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STABILITY ANALYSIS OF UNDERGROUND MINING OPENINGS WITH COMPLEX GEOMETRY

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Abstract: Stability of mining openings requires consideration of a number of factors, such as: geological structure, the geometry of the underground mining workings, mechanical properties of the rock mass, changes in stress caused by the influence of neighbouring workings. Long-term prediction and estimation of workings state can be analysed with the use of numerical methods. Application of 3D numerical modelling in stability estimation of workings with complex geometry was described with the example of Crystal Caves in Wieliczka Salt Mine. Preservation of the Crystal Caves reserve is particularly important in view of their unique character and the protection of adjacent galleries which are a part of tourist attraction included in UNESCO list. A detailed 3D model of Crystal Caves and neighbouring workings was built. Application of FLAC3D modelling techniques enabled indication of the areas which are in danger of stability loss. Moreover, the area in which protective actions should be taken as well as recommendations concerning the convergence monitoring were proposed.

Key words: *stability analysis of underground workings, complex geometry and geological structure, 3D numerical modelling, Wieliczka Salt Mine*

1. INTRODUCTION AND BACKGROUND

The long-term maintenance of underground mining openings is bound by the necessity to ensure their stability. Estimation and prediction of stability requires a number of factors, such as: geological structure, the geometry of the underground mining workings, mechanical properties of the rock mass, changes in stress caused by the influence of neighbouring mining openings. All these factors were especially complex in Wieliczka Salt Mine which is unique with regard to geological structure and network of workings resulting from over 700 years of salt exploitation. What is more, the mine is a tourist attraction included in UNESCO list and visited by over million people every year. As a consequence, safety and preservation of mine workings is particularly important issue.

Numerical methods are advanced tools that allow for studying complex conditions as well as modelling of material behaviour [1]–[3]. Numerical modelling with reference to the salt deposits was applied mainly to design, monitoring and stability prediction of salt caverns used as underground storages or radioactive waste repositories [4]–[6]. However, the stability models for caverns or rooms in the bedded salt formations were also analysed [7], [8].

The stability of underground mining openings with complex geometry and structure was verified on the basis of 3D modelling. The 3D model of chambers characterized by a very complicated geometry and geological structure (Crystal Caves in Wieliczka Salt Mine) was built as well as numerical simulations were carried out with the use of the FLAC 3D v 5.0 software. FLAC modelling techniques are useful in prediction and monitoring of caverns and rooms stability in salt mines because the programme can simulate the behaviour of materials that exhibit creep [7], [8].

2. GEOLOGICAL ENVIRONMENT

2.1. THE GEOMETRY OF THE CRYSTAL CAVES

The Crystal Caves reserve, situated between mining levels upper II and III in Wieliczka Salt Mine

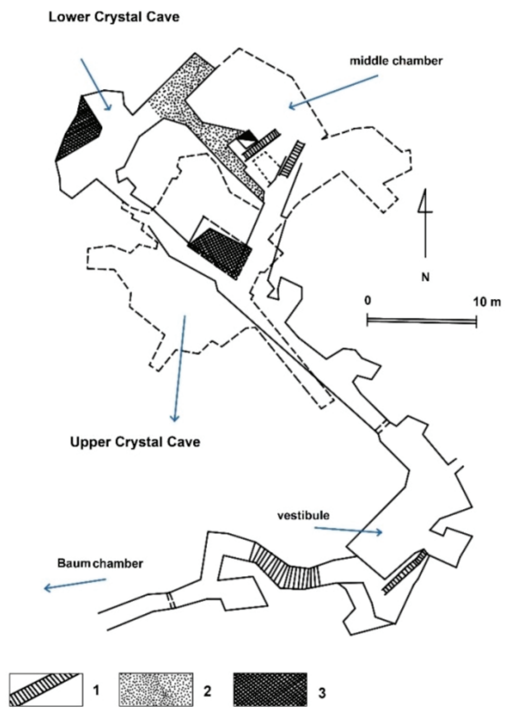

Fig. 1. Schematic intersection through the Crystal Caves [9]:
1 – stairs, 2 – backfill, 3 – crib

(Fig. 1), is considered as unique and was promoted to the List of Sites of the Geological Heritage of the World (Fig. 2). The vertical axis of the Upper Crystal Cave is shifted a few metres to south-east in relation to the axis of the Lower Crystal Cave [9].

