THE UNVERITY OF PETROSANI

THE DOCTORAL SCHOOL

UNIVERSITY OF PETROSANI

Eng. SORINEL POPESCU

DOCTORAL THESIS SUMMARY

Scientific leader
prof.univ.dr.in eng. ***RADU Sorin Mihai***

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DOCTORAL THESIS

ANALYSIS OF THE STABILITY OF THE VOIDS AND THE MINING RISKS FROM THE SALT EXPLOITATION IN SOLUTION IN ROMANIA, IN ORDER TO USE THEM AS UNDERGROUND DEPOSITS

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CONTENT

In this paper, I aimed to identify various aspects regarding the mining risks in the salt mines in Romania, by analysing the stability of the voids that are formed as a result of the salt exploitation by dissolution, in order to use them as underground deposits.

Based on the choice of this research topic, there were several criteria as follows:

- ***Personal motivation.*** Being a graduate of the Faculty of Mine in Petrosani, class 1985, I started as a trainee at the Livezeni mine, at a moment of maximum intensity in the mining industry, then as a designer at the Institute of Mining Research and Design ICSITPML Craiova. The dream and career as a mining engineer could have ended in 2000, with the closure of a critical number of mining operations in all the basins in the country. Despite this, the research activity at the University of Petrosani supported the ideals of many engineers, including myself, by opening research niches for new activities in Romanian mining, such as the use of salt caverns as underground deposits. I considered that this topic is relevant and responds not only to general wishes, but also to Romania's commitments as an EU member state to the CO2 reduction targets. Caverns resulting from the exploitation of salt in solution can transform from simple voids filled with brine, consuming financial resources to maintain them in conservation, into real underground deposits bringing income.
- ***The European context.*** The European Union has drafted a package of legislative measures called "ready for 55 in 2030" to reduce emissions by 2030 from 40% to 55%, making achieving climate neutrality by 2050 a legal obligation.
- ***Available financial and material resources***. Under the EU emissions Trading Scheme (***ETS***), companies must auction these allowances, corresponding to the quantities of CO2 emitted. The emissions Trading scheme is the world's first and largest carbon market and remains the largest such market. This market covers around 40 % of total Union greenhouse gas emissions and applies to around 10 000 power plants and production plants. The National Plan for Research, Development and Innovation 2022-2027 (PNCDI IV), recently approved by the Romanian Government, provides approx. 60 billion Romanian lei for technology transfer and stimulation of partnerships between national research institutes, or between research organizations and the Romanian private environment.
- ***Research methods used***. The documentation method was used to search for solutions applied in countries with tradition in the field and the experimental method. The experimental method is a basic method in scientific research and has been applied to obtain a mini-cavern by dissolution in a small salt block (400x400x1200mm), to pressurize it and measure deformations. The experimental results were compared with the results of the 3D simulation using FLAC 3D.

The work was structured on three parts:

1ST PART

The first part refers to THE GEOPHYSICAL AND MECHANICAL CHARACTERIZATION of salt massifs in Romania, by presenting geology, physical, mechanical and rheological properties, METHODS OF EXPLOITATION, especially of salt deposits with solution exploitation, with the recommendation of the salt deposit from Tg.Ocna, Bacău County. Given the new destination of deposits, salt caverns resulting from dissolution, we presented their technical characteristics, necessary for obtaining, measuring and monitoring THE TIGHTNESS OF CAVERNS, a prerequisite for any gas or liquid storage. The first part is structured into 4 chapters as follows:

Chapter 1. GENERAL ASPECTS OF STORAGE IN GEOLOGICAL FORMATIONS IN THE CONTEXT OF THE DEVELOPMENT OF CCS TECHNOLOGIES TO REDUCE CO2 EMISSIONS. The development of carbon capture and storage technologies to reduce CO2 emissions has become a global concern, and in this context we have shown the state of development and implementation in our country of CCS technologies.

Chapter 2. GEOMECHANICAL CHARACTERIZATION OF SALT IN ROMANIA. Detailed knowledge of the geological conditions (depth and water intake, mechanical and elastic physical properties) of the deposit, leads to the possibility of predicting the mechanical behaviour of the salt in time, as real and therefore as likely as possible, which will allow for adequate decisions to be made and finally to reduce the risks.

Chapter 3. METHODS OF SALT EXPLOITATION BY DISSOLVING PROBES. In this chapter are presented the methods of mining salt in terms of engineering practices in Romania. The technical aspects regarding the construction and operation of salt dissolving wells, as well as checking the tightness of the anchorage columns are presented.

