiza and oldest salt deposits show that the most of them have relatively flat roofs. This suggests that it is possible to assume a certain average height for each chamber and to create an excavation body with a volume similar to the actual one basing on the outline of the mining map. This assumption is a simplification. First of all, mapped chambers are located horizontally, which is not always the case at the "Wieliczka" Salt Mine, although many chambers are in fact situated in such a manner. Secondly, the shapes of the chambers in the brecciated deposit are irregular and their ceilings are vaulted. Vaulted ceilings have a better stability than their numerical equivalents with flat ceilings. The assumption of flat roofs of the chambers gives some additional safety margin in the numerical analysis performed.

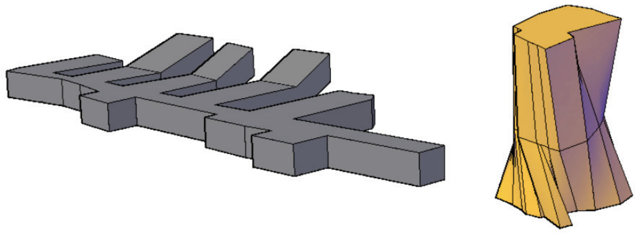
(a) (b)

Fig. 3. A chamber stretched perpendicularly (a)
a multi-level chamber (b)
(a – Geramb chambers, b – the Staszic chamber)

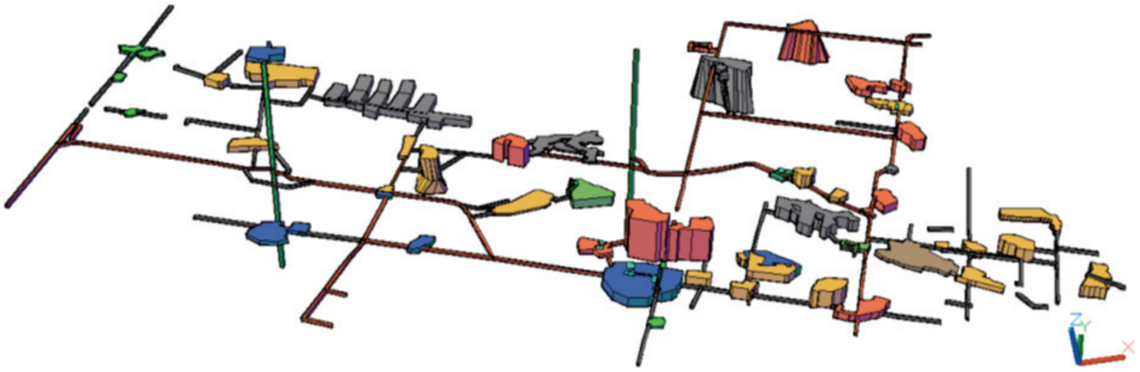

Fig. 4. Sample geometry of level excavations (lower Level II)

