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SELECTED ASPECTS OF NUMERICAL MODELLING OF THE SALT ROCK MASS: THE CASE OF THE "WIELICZKA" SALT MINE

WYBRANE ASPEKTY MODELOWANIA NUMERYCZNEGO MASYWU SOLNEGO NA PRZYKŁADZIE KOPALNI SOLI „WIELICZKA"

Each excavation or excavation complex intended to be backfilled or secured requires an individual approach, and conducting a detailed geomechanical analysis which will allow the selection of the appropriate manner of securing or backfilling or liquidation, and the order of performing mining works. The numerical model of the selected chamber or group of chambers must accurately reflect the reality and have an appropriately selected calculation model.

The paper presents the selected aspects of numerical modelling of the "Wieliczka" salt rock mass. There are method of selection of geotechnical and rheological parameters of salt, the geometrization of the excavations continues and selection calculation model.

Keywords: selection of geotechnical and rheological parameters of salt, numerical stability analysis

Kopalnia Soli „Wieliczka" jest najcenniejszym zabytkiem górniczym, zarówno w kraju jak i na świecie, wpisanym na Listę Dziedzictwa UNESCO. Jest przykładem wielowiekowej sztuki górniczej, która odznacza się bardzo skomplikowanym układem przestrzennym wyrobisk. Ciekawa budowa geologiczna odznaczająca się różnorodnością postaci występujących tam soli wiąże się niestety z trudnością oceny i doboru parametrów geomechanicznych i reologicznych górotworu. Wpływa to na konieczność uśredniania tych parametrów. W obrębie złoża bryłowego istotne rozróżnienie dotyczy właściwości brył soli kamiennej oraz zubrów solnych czyli bezstrukturalnej masy, wymieszanych kryształów halitu i iłów. Szczególnej uwagi wymagają badania wykonywane w złożu pokładowym. Parametry geomechaniczne ulegają tam zasadniczym zmianom w przypadku występowania przerostów ilastych, a zawilgocenia i wszelkie objawy występowania wód powodują skokowe zmiany parametrów. Najtrudniejszą sytuacją dla określenia parametrów geomechanicznych jest kompleks naprzemianległych, kilkucentymetrowych warstw soli poprzedzielanych kilkumilimetrowymi warstwami, niekiedy zawilgoconych iłów.

Podstawą w Kopalni Soli „Wieliczka" do wszelkich prac projektowych, dotyczących zabezpieczenia zabytkowych wyrobisk lub likwidacji zbędnych są analizy geomechaniczne. Budowę modelu numerycz-

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nego kopalni, a nawet niewielkich jej rejonów bardzo komplikuje zarówno budowa geologiczna z dużą różnorodnością właściwości geomechanicznych, jak i wzajemne usytuowanie wyrobisk.

W pracy zaprezentowano wybrane zagadnienia modelowania numerycznego masywu wielickiego. Skupiono się przede wszystkim na doborze właściwości geomechanicznych i reologicznych soli wielickich, geometryzacji wyrobisk oraz doborze modelu obliczeniowego.

Na podstawie dostępnych dokumentacji badań laboratoryjnych stwierdzono, że próby zaliczone makroskopowo do jednego rodzaju skały charakteryzują się dużymi przedziałami zmienności parametrów odkształceniowo-wytrzymałościowych. Na podstawie zebranych wyników określono jedynie przedziały zmienności poszczególnych parametrów, które zawarto w tabeli 1. Na temat własności reologicznych soli wielickich informacje pojawiają się jeszcze bardziej sporadycznie. Współczynnik lepkości η soli wielickiej zawiera się w bardzo szerokich granicach od $0{,}14 \times 10^{15}$ do $5{,}29 \times 10^{17}$ Pas, co w głównej mierze związane jest z różnymi warunkami naprężeniowymi i czasowymi podczas badania. Odmiennym zagadnieniem jest dobór modelu reologicznego soli. Dla warunków wielickich poczynione zostały tylko próby adaptacji opracowanych modeli dla innych rodzajów soli. Do najpopularniejszych opisów pełzania soli należą model reologiczny Bürgersa (1) i potęgowe prawo Nortona (2). Często parametry reologiczne określane są na drodze, tzw. „analizy odwrotnej", polegającej na takim doborze właściwości górotworu do modelu numerycznego, aby w wyniku symulacji uzyskać, np. rzeczywiste wartości przemieszczeń konturów wyrobiska lub jego konwergencję. Bardzo dużo trudności nastręcza odwzorowanie geometrii i wzajemnego usytuowania komór, szczególnie w ujęciu przestrzennym oraz powiązania z warunkami geologicznymi, a niekiedy nawet hydrogeologicznymi. Geometryzację modeli wykonuje się zwykle na podstawie materiałów geodezyjnych oraz opisów stanu technicznego. Często z powodu braku dokładnych danych lub niemożliwości określenie kształtu wyrobiska (np. z powodu braku dostępu, zawału, podsadzenia, itp.) lub z ograniczeń wynikających z programu czy sprzętu komputerowego konieczne staje się uproszczenie geometrii. Najczęściej stosowane metody numerycznych obliczeń: elementów skończonych (MES), elementów brzegowych (MEB) oraz różnic skończonych (MRS) pozwalają na określenie z wystarczającą dokładnością wartości naprężeń i przemieszczeń w całym analizowanym modelu, nawet wówczas, gdy posiada on niejednorodną strukturę. Każda metoda numeryczna na własny algorytm obliczeniowy i do każdego rozwiązywanego problemu należy podchodzić indywidualnie.