The Lower Crystal Cave is in the shape of regular cavern with a volume of 706 m^3, and is situated about 22 m above the mining level II lower (Fig. 1). It is 5.75 m high and its roof rises to the north-east. The lower part of the natural cavern was filled up and makes the floor of the Lower Cave.

The shape of the Upper Crystal Cave is irregular as a result of intensive prospection and exploitation (Fig. 1). The Cave has a volume which amounts to 1000.17 m^3, and is situated about 5 m above mining level II upper. The Upper Cave is divided into two levels: lower and higher. The lower lever which is located near the entrance to the Cave is 3.5 m high. The upper level is similar in height (3.75 m) and from this part the lower level is accessible [9].

Between the Lower and Upper Cave another cave called a middle chamber is situated [9], [10].

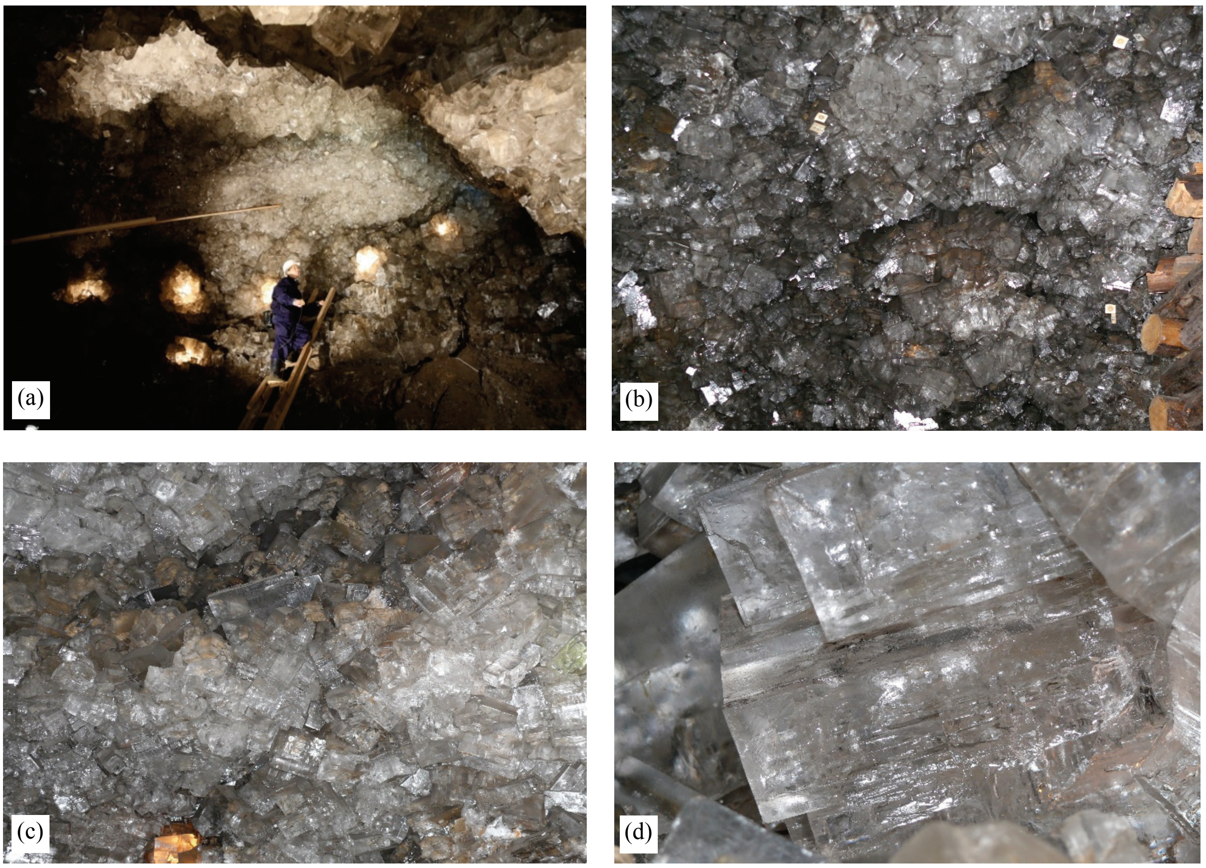

Fig. 2. Pictures of Crystal Caves: (a) the roof and walls of the Lower Cave,
(b), (c) – fragment of crystalline cover of walls of the Lower Cave, (d) aggregation of halite crystals

2.2. GEOLOGICAL STRUCTURE OF THE CRYSTAL CAVES AND THEIR VICINITY

The Wieliczka Salt Deposit extends from west to east along the front of the Carpathian thrust. The salt body is 7 km long and 1 km wide and mining workings are situated at a depth of 64–327 m below the surface level (Fig. 3). The northern boundary of the deposit is determined by an overthrust plane. The southern border is, however, limited by the tectonic contact between zuber sediments and Chodenice Beds (oversalt beds). Chodenice Beds are strongly folded and brecciated in the surroundings of the deposit [11].