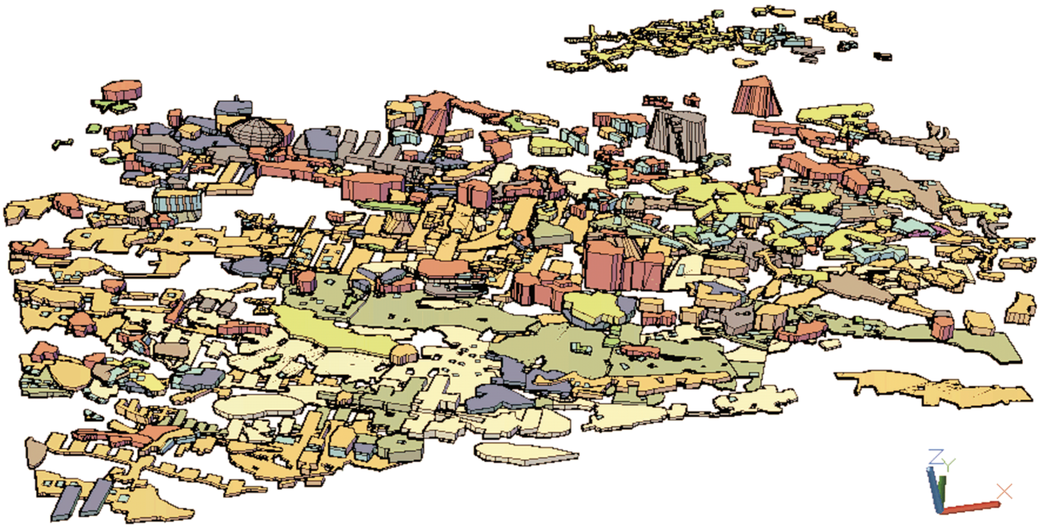

Fig. 5. View of the mapped geometry of the chamber excavations

In the next stages, models were created for each of the excavations (Fig. 3), at each level (Fig. 4), and finally for the entire model (of the analysed part of the mine) (Fig. 5).

In comparison to chamber excavations, gallery excavations are of relatively small ~~in~~ size, and the majority of them are protected by mining support. Due to this fact, they are not an essential element influencing the stability of the rock mass for the purpose of the global numerical analysis of the mine.

At the "Wieliczka" Salt Mine, a number of types of mining linings have been used, such as supporting timber linings, cribs, and rock bolts. The role of each type of lining, and their impact on the rock surrounding the excavation, are different. The rock bolts aim, on the one hand, at strengthening the roof and side walls, by creating a strong layer of rock in the shape of a vault around the chamber, while, on the other hand at protecting against the stratification of rocks and collapse. Numerical modelling of the impact of the rock bolts on the behavior of the rock mass in the vicinity of the excavations [2], is only possible for an individual excavation, or a small number of excavations, and in the numerical analysis of the entire mine, or a large part thereof, it is virtually impossible to take the rock bolts into account, as the bolts are too small in relation to the size of the whole analysed rock mass model. Moreover, rock bolts have an impact on the stability of rocks surrounding a single chamber, but does not significantly affect the condition of the failure concerning the whole rock mass, which consists of a large number of gallery and chamber excavations. Therefore, rock bolts can be neglected when analysing the stability of the rock mass of the "Wieliczka" mine, which contains multiple excavations.

The role of timber support linings (with the exception of cribs) in the Wieliczka mine is similar to the role of rock bolts. It only protects individual chambers against collapses and their further propagation. Like the rock bolt, it only has a local impact. The purpose of this type of lining is primarily to ensure safe use of excavations.

In contrast to the lining types described above, the crib lining has a significant impact on larger volumes of the rock mass. It is characterized by a relatively high rigidity and is used extensively over wide areas in the "Wieliczka" Salt Mine. This type of support allows for the transfer of very high compressive loads, with relatively limited vertical deformation. Only in the case of very large rock pressure, can the crib lining be partially destroyed, but even then, it is still able to transfer very heavy loads. Therefore, it is necessary to take crib linings and their distribution on the mining maps of the "Wieliczka" Salt Mine into account in the numerical model. Given the scale of the analysis presented, cribs can be modelled with a suitable approximation as a continuous elastic medium with deformability described by Young's modulus and Poisson's ratio.

The Wieliczka rock mass strength parameters vary greatly and depend mainly on location, degree of rock

Table 1. Mechanical parameters of rocks

Era	Formations	Material	UCS [MPa]	Tensile strength [MPa]	γ [kN/m^3]	E [GPa]	ν [–]	c [MPa]	ϕ [$^{\circ}$]
Holocene, Pleistocene, Pliocene	Formations classified as Quaternary and local Chodenice layers	Clay, silty sediments, with sand, gravel and flysch debris inserts			20.0	0.07	0.2	0.2	30
Miocene	Lagging	Gypsum-clay cap	15	1.0	22.5	0.75	0.30	0.85	35
	Brecciated deposit	Marly claystone of the brecciated deposit and zubry	23	1.5	21.5	1.0	0.25	1.27	35
	Sulphate and chloride evaporites (layered bed)	Spiza and sandy salt	35	2.0	22.0	1.5	0.35	1.84	40
		Oldest, green layered, and shaft salt	36	2.0	21.5	2.0	0.35	1.84	40
		Spiza salt	35	2.0	22.0	1.5	0.35	1.84	40
Sand backfilling			–	0	1960	0.036	0.20	0.01	25