Słowa kluczowe: dobór właściwości geomechanicznych i reologicznych soli, numeryczna analiza stateczności

1. Foreword

The Salt Mine in Wieliczka, whose origins go back to the twelfth century, is one of Poland's most valuable monuments of material culture, renowned and admired throughout the world. The primary objective of the underground mining operations conducted in the mine is to protect its historical past and preserve it for future generations. All projects of mining securing of historic workings or backfilling of chambers with no historic value must be preceded by a thorough geomechanical analysis which normally involves a numerical stability analysis. The numerical model of the selected chamber or group of chambers must accurately reflect the geometry of the voids, their mutual location, geological structure, geotechnical and rheological parameters of the rock mass and a an appropriately selected calculation model.

The most distinctive feature of the Wieliczka deposit is its lithostratigraphic and tectonic dichotomy. The deposit was strongly folded, and additionally, chambers created during over seven hundred years of exploitation are characterised by a complex form and mutual arrangement. Both the geological structure, characterised by a large variety of geomechanical properties, and the excavation layout complicate the construction of numerical models of the entire mine and even small parts of it. Additionally, the ability of salt mass to deform over time, without interrupting the continuity, and the difficulties associated with the selection of the appropriate rheological model create further problems in performing numerical analysis of the geomechanical stability of the excavations. Numerical techniques verified on the basis of laboratory and *in situ* tests are continuously improved, and the results of analysis obtained continue to better and better reflect the actual situation.

2. The geological structure and hydrogeological conditions

The Wieliczka rock salt bed was created in the Neogene (Badenian, Middle Miocene) and forms at present a narrow strip with a length of approximately 12 km and a width of up to 1.5 km (Fig. 1) extending along the northern edge of the Carpathians (Gawel, 1962), Oszczypko et al., 2006). In the western part, the bed takes on a wedge shape, and salt deposits are transformed into sulphates. The eastern part of the bed has been found to extend for about 5 km from the town of Wieliczka and probably continues in the easterly direction. The northern border of the bed is formed by the contact zone with clayey-gypsum-anhydrite formations of the Chodenice layers. In the south, salt formations have been forced under the superimposed Carpathian flysch, where the folded autochthonous and paraautochtonic Miocene formations were pressed onto the autochthonous Miocene ones.

The structure of the bed can be divided into two contrasting parts: the blocky bed and the layered bed (Fig. 2). In the upper part of the deposit adjacent to the surface, the bed is dominated by blocks of rock salt distributed among unstructured gangue. Blocks of up to several thousand cubic metres are set in the mass of marl claystone and halite crystals scattered in them (in clay-

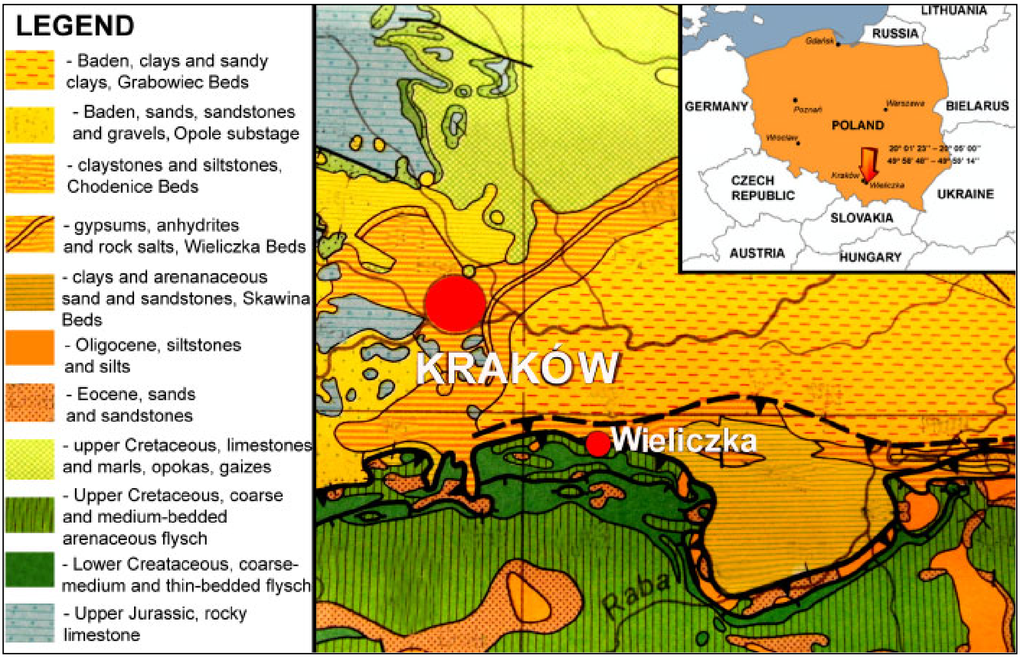

Fig. 1. Fragment of the geological map of Poland without Quaternary formations (based on Rühle, 1977)