The Wieliczka salt deposit has two parts which are distinguished as: stratiform and brecciated deposits. The stratiform deposit consists of folded salt layers (from the bottom: the oldest salts, green salt, shaft salt, spisa salt) with intercalations of barren rocks

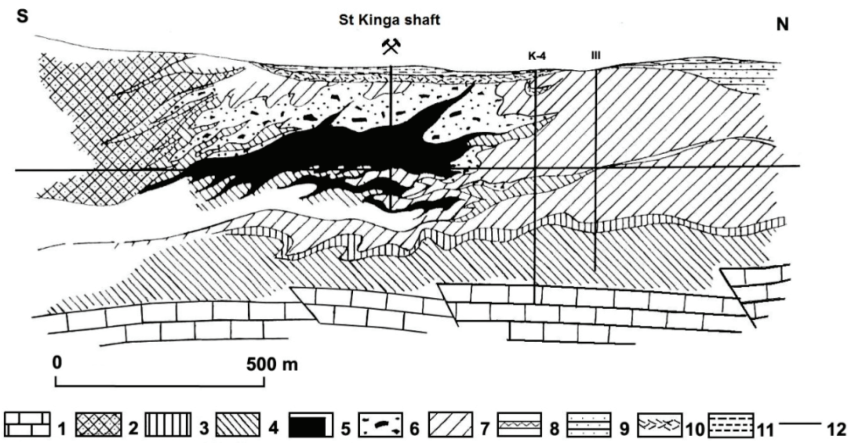

Fig. 3. Geological cross-section through Wieliczka salt deposit [15]: 1 – upper Jurassic limestones, 2 – Carpathian flysch, 3 – Skawina Beds, 4 – sulphate facies, 5 – stratified salt, 6 – zuber sediments, 7 – Chodenice Beds, 8 – gypsum of zuber complex, 9 – Grabowice Beds, 10 – waste of clay and gypsum, 11 – Pleistocene clays, 12 – thrust planes