Chapter 4. THE TIGHTNESS OF THE SALT CAVITIES. The technical characteristics as well as the standard tests required to assess the tightness of the cavern are presented. The chapter is based on literature in countries where the storage of various gases or hydrocarbons has a history. Mechanical integrity tests (MIT) for salt storage caverns are used to determine the condition of the cavernous access well and the integrity of the fluid or gas storage system.

2ND PART.

Second part, in which we presented THE THEORETICAL BASIS FOR THE STABILITY OF THE SALT MASS and case study for the salt deposit TG.OCNA- Gura Slănic perimeter. There are also presented notions regarding artificial intelligence, the stage of knowledge and the use of artificial intelligence in the mechanics of rocks.

Chapter 5. ***THEORETICAL NOTIONS ABOUT THE STABILITY OF THE SALT MASS.*** For the prediction of the stability in time of the cavern, it is necessary to have a real knowledge of the geomechanical characteristics and a value determination of the natural state of tension of the salt massif and after the execution of the mining work, the determination of the secondary state of tension, determinations that are made based on hypotheses. There are aspects of salt creep taken from the literature. There are presented schemes for assessing the stability of rocks, their use can be quite beneficial in the elaboration of a project, especially in preliminary phases when less information about the physical-mechanical properties of rocks, and their hydrological characteristics are available. For engineering calculation as a tool for design and verification of structures, two (the most common) of the mathematical models for assessing the voltage state are presented: Mohr-Coulomb and the newer Hoek-Brown. Research has shown that problems with rock mechanics/geoengineering are very related to the insufficiency of site-specific data. Therefore, it has been attempted to solve this problem by artificial intelligence (AI)-based prediction methods. Some theoretical aspects and examples of application are presented.

3RD PART

Third Part, represents the purpose of this paper, that by applying methods OF ANALYSIS OF THE STABILITY OF CAVERN ON 3D MODELS and interpreting the results to make contributions to the understanding and to the way of engineering calculation regarding the determination of the technical characteristics of the tightness of salt caverns, in their new destination as underground deposits. The presentation OF THE POSSIBLE RISKS OF CO2 STORAGE in these caverns, with cases taken from the literature of the countries with experience in the field, only complements the working model and the way of approaching such a theme in engineering design.

Chapter 6. ***CAVERN STABILITY ANALYSIS ON 3D MODELS.*** Although traditionally, numerical methods (analytical methods, basic numerical methods, finite element method (FEM), distinct elements method (DEM), hybrid methods, numerical methods, etc.) have been used to assess the stability of underground constructions, performing laboratory or field analysis is necessary to confirm the results of the other methods, despite the fact that the method is very cumbersome, time consuming and expensive. This chapter presents the construction of the scale model of a cavern with known characteristics (location, depth, shape and dimensions). In addition to the above, the construction of a 3D model at scale gave the possibility to measure the deformations on the external walls of the pressurized cavern by tensiometry with tensiometric stamps. The measurement values were compared to those derived from the cavern stability analysis used by FLAC 3D for the radial creep problem of an infinitely long, thick-walled cylinder.

Chapter 7. ***RISKS AND RISK MANAGEMENT WHEN STORING C02 IN SALT CAVERNS.*** The risk assessment of geological storage of CO2 was made on the basis of **ISO 2009 standards: 31000**, showing typical scenarios of failure in the CO2 storage activity are leaks along the well, destruction of the probe head and leaks through existing or induced defects and fractures. The monitoring presented in this chapter is carried out through the CavInfo Software Suite software package created by *SOCON Sonar Control Kavernenvermessung GmbH* and is specially designed for the analysis and display of individual caverns and cavernous fields.

Chapter 8. ***CONCLUSIONS, PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS***.

The purpose of this paper, presented in the third part, was that by applying the methods OF ANALYSIS OF THE STABILITY OF CAVERN ON 3D MODELS and interpreting the results to make contributions to the understanding and way of engineering calculation on the determination of the technical characteristics of the tightness of salt caverns, in their new destination as underground deposits.

The presentation OF THE POSSIBLE RISKS OF CO2 STORAGE in these caverns, with cases taken from the literature of the countries with experience in the field, only complements the working model and the way of approaching such a theme in engineering design.