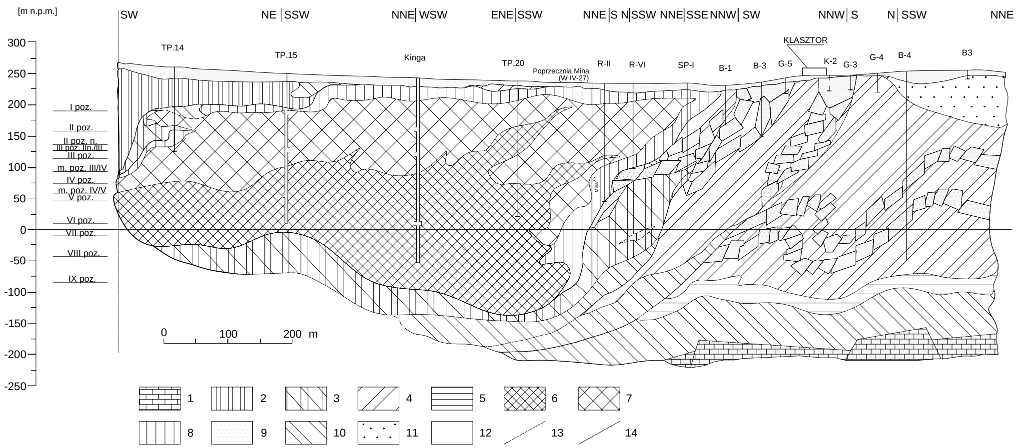

Fig. 2. Geological cross-section of the "Wieliczka" salt bed (Szybist, 2011)
1 – Jurassic; 2 – Carpathian Flysch; 3 – Skawina beds + Flysch (undivided); 4 – Skawina beds;
5 – parautochthonous salt series; 6 – salt series of the bedded deposit; 7 – salt series of the breccia deposit;
8 – clay–gypsum caprock; 9 – sandstone series (Chodenice beds); 10 – Chodenice beds; 11 – Grabowiec beds;
12 – Quaternary; 13 – probable main thrust zone; 14 – minor thrust zone

stone micrite/silt-halite (*zubry solne*).The layered bed is composed of rock salt layers separated by layers of gangue, mainly claystones. The Wieliczka bed is separated from the surrounding geological structures by secondarily formed silt-gypsum coating. The entire complex was subjected to tectonic strain and folded in three major tectonic thrust slices pressed onto each other in the northern direction (Wiewiórka, 1985; d'Obyrn & Przybyło, 2010).

As a result of the tectonic origin of the bed, its thickness reaches 350 m, even though it was originally of approximately 80 m (Garlicki & Wiewiórka, 1989). Above the bed, Quaternary formations of the thickness of approximately 5 m to 40 m are located. Pleistocene formations are in the form of particulates, silt loam, sandy particulates, fine- and medium-grain sand and silty sands. Holocene formations are represented by water accumulation deposits in the form of loams, clays, sand and peat.

The solubility of salt in water, which reaches the value of 360 g/dm^3 is the reason for the special significance accorded to all water inflows into the salt mine. The inflow of unsaturated water from the exterior can lead to uncontrolled leaching and loss of the stability of the excavations located above. The hydrogeological conditions of the Wieliczka bed indicate that the largest inflow into the Mine originate from the sandy-loam Chodenice layers located at the northern outskirts of the bed. Some of these inflows were originally of catastrophic nature, threatening the existence of the mine. The silt-gypsum coating insulating the bed from the aquifers has been pierced by mine shafts, boreholes drilled from the surface and the excavations, chamber collapses reaching the surface level, gallery excavation and the uncontrolled growth of leaching chambers. The drill holes and the excavations form the routes for the migration of water in the bed. Most inflows have been inventoried and are controlled, but the exploitation of the bed over more than seven hundred years, the collapses and the compressing of the excavation resulted in the inability to fully control the water hazards in the mine. The observations and chemical tests of mining inflows conducted indicate that in 2010, the natural inflow into the mine workings from the recorded 162 spills was of approximately 250 l/min. Overall, in 2010, 136,278 m^3 of water from inflows flowed into the mine with an average salinity of NaCl equal to 129 g/dm^3 (d'Obyrn & Brudnik, 2011).

3. The rheological model of salt – rock salt mass destruction criteria

Forecasting the stability of excavations in salt rock mass requires addressing a number of problems in the field of geomechanics. Because of the rheological properties of salt, those include the problem of the impact of time on the stress and strain properties. Rock salt is not an elastic medium and its deformational properties can vary widely.

In general, the process of rock salt creeping can be divided into three stages (Fig. 3.

- creep development stage (primary creep) – decreasing strain intensity,
- steady-state creep stage – stationary creep,
- final creep phase: accelerating of creep leading to the destruction of the material (D_1), the disappearance of creep (D_3), creep remains unchanged (D_2).