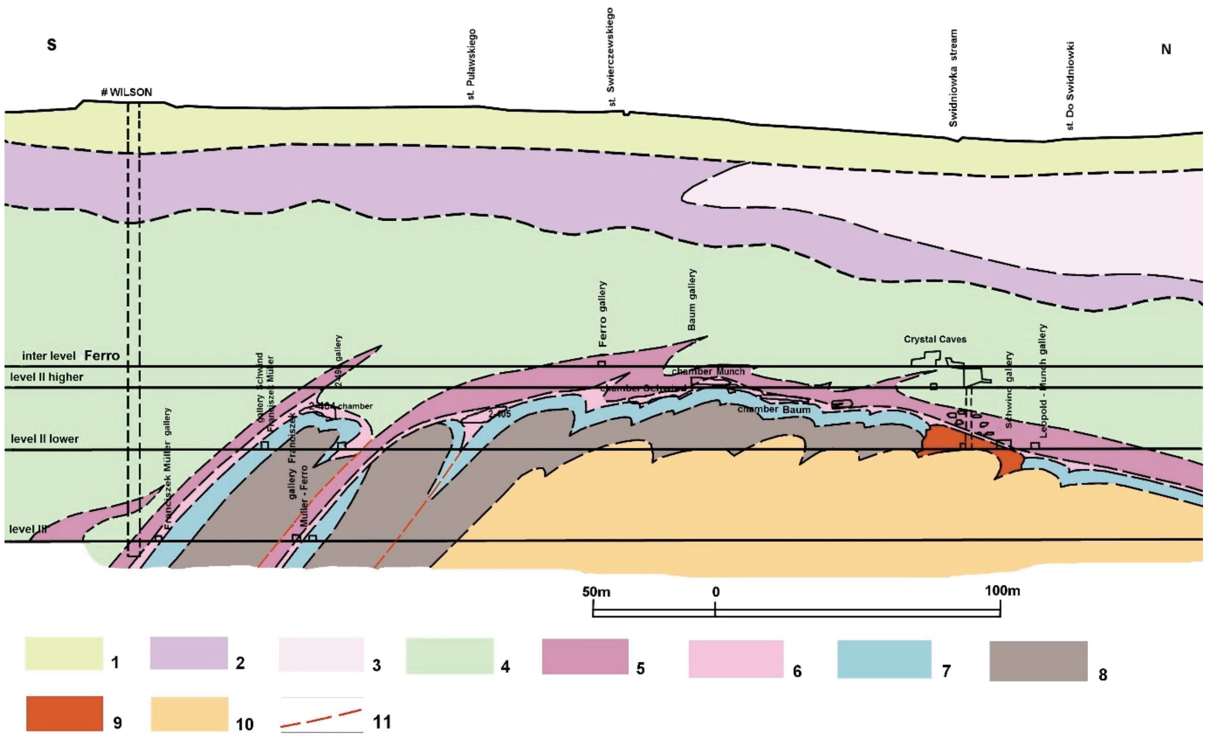

Fig. 4. Geological cross-section through Crystal Caves zone along meridian +284 055 [9], [10]: 1 – Quaternary sediments, 2 – Chodenice Beds, 3 – argillous-gypsum buffer cover, 4 – sediments of brecciated deposits, 5 – spisa salt, 6 – shaft salt, 7 – green salt, 8 – breccia composed of zuber, marly claystones and blocks of the oldest salts, 9 – undersalt sediments – claystones, siltstones, sandstones with veins of gypsum and anhydrite, 10 – residual sediments after leached salt rocks, 11 – thrust plane

(Fig. 3). The brecciated deposit is formed by zuber sediments (marly claystone with suspended grains of crystalline halite), marly claystones, blocks of green salt and blocks of barren rocks. The layers of the stratiform deposit are covered by megabreccia sediments as a result of tectonic and depositional processes [11]–[14].

In the Crystal Caves area, sediments of both stratified and breccieted deposits occur (Fig. 4). The brecciated deposits are represented by a mass of marly claystones and zuber in which blocks of salt are irregularly dispersed. In the stratified deposits salt layers are interbedded with barren rocks like claystones and siltstones with anhydrite. The complex of strata forms domal uplift which is called the Crystal Cave's Dome. The Crystal Caves themselves are situated in sediments of brecciated deposits in the northern part of the dome near the contact zone between the stratified and brecciated deposits (Fig. 4). The dome is overlaid by an argillous-gypsum buffer. At the top of this complex there are Chodenice Beds (oversalt strata) represented by claystones, siltstones, marly claystones and Quaternary sediments such as clays with lens of sands and ashes. In this part of Wieliczka deposit, the oldest salts are divided into blocks distributed in sediments similar to zuber [9], [10].

The dome is 150 m wide on mining level II upper and 400 m on mining level III. The southern limb of the dome dips about 50° to the south but the northern limb is characterised by northwards dipping at about 20°. As a result, the chambers adjacent to Crystal Caves located in the northern limb of the dome are wide and plane, whereas in the southern limb chambers are steep and narrow [9], [10].

3. NUMERICAL ANALYSIS

3.1. DESCRIPTION OF PROBLEM

Stability estimations for the Crystal Caves in Wieliczka Salt Mine required consideration of both components: the complex geometry of the Crystal Caves as well as adjacent workings (chambers, galleries, headings) and complicated geology in this section of the mine. However, the convergence was not monitored in the Crystal Caves. Data concerning horizontal and vertical displacements were available only for neighbouring openings in danger of collapsing. Therefore, the state of these openings affected the stability of the Caves and this point was taken into consideration in the analysis.

The complexness of all these factors demanded using 3D numerical modelling which is perfectly suited for the analysis of stress-strain behaviour of mining openings [2], [3], [7]. FLAC 3D v 5.0 modelling techniques based on the Finite Difference Method were used to examine the stability of Crystal Caves.

3.2. CONDITION AND STEPS OF ANALYSIS

In the first step, a 3D model of Crystal Caves and surrounding openings (Baum Chamber, Munch-Schwind chamber, Ferro chamber and galleries) was built utilising laser scanning, photogrammetry, maps of mining levels and cross-sections (Fig. 5). The chambers, located at a long distance from the Crystal Caves and/or of a small size were excluded from 3D model, which does not influence the quality of calculations. The dimensions of the 3D model were 400 m × 400 m × ca. 200 m (Fig. 6).