As for the monitoring of land deformation phenomena in salt mines, which are discontinuous deformation phenomena, are difficult to monitor and predict, as they occur suddenly and at difficult to define time intervals. Therefore, the only possibilities for forecasting are provided by numerical modelling, and periodic cavernometric measurements for monitoring deformations in the walls of salt caverns under preservation or as underground deposits.

The literature shows thousands of storage caverns that have been operated around the world for decades, recording only a small number of leaks. Most of the leaks came from steel column failure due to overstretching, shearing, corrosion, or fatigue, sometimes followed by gas entering through the cement mantle. To prevent and reduce the risks of leaks, integrity TESTS are performed periodically, presented in terms of optimal values for the measured sizes.

With regard to the integrity of a cavern, we can conclude that special attention must be paid to the integrity of the well and for this the following must be considered:

(a) the physical, mechanical and elastic properties of the host rock;
(b) the quality of the cement work;
(c) well architecture (i.e. number and length of cemented tubes);
(d) the nature of the products stored and
(e) pressure and pressure changes of stored products.

The characteristics of the rocks play an important role in the design and operation of both surface and underground mines and require a quick and accurate assessment of these characteristics both on the ground and in the laboratory, but conducting these analyses is very cumbersome, time-consuming and expensive. In addition, a high level of expertise is also required. As a result, the researchers proposed some empirical/mathematical models to estimate some mechanical properties of the rock indirectly or through simple parameters that can be measured in situ or in the laboratory. This is because many METHODS OF AI are methods without hypotheses that do not require prior knowledge or experts or specific rules, as opposed to statistical methods that can only be used by experts. The AI method has recently gained ground in various fields of science and engineering because of its ability to solve complex problems, such as those encountered in rock mechanics.

AI methods provide more accurate results, but their practical applicability is still uncertain, as it takes repeating such a pattern before it can be applied. This requires a certain level of expertise, which can be difficult to obtain among users. In the subchapter ARTIFICIAL INTELLIGENCE IN THE MECHANICS OF ROCKS, some of the research that has been carried out in the last decade on the application of AI in the field of rock mechanics are reviewed in order to determine which AI approaches are most suitable and most commonly used in the field of rock mechanics.

In conclusion, numerous studies have used AI to solve various problems of rock mechanics, as discussed in this paper, but there are still some problems in their applications, from insufficient data to the unavailability of a simple form of models for users.

Future research should therefore be adapted to the use of advanced numerical modelling methods such as FEM and DEM to simulate field situations and generate sufficient data for AI entry.

The modelling of geoengineering processes involves special considerations and a design philosophy different from that followed in the design.

For the cavern stability analysis, we used the FLAC 3D model for the radial creep problem ***of an infinitely long cylinder with thick walls.*** The creep behaviour of the material is defined by a single component power law: $\dot{\varepsilon}_{cr} = A \cdot \sigma_c^{n}$

THE CASE STUDY was carried out on a cavern in the area of Gura Slănic Tg.Ocna, which is under conservation.

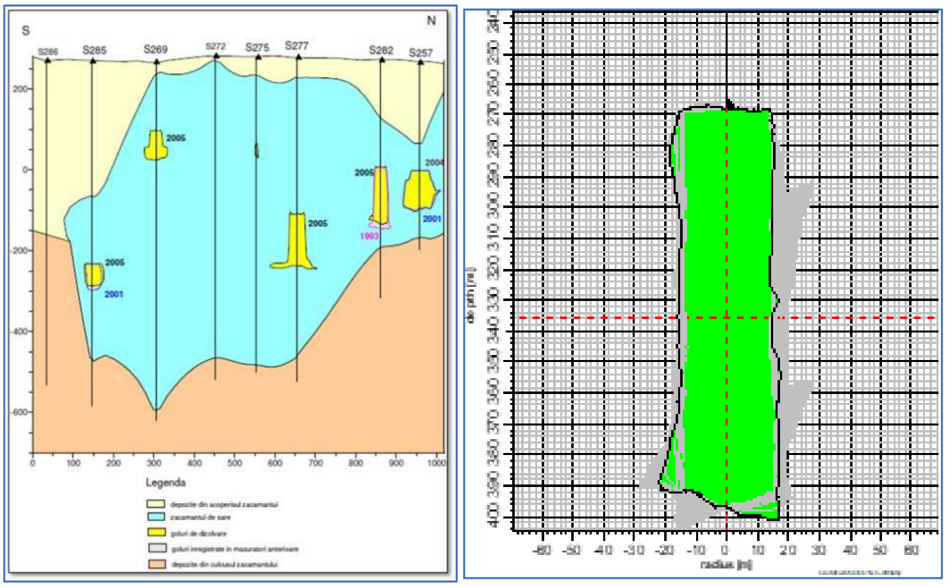

Figure 1. Vertical sections through salt caverns in the perimeter of the Gura Slanic Tg.Ocna