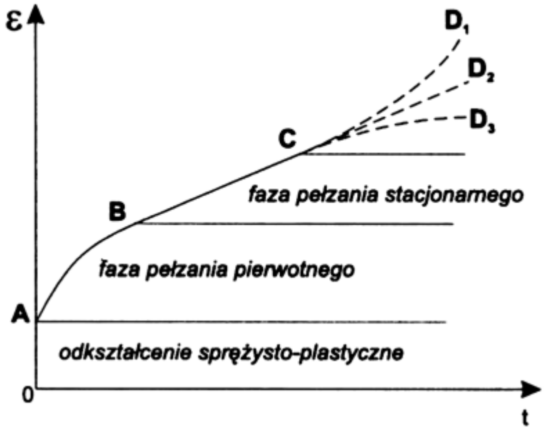

Fig. 3. Phases of rock salt strain (Ślizowski, 2006)

The relationship between stress and creep rate of salt is not linear. In the stress range below the dilation threshold, or the strain level above which an increase in the rock volume occurs, it is possible to apply traditional, linear rheological models with some approximation. For greater values of stress, the increase in load causes a disproportionate increase in strain rate. Creep tests are most often conducted in uniaxial stress state, and since they are time-consuming, the number of tests that can be conducted, or their duration, is limited. For this reason, short-duration creep tests with gradual increase of load or with cyclic loading and unloading of samples are especially popular. Laboratory creep tests (modified in various ways) produce a series of mathematical relations widely described in the works by Flisiak (2002), Wang (2004) and Ślizowski (2006). These relationships have an important scientific value, but applying them in practical calculations, even with the use of numerical methods, is generally impossible due to their very complex formulas and difficulties in the selection of all the parameters. For this reason, much simpler mathematical formulas are used which reflect the actual state adequately.

One of those is Burgers' rheological model used in mapping the behaviour of the salt rock mass by, among others Swift and Reddish (2005) and Minkley and Mühlbauer (2007). It was created by combining Kelvin's and Maxwell's models, and it is described by the following relation (1):

$$\varepsilon(t) = \begin{cases} \dfrac{\sigma_0}{E_M} + \dfrac{\sigma_0}{\eta_M} t + \dfrac{\sigma_0}{E_K}\left[1 - \exp\left(-\dfrac{E_K}{\eta_K} t\right)\right] & (t < t_0) \\ \dfrac{\sigma_0}{\eta_M} t_0 - \dfrac{\sigma_0}{E_K} \exp\left(-\dfrac{E_K}{\eta_K} t\right)\left[1 - \exp\left(-\dfrac{E_K}{\eta_K} t_0\right)\right] & (t > t_0) \end{cases} \tag{1}$$

where,

E_M, η_M — Maxwell body parameters,
E_K, η_K — Kelvin body parameters,
t_0 — time of unloading impulse.

Another mathematical formula for creep is Norton's power law used and modified by many authors (Wang, 2004), (Kortas, 2006), (Fahland et al. 2007) in the following form:

$$\frac{d\varepsilon}{dt} = A\sigma^n \exp\left(-\frac{Q}{RT}\right) \tag{2}$$

where,

R — universal gas constant (1.987 cal/mol K),
T — temperature in Kelvin,
Q — so-called activation energy, whose value can be determined on the basis of laboratory creep tests at different temperatures or *in situ* convergence measurements.

In a paper by Ślizowski et al. (2011), Norton's creep law parameters are presented for salt at the Polkowice-Sieroszowice layer. The parameters were obtained by back analysis with the use of convergence measurements on the contour of the excavation and inside the rock mass. Finally, Norton's law parameters were established as follows:

- $n = 5$
- $A = 0.010772$ MPa^{-5}
- Q/R = 5750 K.

Both Burger's model and Norton's creep law are used among others as computational modules in the MRS FLAC software (FLAC 3D, 2008).

In order to describe the rheological processes occurring in the salt rock mass surrounding shallow excavations, in which low values of deviatoric stress permit the application of linear rheological models, linear heredity theory is also applied, based on Boltzmann's and Volterra's integral equations (Flisiak, 2010; d'Obyrn, 2011). The theory offers the advantage of accurate mapping of the process of rock creep, depending only on the proper selection of the kernel of the integral equation, on the basis of both laboratory tests and measurements of rock mass displacements in the mine workings. The theory of linear creep is based on the assumption that the strain at any time depends not only on the stress operating at that time, but also on the entire previous history of the load. This means that if at $t = \tau$, the rock mass is loaded with a force which causes stress $\sigma(\tau)$, the elementary strain increment $d\varepsilon$ over the time $d\tau$ depends on the stress value $\sigma(\tau)$, time $d\tau$ and the difference $(t - \tau)$, i.e. the time elapsed from the time τ of load application to the analyzed time t. Therefore, strain increment can be expressed as the following linear equation:

$$d\varepsilon = \frac{1}{E}\sigma(\tau)\,d\tau\,L(t-\tau) \tag{3}$$

where,

E — Young's modulus,

$L(t-\tau)$ — a decreasing function with respect to time $(t - \tau)$.

Since at any point in time, the strain is the sum of elastic creep strain, the total strain over time t can be determined by integrating the expression (3) relative to the time variable τ and adding the value of elastic strain.