The geology in 3D model was projected on the basis of the mining level maps IV, III, II lower, II upper, I and vertical cross-section. The model extends from 77 m to 272 m above sea level. The horizontal cross-section of the model is the square of size 400 × 400 m.

In bedded salt deposits the mechanical properties of layers are differentiated, consequently more attention should be paid to mechanical properties of beds [7].

The following layers were distinguished for the needs of modelling:

- Quaternary sediments,
- Chodenice Beds,
- buffer cover,
- sediments of brecciated deposit,
- spiza salt,
- the oldest salts breccia,
- undersalt sediments.

In numerical calculations, a model of elastic-ideally-plastic material was applied with the Coulomb–Mohr failure criterion described by the following parameters:

- volume density,
- Young's modulus,
- Poisson's ratio,
- cohesion,
- angle of internal friction,
- tensile strength.

The mechanical parameters of the layers listed above applied to numerical analysis are presented in Table 1.

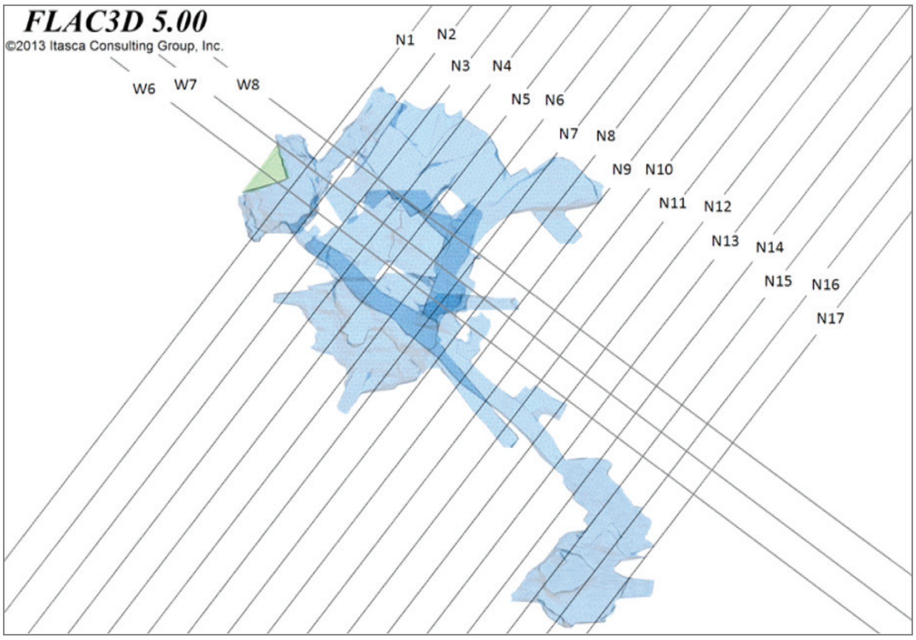

Fig. 5. The geometry of the Crystal Caves. Localisation of vertical intersections
("N" – in NE-SW direction, "W" – in NW-SE direction)

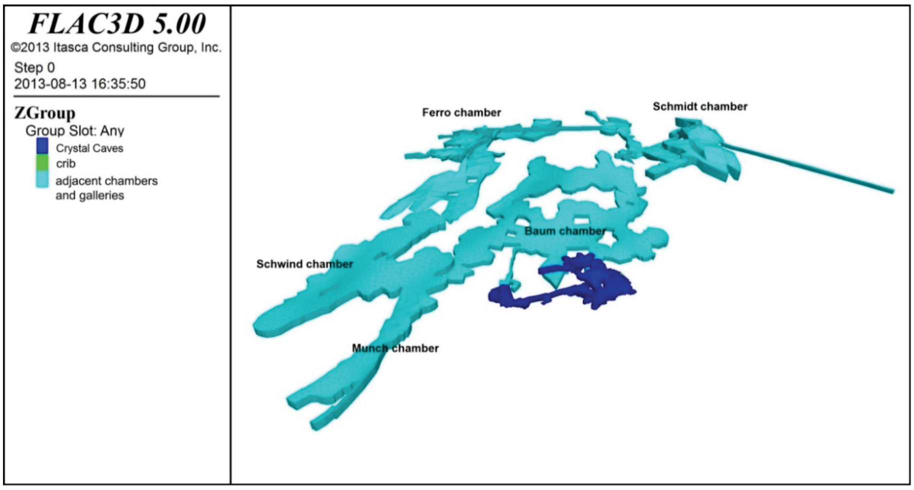

Fig. 6. Crystal Caves and surrounding workings (close left – Munch and Schwind chambers,
far left – Ferro chambers, central part, above Caves – Baum chamber,
far central part – Upper Leopold chamber, right side – Schmidt chamber and Schmidt heading)