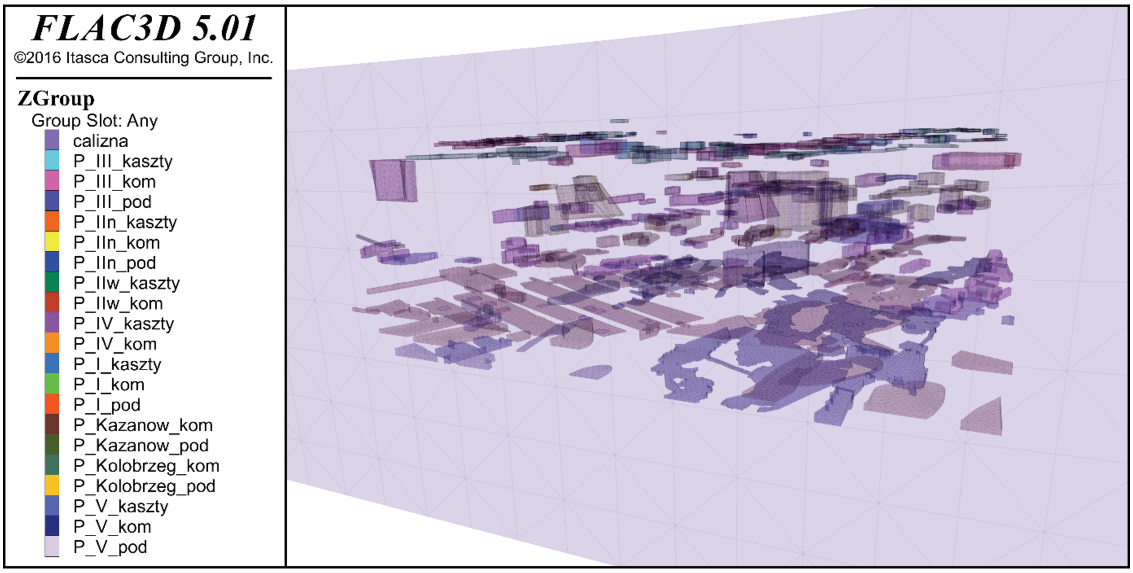

Fig. 6. View of Model II

mass contamination, water inflow, state of the rock body (cracks, fissures), but also on the location where samples are collected and the testing methods. For example, the compressive strength of selected layers of rock is as follows:
(a) block green salt 23.0–55.0 MPa, av. 41.1 MPa;
(b) spiza salt 19.0–50.0 MPa, av. 36.0 MPa;
(c) shaft salt 25.2–48.0 MPa, av. 36.6 MPa;
(d) zubry 8.7–38.0 MPa, av. 23.0 MPa;
(e) marly claystone 8.0–32.0 MPa, av. 19.0 MPa.

In addition, many studies [4], [6], [8], [11], [12] demonstrate that the, a tensile strength of the block green salt by Brazilian test is on average from 1.47 to 1.81 MPa, shear strength is on average between 2.89 and 12.6 MPa, the flexural strength, depending on the load pattern, is on average between 3.89 and 4.28 MPa, and breaking strength tested by direct tension is on average between 1.72 and 2.06 MPa. This data confirms the significant variability of stress and strain parameters of the rocks forming the Wieliczka deposit and its immediate surroundings. The interval for these parameters can be narrowed if data is available for a particular area of the mine or a single excavation [7].

The values of physical and mechanical properties for various lithological varieties of rocks found in the Wieliczka rock mass, adopted for numerical calculations are given in Table 1.

Based on the data described above, two numerical models were constructed corresponding to the areas presented in Fig. 1. Each of them was formed out of approximately 2.5 million tetrahedral elements. The dimensions of the elements were smaller (approximately 1 m) in the vicinity of excavations and larger (approximately 30 m) on the edges of the model. Figure 6 presents Model II.