Therefore, the total strain is:

$$\varepsilon(\sigma,\tau) = \int_0^t \sigma(\tau)\,L(t-\tau)\,d\tau + \frac{\sigma(t)}{E} \tag{4}$$

Integral equation (4) represents the general law of the rock mass strain over time. The function $L(t - \tau)$, which is the kernel of the integral equation, is called the kernel of creep. The form of the function depends on the type of rock mass and is determined through empirical tests and laboratory creep tests or as a result of excavation contours convergence measurements. The rock mass characterised by linear heredity can be considered as an elastic medium with instantaneous parameters being a function of time. The strain state of such a medium at any time t is therefore defined by equations in the form of the generalized Hooke's law, where the coefficients $E(t)$, $\nu(t)$ and $G(t)$ adopt values calculated for time t. The kernel $L(t - \tau)$ of time operators $E(t)$, $\nu(t)$ and $G(t)$ depends on the properties of the rock mass. Because it defines the nature of the creep, it can be selected as a function approximating the empirical creep curve.

Another issue is constituted by the criteria adopted in the calculation of rock mass destruction on the basis of which the stability assessment is carried out. The most commonly applied hypotheses are those by Coulomb-Mohr and Drucker-Prager, both of which assume a linear relationship between variables, but differ in the shape of the area limited by the so-called yield surfaces. While in the case of Drucker-Prager hypothesis, the yield surface is formed by a cone, in the Coulomb-Mohr hypothesis, it is a hexagon designated by stress axes.

Drucker-Prager's hypothesis is parameterised by tensile strength and compressive strength, or one of these factors along with their quotient. In this case, the yield surface is expressed by the following equation:

$$(1+\alpha)\sigma_{ef} + (1-\alpha)\sigma_m - 2\alpha R_c = 0 \tag{5}$$

where

$$\alpha = \frac{R_r}{R_c},$$

R_c — uniaxial compressive strength,
R_r — uniaxial tensile strength,
σ_{ef} — effective stress,
σ_m — mean stress.

The calculation model based on this hypothesis is used in solutions which focus on assessing the stability of salt caverns used for underground storage of gas. Such solutions were presented among others by Yin et al. (2007) and Wang et al. (2011).

Coulomb-Mohr's hypothesis assumes a relation between cohesion and the angle of internal friction (6), determined on the basis of the values of shear stress and the corresponding normal stress:

$$\tau_{\max} = \sigma_n \cdot \mathrm{tg}\varphi + c \tag{6}$$

where,

$\sigma_n = \dfrac{\sigma_1 + \sigma_2}{2}$ — normal stress corresponding to the maximum tangential stress,
φ — angle of internal friction,
c — cohesion.

Based on the parameters of this hypothesis, the elastic-plastic model of the rock mass with the Coulomb-Mohr plasticity condition and non-associated flow law is often used for the calculation of stability. Calculations are performed on a calculation model in which long-term endurance parameters are assumed for the condition of ductility. In numerical calculations, such a model allows to take into account the nonlinearity of the rock mass stress and strain characteristics (ductility), by adopting the assumption that within yield surfaces, the rock mass behaves in an elastic manner, and outside the area, in a ductile manner. Solutions of geomechanical problems by means of this model are widely applied in assessing the stability of salt rock mass surrounding chambers (Swift and Reddish 2005), (Minkley and Mühlbauer, 2007), (Cieślik et al., 2009), (Cała et al., 2009, 2010), (Ślizowski et al., 2011).

In order to assess long-term stability of the salt rock mass, in the work by Flisiak (2002) the phenomenon of dilatancy was applied. In the process of dilatancy, once that a certain level of stress (the so-called dilation threshold) is exceeded, an increase in the volume of rock occurs. Inelastic volume increase as a result of applying stress is a phenomenon preceding brittle destruction of the rock medium (Kwaśniewski, 2007). The hypothesis on the relation between dilatancy and long-term endurance limit presented in the work (Flisiak, 2002) allows its determination through the criterion of non-dilatancy deformation of rock salt, formulated as a result of triaxial laboratory tests:

$$K_2 = A_d + B_d I_1 \sqrt[3]{K_3} \tag{7}$$

where,

I_1, K_2, K_3 — stress state invariants,
A_d, B_d — parameters defined in triaxial tests.

4. Selection of geotechnical parameters of salt

Values describing the strength and deformational properties of rock, determined by laboratory tests are basic parameters necessary for modelling the behaviour of the rock mass surrounding underground excavations. The Wieliczka bed is very complex in terms of stratigraphy and lithology, and the rocks forming it are characterized by considerable mineralogical diversity. On the basis of the available documentation of laboratory tests (Flisiak, 2002; Flisiak & Cyran, 2008; Bieniasz & Wojnar, 2007; Cieślik et al., 2009; Cała et al., 2010; Tajduś et al., 2010), it can be concluded that the samples classified macroscopically as one kind of rock are characterized by high variability of mechanical parameters. On the basis of those results, one can only determine the ranges of variation for the different parameters (Table 1).