Fig. 7. The crib built in Crystal Caves

Table 1. Mechanical properties of layers

Layer	Volume density, ρ [kg/m^3]	Young's modulus E [MPa]	Poisson's ratio ν [–]	Cohesion c [kPa]	Friction angle ∏ [°]	Tensile strength [kPa]
Quaternary sediments	2200	72	0.20	30	30.0	0
Chodenice beds	2200	500	0.35	90	4.5	150
Buffer cover	2200	500	0.35	80	12.0	160
Sediments of brecciated deposit	2200	2000	0.30	1500	30.0	1200
Spiza salt	2200	2000	0.35	1000	20.0	700
The oldest salt breccia	2200	1000	0.25	500	25.0	500
Undersalt sediments	2200	4000	0.20	2000	40.0	1500

The presence of the crib which was built at the beginning of the 20th century and few times renovated (Fig. 7) is an important element in view of the Crystal Caves stability. For this reason the crib and its mechanical parameters (Table 2) were included in the model.

Table 2. Mechanical properties of the crib

Material	Volume density ρ [kg/m^3]	Young's modulus E [MPa]	Poisson's ratio ν [–]
crib	1500	500	0.20

The 3D numerical model of Crystal Caves and the adjacent openings consists of 2 million tetrahedral elements (Fig. 8). The dimensions of the elements in the vicinity of Crystal Caves were smaller (ca. 0.5 m) and bigger at the edges of the model (ca. 10 m).

The last element in building of the model was introducing the boundary conditions. Displacement in the vertical direction to bottom and side planes of the model was blocked. The value of horizontal stress was set at 0.7 of vertical stresses.

In the second step, the initial calibration of the model was based on the stability estimation of surrounding chambers for which convergence was monitored for 15 years. The authors also visited the sector where the Crystal Caves are located in order to investigate the direction and intensity of displacements. Based on the strength/stress ratio analysis, the stability of chosen underground openings was determined and endangered areas indicated.

3.3. RESULTS

The results of the 3D numerical simulations are presented on the chosen vertical and horizontal cross-sections (Fig. 9). Low strength/stress ratio (value 1.0 implies a state close to failure) was indicated on the walls of the gallery leading to the Crystal Caves (cross-section H176).

The value of strength/stress ratio in the vicinity of the lower Crystal Cave (sections from W6 to W8 and

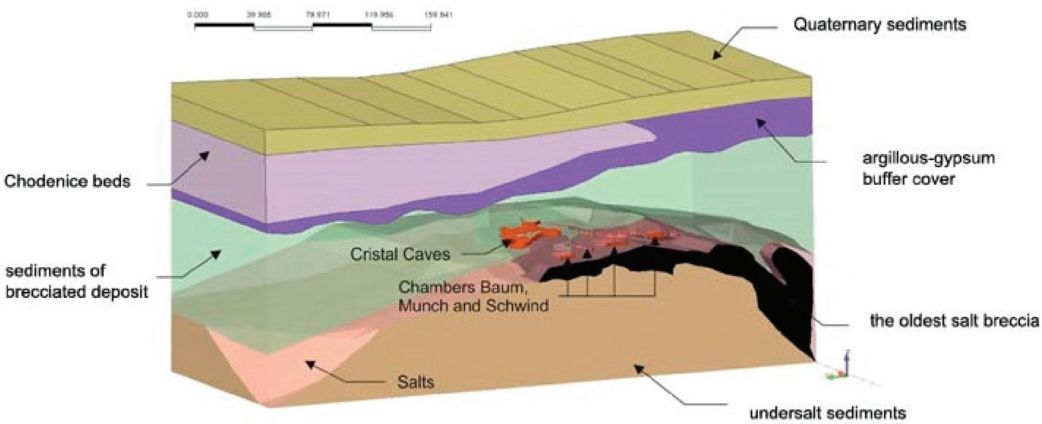

Fig. 8. The location of Crystal Caves with geology and surrounding openings – 3D model