5. MODELLING METHODOLOGY

At present, the main method of three dimensional modelling consists of simulating the actual rock mass with excavations of a chosen and specific location [4], [6], [9], [17], [21], [22]. The most commonly used numerical methods: the Finite Element Analysis (FEA), the Boundary Element Method (BEM) and Finite Difference Method (FDM) provide sufficient accuracy to determine the state of stress and displacement of the modeled part of the mine, even if the rock mass is of heterogeneous nature.

For stability calculations, the elastic-plastic model with Coulomb–Mohr failure criterion and non-associated plastic flow rule was used. The dilatancy angle was assumed to be equal zero. Calculations were performed on a model in which the parameters of long-term strength were assumed for the plasticity criterion. In numerical calculations, such a model allows the non-linearity of stress–strain characteristics of the rock mass to be taken into account, thanks to the assumption that inside the area below the boundary surface, the rock mass behaves in an elastic, while outside the area, in a plastic manner. Solutions to geomechanical problems with the use of the model are commonly employed in assessing the stability of the salt rock mass in the vicinity of the chambers [3], [4], [6], [18], [19].

Spatial calculations with the use of the Finite Difference Method [10] were conducted in three stages.

The first stage (original state) concerned the time when none of the excavations had yet been backfilled. At this stage, the presence of cribs and their location were taken into account. The calculations aimed to check how the chambers affect each other and in which regions of the rock mass the lowest safety factor was observed. At the second stage (present state), the backfilling of the excavations was modeled. The purpose of the calculations for this variant was to analyse the influence of backfilling of selected excavations on the state of strain of the rock mass. The model calibrated in this manner was the basis for further calculations and allowed for global geomechanical analysis of the target model for the "Wieliczka" mine. The third stage (the final stage) of the modeling allowed for the analyses of the planned target model of the "Wieliczka" Salt Mine, based on the plans of the Mine management. In the numerical model, it was assumed that all the chambers which are to be closed have been fully backfilled. The calculation at this stage was aimed at examining the influence of backfilling of a large part of excavations on the state of the rock mass, particularly in the historic part of the mine.

The global assessment of the stability of the rock mass in the vicinity of the excavations of the "Wieliczka" Salt Mine was conducted on the basis of the distribution and the values of factors of safety. Results are shown in the form of a map for each section, which present the distribution of "the level of safety factor". The term "level of safety factor" refers to the ratio between the maximum tangential stress τ_{max}□ resulting from the Mohr–Coulomb hypothesis and the average stress calculated for the analysed element $\sigma_{av} = 0.5(\sigma_1 + \sigma_3)$. The stress on each element were ordered as follows: $\sigma_1 \geq \sigma_2 \geq \sigma_3$. Maximum Mohr's circle tangent to the Coulomb–Mohr's failure envelope was achieved by adopting a calculated numerical value σ_3 until obtaining contact. In point of contact the value τ_{max} was obtained.

When the "level of safety factor" for a given element reached the value of 1 (or less than 1), it meant that the rocks at this location were at failure. The higher the value of the factor of safety was, the more

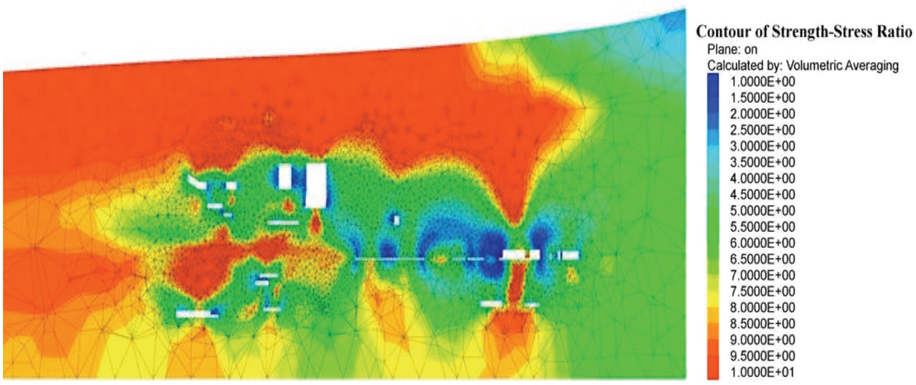

Fig. 7. The safety factor in the cross section $X = -85{,}810$.
Interaction between the Staszic and Saint Kinga's Chapel chambers and the safety factor in the region of the Mirów Chamber (Level IV) – current state