TABLE 1

Summary of ranges of mechanical parameters of the rock salt bed (collected on the basis of: (Flisiak, 2002; Flisiak & Cyran, 2008; Bieniasz & Wojnar, 2007; Cieślik et al., 2009; Cała et al., 2010; Tajduś et al., 2010)

No.	Type of rock	Compressive strength	Tensile strength	Angle of internal friction	Cohesion	Young's modulus	Poisson's ratio
		R_c, MPa	R_r, MPa	φ, deg	c, MPa	E, GPa	ν
1.	Bed salt	27.0-45.4	0.72-1.68	37.7-63.0	3.8-12.8	1.90-3.36	0.17-0.24
2.	Shaft salt	25.2-39.4	1.80-2.4	64.	4.00	–	–
3.	Bronze salt	24.3-43.3	0.93-1.02	39.7-71.00	3.3-11.4	1.28-2.63	0.19-0.25
4.	claystone micrite/ silt-halite (*zubry solne*)	8.6-33.9	0.4-2.7	30-75	1.7-7.4	0.17-0.96	0.06-0.36

Recent laboratory testing of samples of salt from the Wieliczka bed (Tajduś et al., 2010) included the determination of dilation threshold values. On average, dilation thresholds are as follows: for layer salt, 10 MPa, for bronze salt 5.6 MPa, and for claystone micrite/ silt-halite (*zubry solne*) 2.3 MPa.

Information on the rheological properties of the Wieliczka salt appears sporadically. The coefficient of viscosity η of the Wieliczka salt is in the range between 0.14×10^{15} and 5.29×10^{17} Pas (d'Obyrn, 2011).The stated values of the coefficient of viscosity are very difficult to compare because tests were performed at varying conditions of stress and in different time periods. A clear effect of time on the value of the breaking stress during bronze salt creep tests was observed in a study conducted by Tajduś et al. 2010. The samples were destroyed after about 30 days of applying the average stress of 14 MPa, which accounted for 64% of the specified ultimate strength in uniaxial compression tests. This was the result of exceeding the dilation threshold at relatively low values of stress and the development of self-sustaining process of destroying the structure of rocks.

When the rheological parameters from laboratory tests are adopted, as a result of analytical or numerical calculations, we obtain the values of the displacement of excavation contours, which generally differ substantially from those measured in the mine. This is due to differences between the parameters of rock samples and the actual parameters of the rock mass. Therefore, in recent years, a method called "back analysis" was developed (Kwon & Wilson, 1998; Kortas, 1999; Cieślik et al., 2009; Cała et al., 2010; d'Obyrn, 2011; Ślizowski, 2011), which allows, thanks to using measurements of displacement of excavation contours or of convergence, to assess the parameters of the rock mass and the original strain. In this manner, on the basis of long-term geodetic measurements in the surroundings of the Warsaw Chamber, rheological salt strain parameters were determined for the Wieliczka salt rock mass, in the form of time operators (d'Obyrn, 2011):

– For bronze salt $E(\mathbf{t})$ = 2,570 MPa,
– For claystone micrite/ silt-halite (*zubry solne*) $E(t)$ = 850 MPa.

5. Numerical stability analysis of selected examples

5.1. The construction of numerical models

The results of numerical geomechanical analysis are very helpful in deciding on the securing or backfilling an excavation chamber, in particular excavations of a historic value, as they provide the image of zones or regions where the largest concentration of rock mass stresses and strains occur. The evaluation of the Wieliczka rock mass strain allowed selecting the chambers or chamber ensembles which are characterized by relatively worst working conditions and are therefore most vulnerable to destruction.

The methods of predicting stress prevailing in the vicinity of underground excavations are systematically improved. The currently preferred direction is to model in spatial terms the actual rock mass with excavations created in it of any shape and determined location, (Yin et al., 2007; Fahland et al., 2007; Prusek & Bock, 2008; Cieślik et al., 2009; Cała et al., 2010; Wang et al., 2011). The most commonly used methods of numerical calculations-finite element (FEM), boundary element (BEM) and finite difference (FDM) allow determining with sufficient accuracy the values of stresses and displacements in the entire analysed model, even if it has a heterogeneous structure. Each numerical method has its own calculation algorithm and each problem to be solved should be approached individually.

A great number of problems are posed by mapping the geometry and the mutual position of the chambers and their associations with geological, and sometimes even hydrogeological conditions. The geometrisation of models is performed on the basis of geodetic documentation, i.e., maps of the mine levels, vertical cross-sections through each excavation, geological cross-sections and descriptions of their technical condition, which are usually prepared by the persons modelling each issue. Often, due to the lack of accurate data or the inability to determine the shape of the excavation (e.g. because of lack of access, collapse, backfilling, etc.) or because of the limitations resulting from the nature of the computer software or hardware, it becomes necessary to simplify the geometrical shape of the chambers. Sometimes CAD scripts are used for spatial mapping of the chambers (Cieślik et al., 2009; Cała et al., 2010).