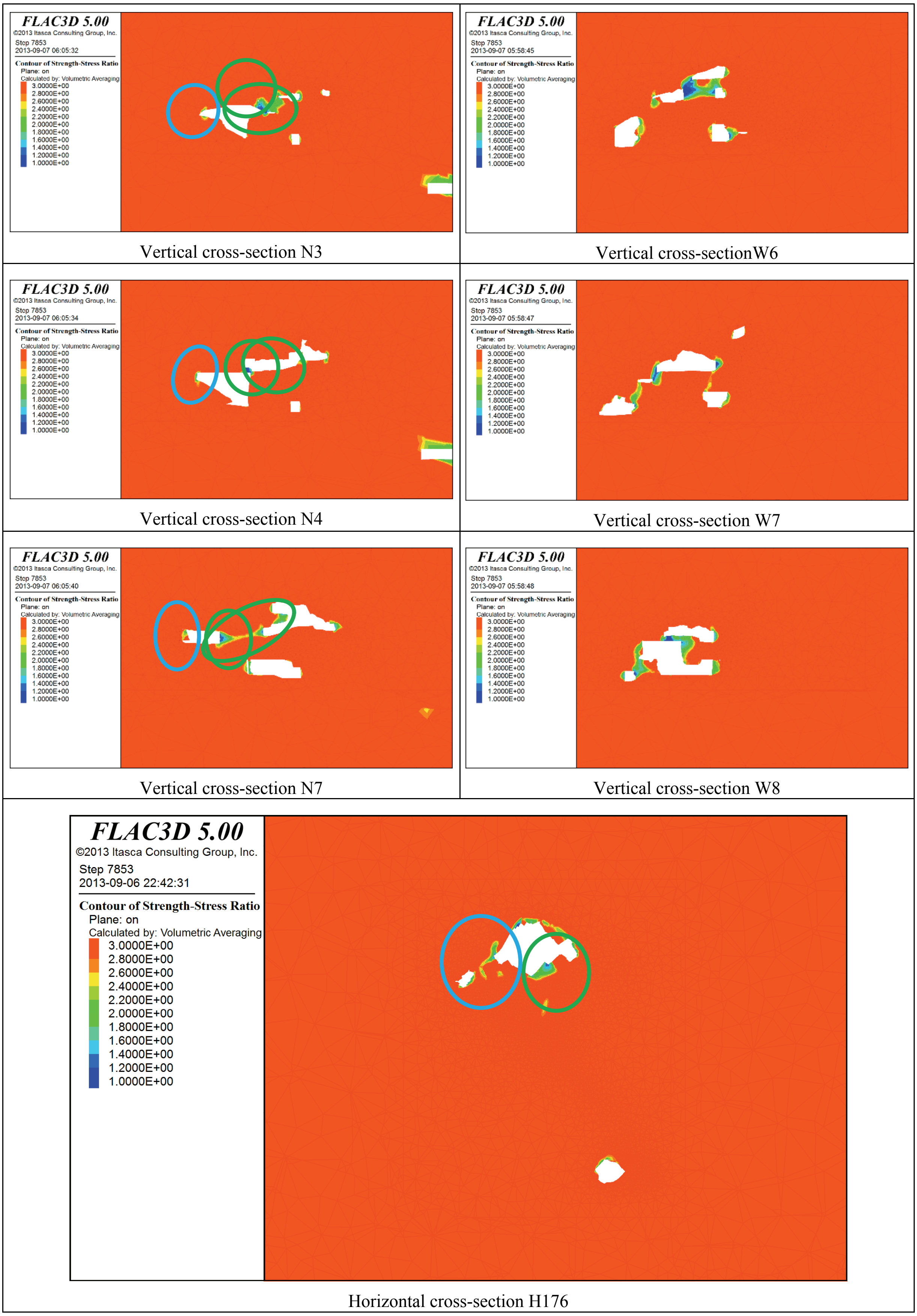

Fig. 9. The strength/stress ratio distribution for selected cross-sections, an ordinate 176 m above sea level – value close to 1.0 (blue color) implies state close to collapsing

H176) in some places is critical and close to 1.0. The development of destructive processes was observed mainly on walls of the Lower Cave. Endangered areas are particularly visible in the cross-sections from W6 to W8 and H176 (marked with blue circles). The state of the Upper Crystal Cave and its vicinity is presented on cross-sections N3, N4 and N7. Zones with low strength/stress ratio are marked with green circles and also visible on cross-sections from W6 to W8 (Fig. 9). Moreover, in horizontal cross-section H176 zones in the state of creep are clearly visible.