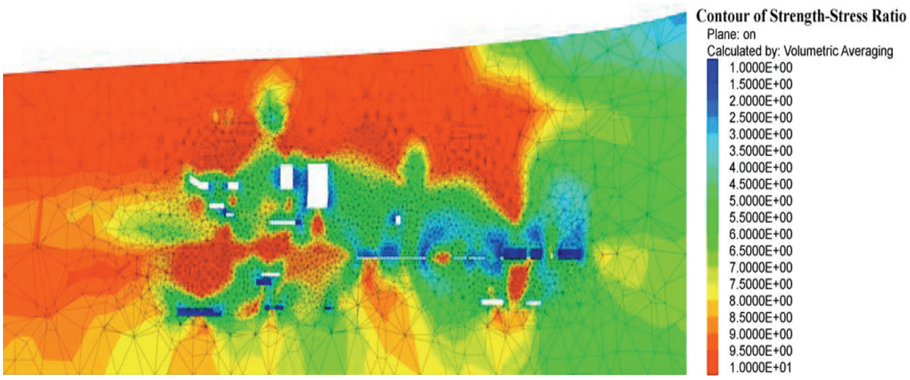

Fig. 8. The safety status in the cross section $X = -85{,}810$.
Interaction between the Staszic and the Saint Kinga's Chapel chambers and safety factor in the region of the Mirów Chamber – target model of the mine

stable the rocks at the location under consideration became. The 3D numerical model was casualty validated and calibrated basic on the in situ measurments.

Such a method of calculation enabled locations in which the rock mass may lose stability to be identified. Below, the map of the safety factor in the cross section $X = -85,810$ is presented as an example, (Fig. 7), which shows the safety factor in the region of the Staszic, Saint Kinga's Chapel and Mirów chambers (Level IV) as of the present day before the planned backfilling of excavations in the area.

By contrast, Fig. 8 presents the map of the safety factor of the same cross-section $X = -85,810$, which shows the safety factor in the region of the Staszic, Saint Kinga's Chapel, and Mirów chambers (Level IV) after planned backfilling of the excavations in the region of the Mirów Chamber.

The comparison of the two maps demonstrates that in the region of the Staszic and Saint Kinga's Chapel chambers, no significant differences in the level of rock mass safety factor can be observed between the present state (Fig. 7) as well as after reaching the target model of the mine (Fig. 8). This is due to the fact that it is not planned to conduct backfilling in the vicinity of these chambers. On the other hand, clear changes were observed in the region of the Mirów chamber after planned backfilling operations in the area.

6. CONCLUSIONS

On the basis of the analyses conducted, it can firstly be concluded that the greatest impact on the rock mass state in the historic part of the "Wieliczka" mine is exerted by excavations on the IV, Kołobrzeg and V levels. This is due to their large number, considerable horizontal dimensions and significant concentration. In the long term, those need to be backfilled. Backfilling schedule should be based on the fact that under those excavations the chambers located on levels VI–IX are situated. Given the large volume of chambers on levels IV, Kołobrzeg and V, stress concentration due to their prior backfilling would create a very considerable hazard for chambers located on lower levels, as it was shown in the numerical analyses. The order of backfilling should also take the water hazard, the technology applied and the organization of work into account.

Within Levels I–III, zones of lower safety factors occur only locally, mainly in the vicinities of large chambers situated in close proximity, for example, the Staszic and St. Kinga's Chapel chambers. A large number of those are to be preserved due to their historic value; therefore, they should be reinforced by rock bolts and/or supporting lining.

Numerical modelling also reveals that backfilling the chambers located above existing excavations has a very negative impact. Therefore, chambers located above historic chambers should not be backfilled, unless this is required due to collapse hazard. In this case, chambers located below the backfilling region should be further reinforced.

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