The Kazanów mid-level comprising the Warszawa-Wisła-Budryk chambers is the best described in terms of the geometry of the chambers and their mutual positioning. Geomechanical analysis (Cieślik et al., 2009; Cała et al., 2009, 2010) of the area of the mine indicate that the mapping of the geometry of the area is becoming more accurate. The analyses conducted concerned the chamber excavations at Levels IIw, IIn, Kazanów mid-level and Level III. Based on the information collected on chambers located in the area, a very accurate spatial model has been created, which is shown in Figure 4.

a)

b)

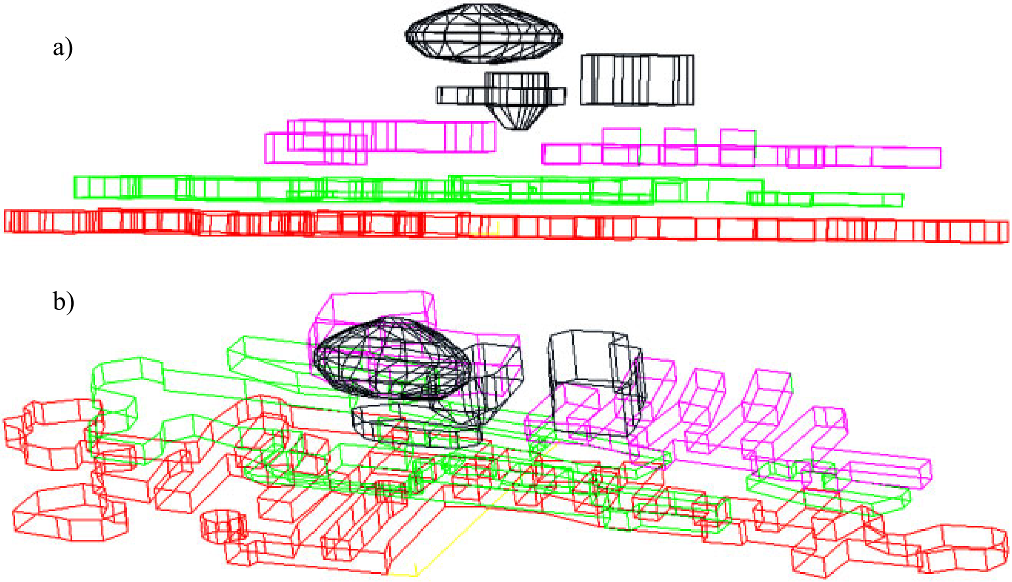

Fig. 4. Summary presentation of the spatial models of chambers in the vicinity of the Warszawa Chamber and Levels from II to III adopted for numerical modelling: a) view from the south on the chamber model, b) view "from the top" towards south-east (Cieślik et al., 2009)

The greatest challenge for geomechanical specialists is posed by conducting a comprehensive analysis of the entire mine, which is characterized by a complex geological structure, diversified shapes and mutual locations of the excavations, their varied state of repair and availability. In 1999, a so-called macro analysis was conducted aimed at determining the target structure of the underground part of the "Wieliczka" Salt Mine. Analytical studies and spatial numerical analysis with the use of the finite element method (FEM) were conducted for two variants. The first included all not backfilled excavations at levels I-IX, a total of 1,794 chambers. Among these were 350 chambers of historic value, including 57 located along the Tourist Route and at the Museum and 42 situated outside the Route, but of particular historical value. Due to the large number of excavations, some simplifications were made, namely, excavations were modelled as rectangular voids with replacement dimensions. The remaining 1,444 not backfilled chambers with no historic values were modelled as elements with modified values of the rock mass strain replacement modulus. The second numerical model included only 57 chambers located along the Tourist Route and in the Museum, with all the other chambers treated as having been backfilled and characterised by the same parameters as the surrounding rock mass. Due to the securing and backfilling work conducted at the mine in previous years, recently also a geomechanical macro analysis of the entire mine was commissioned concerning its target structure along with an evaluation of rock mass stability.

5.2. Discussion of geomechanical analysis results

The results obtained in macro analysis of the entire Wieliczka mine, especially the distribution of reduced stress, determining rock mass state, allowed to determine that at Levels I-III, the values of these stresses are relatively moderate and reach 3.0 MPa, whereas at lower levels they increase with depth. This is due to the existence of less deformed formations, i.e., layered salt and claystone micrite/ silt-halite (*zubry solne*) also local concentrations of their values were observed near the chambers with large dimensions and the contact points between marl claystones and salt formations and claystone micrite/ silt-halite (*zubry solne*). The analysis of strain increments also indicated dangerous concentrations of shear strain in the eastern part of the mine. Their values reach the level of 0.05 mm/m at Level IIw, and 0.1 mm/m at Levels IIn and III. In order to reduce this type of strain, the need was indicated to conduct securing or backfilling work in the area in the first place. Similar conclusions were drawn from the analysis of the distribution of the largest stress and principal strain. Areas selected for securing and backfilling with significant values of stress are generally located in the eastern and central parts of the mine, and include Levels between IIw and IV. Backfilling all non-historic chambers at levels IV-IX should not dramatically influence the strain characteristics of the historic chambers located on the upper levels. On the other hand, backfilling selected non-historic or particularly vulnerable chambers at Levels I-III can result in improving working conditions (reducing strain increments) in the central part of the mine and a slight deterioration in the east.

The "Wieliczka" Salt Mine systematically commissions detailed geomechanical analysis of the areas of the mine which are planned for securing or backfilling work, are in danger of collapse, or when it is suspected that after mining operations planned changes in rock mass state and displacement may occur. These areas include, among others: the Warszawa-Budryk-Wisla Chambers area (due to sealing work in the Witos Chambers complex located directly beneath these chambers), the Regis Shaft area and the excavations at Levels I-III (due to their planned inclusion in the new tourist route), the Jakubowice and Ksawer Chambers (due to the poor technical condition), etc.