On the basis of the above information, it should be stated that the low (close to 1.0) value of strength/stress ratio was indicated locally on the walls of Crystal Caves. The overall condition of Crystal Caves and their vicinity is stable. However, in the long run, the state of Upper Crystal Cave can lead to collapsing and requires conservation, e.g., building cribs and timbering. What is more, monitoring of the convergence in the Crystal Caves and adjacent workings is recommended.

4. SUMMARY

The use of 3D numerical modelling in stability estimation of workings with complex geometry was described on the Crystal Caves example. Preservation of the Crystal Caves reserve is particularly important with a view to their unique character as well as protection of the adjacent galleries. Application of 3D numerical modelling enabled projection of complex geological structure, complicated geometry of the Caves and neighbouring workings as well as their stability conditions. Based on the detailed model identification of failure zones was possible. The influence of adjacent galleries on the stability of the Crystal Caves was also estimated. Moreover, the area in which protective actions should be taken as well as recommendation concerning the convergence monitoring were proposed. The future convergence measurements may lead to more precise calibration of 3D model and consequently detailed prediction of The Crystal Caves stability.

REFERENCES

[1] MORTAZAVI A., HASSANI F.P., SHABANI M.M., *A numerical investigation of rock pillar failure mechanism in underground openings*, Comput. Geot., 2009, 36, No. 5.

[2] JING L., HUDSON J.A., *Numerical methods in rock mechanics*, Int. J. Rock Mech. Mining Sci., 2002, 39, No. 4.

[3] JING L., *A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering*, Int. J. Rock Mech. Mining Sci., 2003, 40, No. 3.

[4] CHEN L., DUVEAU G., POUTREL A., JIA Y., SHAO J.F., XIE N., *Numerical study of the interaction between adjacent galleries in a high-level radioactive waste repository*, Int. J. Rock Mech. Mining Sci., 2014, 71.

[5] WANG L., BÉREST P., BROUARD B., *Mechanical Behavior of Salt Caverns: Closed-Form Solutions vs Numerical Computations*, Rock Mech. Rock Eng., 2015, 48, No. 1.

[6] WANG T., YANG C., YAN X., LI Y., LIU W., LIANG C., LI J., *Dynamic response of underground gas storage salt cavern under seismic loads*. Tunnelling and Underground Space Technology, 2014, No. 43.

[7] ZHANG G., WU Y., WANG L., ZHANG K., DAEMEN J.J.K., LIU W., *Time-dependent subsidence prediction model and influence factor analysis for underground gas storages in bedded salt formations*, Eng. Geol., 2015, No. 187.

[8] SWIFT G.M., REDDISH D.J., *Underground excavation in rock salt*, Geot. Geol. Eng., 2005, No. 23.

[9] CHMURA J., BEDNARCZYK J., BRZEŹNIAK E., CHARKOT J., CHMURA Ł., LASOŃ A., MIKOŚ T., PAWLIKOWSKI M.M., *Projekt planu ochrony podziemnego rezerwatu przyrody „Groty Kryształowe" w Kopalni Soli Wieliczka*, [*Conservation plan of underground natural reserve "Crystal Caves" in Wieliczka Salt Mine*], Fundacja „Nauka i Tradycje Górnicze", 2009, (in Polish).

[10] ALEKSANDROWICZ Z., (ed.), *Crystal Caves in the Wieliczka Salt Mine*, Studia Naturae, 2000, No. 46 (2000)

[11] GAWEŁ A., *Budowa geologiczna złoża solnego Wieliczka*, [*Geological structure of Wieliczka Salt Mine*], Prace Instytutu Geologicznego 30, 1962, No 3, (in Polish).

[12] KOLASA K., ŚLĄCZKA A., *Sedimentary salt megabreccia exposed in the Wieliczka Mine, (Fore Carpathian Depression)*, Acta Geologorum Polonae, 1985, 35, No. 3/4.

[13] ŚLĄCZKA A., KOLASA K., *Resedimented salt in the Northern Carpathians Foredeep, (Wieliczka, Poland)*, Slovak Geological Magazine, 1997, 3, No. 2.

[14] LAMARCHE J., *Structural geology in the Wieliczka salt mine*, Internal Report, Wieliczka Salt Mine, 1997.

[15] POBORSKI J., *Historyczny rozwój poglądów na budowę geologiczną złoża solnego Wieliczki*, [*Historical development of ideas about the geological structure of Wileiczka Salt Mine*], Studia i Materiały do Dziejów Żup Solnych w Polsce, 1965, No. 1, (in Polish).