For example, in works such as Cieślik et al. (2009), which analyse the effect of the surrounding chambers on the excavations located at the Kazanów mid-level and included in the Tourist Route, it was found that the excavations located above and below those have the greatest impact on the preservation of these chambers and the state of stress in their environment. In practical terms, the fact that these excavations are situated in a vertical line is the cause of compressive stress concentration in the northern side walls of the analyzed chambers. This is confirmed by the analysis of plastic strain; however, at the point where these strains occur, both chambers are secured with cribs. Specially noteworthy are the results of calculations carried out for the complex of chambers located below, at Level III, in which the yield limit is exceeded, as indeed confirmed by the technical condition of the chamber complex. For this reason, a detailed analysis of the stress state was conducted after sealing the residual-slag backfill in those with a mineral mix. The works performed should not cause significant distortions in the state of stress prevailing at present in the rock mass surrounding the analysed complex of chambers; in the long run, an improvement in the state of stress on the ledges between Level III and the Kazanów mid-level may even occur.

Collapse risk assessment is a separate issue. A study (Cała et al., 2009) demonstrates that numeric, spatial modelling of processes occurring in the vicinity of salt chambers may prove to be an effective tool of predicting this risk. For the calculations, the method of reducing the shear strength was applied. The analysed chambers are located at the upper levels in the vicinity of the Tourist Route. The calculated values of stability indices indicate a negligible risk of continuous and discontinuous deformations in the area of the chambers under consideration.

Each excavation or excavation complex intended to be backfilled or secured requires an individual approach, and conducting a detailed geomechanical analysis which will allow the selection of the appropriate manner of securing or backfilling or liquidation, and the order of performing mining works.

Despite the dynamic development of numerical methods and computer equipment, the Wieliczka rock mass remains difficult to model, especially because of its complicated geological structure and a considerable variation in the geomechanical parameters of the salt rock mass, although increasingly accurate mapping of both the complex shape of the workings and their mutual location is possible. Three-dimensional methods of rock mass modelling are especially useful in this regard. Despite the simplifications made, the very visualization of the mutual location of the excavations allows realising how complex the excavation layout, and how complicated and diverse is the geological structure of the Wieliczka bed. Because of considerable variation in values, physico-mechanical and rheological properties of rock salt determined in laboratory and *in situ* tests are more and more often verified through the so-called back analysis, which employs for example, the geodetic measurements of a given area of the mine. The geomechanical parameters of salt rock mass adjusted in this manner provided the basis for numerical analyses. Thanks to the results of numerical geomechanical analysis taking into account the geological structure and the geological conditions, appropriately selected geomechanical and rheological parameters of rock mass, the shape and mutual arrangement of excavation and taking into account of the existing mining securing structure, it is possible to determine the impact of each of these factors on the phenomena occurring in the rock mass and designate the zones of mutual interactions between excavations. The analysis of the mining work already conducted allows the conclusion that the more precise the simulations and forecasts made by numerical methods are, the more closely they reflect the actual state of things.

6. Summary

1. The development of analytical methods, the increased precision of the geodetic measurements of the excavation contours displacement and the improved computing capabilities allow a more and more accurate assessment of stability.
2. The geomechanical analyses performed at the "Wieliczka" Salt Mine provide the basis for all kinds of design work concerning the securing of the excavations with historic value or backfilling unnecessary ones. The increasing accuracy of the results allows to determine the sequence of work to be conducted and its required scope, and to select the type of casing or the backfilling method.
3. The complex geological structure and hydrogeological conditions of the bed result in the need to average the geomechanical parameters of the rock mass. Within the blocky bed, an important distinction concerns the properties of solid rock salt and claystone micrite/silt-halite (*zubry solne*), i.e. the unstructured mass of mixed halite crystals and clays. Particular attention should be paid to tests conducted in the layered bed, in which

the geomechanical parameters undergo fundamental changes in the case of the claystone partings, and humidity and water presence cause abrupt changes in parameters. The situation in which it is the most difficult to determine the geomechanical parameters is the complex of alternating several-centimetre-thick layers of salt separated by millimetre-thick layers of claystones, often damp.

4. Despite increasingly accurate measurements and the ability to create complex models, the geometrization of the excavations continues to be subject to simplification and generalization because of the computational capacity of hardware. Considerable simplification is necessary especially in the case of analysing the entire mine, due to the presence of regions in which the chambers were backfilled or are unavailable and there is no possibility of conducting geometrical measurements, determining the geomechanical parameters of the rock mass and assessing their technical condition.
5. Rock mass parameters obtained through laboratory tests are very diverse. In selecting parameters for the numerical model, the so-called "back method" proves to be very useful. It consists in adjusting the parameters of the rock mass basing on the actual behaviour of the rock mass around the analysed excavation, e.g. on the basis of convergence measurements.
6. In the case of the Wieliczka rock mass, the shear strength reduction method is highly useful in determining the chambers stability indicators for collapse hazard assessment.
7. Methods of creating numerical modelling and performing geomechanical analysis in such a complicated rock mass with highly variable parameters can be used for other layered or diapir salt beds, in which the geological and hydrogeological conditions and excavation conditions are generally simpler.

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