The operation of the cavern as a storage and use of carbon dioxide would cause structural changes and thus change the state of equilibrium. This new state is determined by the demand for the stored product (depressurization at delivery and pressurization at refilling), which requires a variable pressure regime in the cavern in the range (1 - 0.1) of the maximum working pressure. The distribution of the voltages in the salt massif near the cavern, in the two pressure limit situations of 2.928 MPa (29 bar) and depressurization at 0.29 MPa (3 bar), are shown in (Figure 2) and (Figure 3) respectively.

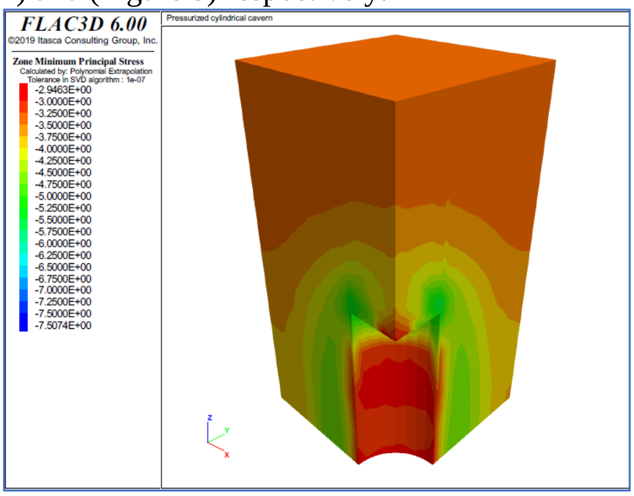

Figure 1. The distribution of tensions for a cavern pressure of P=2.9Mpa

For the situation of supply of products from the cavern, we must bear in mind that the depressurization of this must not be below a critical value. This value is 2.0258 MPa and results from the distribution of the minimum main tension, in the hypothetical "zero" depressurization situation (Figure 3).

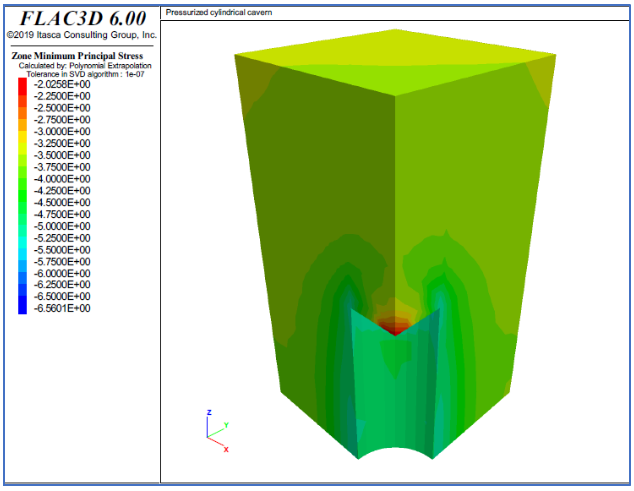

Figure 2.distribution of tensions for a cavern pressure of P=0 MPa

The maximum operating pressure must be selected to avoid fracturing the wall of the cavern, which in principle occurs when the pressure in the cavern is higher than the minimum main load in the rock mass.

It is recommended to perform numerical calculations and verify that the selected operating mode does not lead to unfavourable redistribution of secondary tensions in the rock mass.

Future research should be adapted to the use of advanced methods of numerical modelling, such as FEM and DEM, to simulate field situations.

mine Targu Ocna, Bacau

THE EXPERIMENTAL MODEL

However, performing the analysis in the laboratory or in the field is necessary to confirm the results of the other methods, despite the fact that the method is very cumbersome, time consuming and expensive.

In addition to the above, the construction of a 3D model at scale gave the possibility to measure the deformations on the outer walls of a pressurized cavern.

The construction of the 3D model and the measurements were carried out in the Laboratory of Rock Mechanics of the Faculty of Mines, Petroşani University, between November 2021 and July 2022 and started with the purchase of two salt prisms (400x400x1200mm), weighing about 500 kg each, taken from the mine Totuş, Tg.Ocna Salt Mine, Bacau.

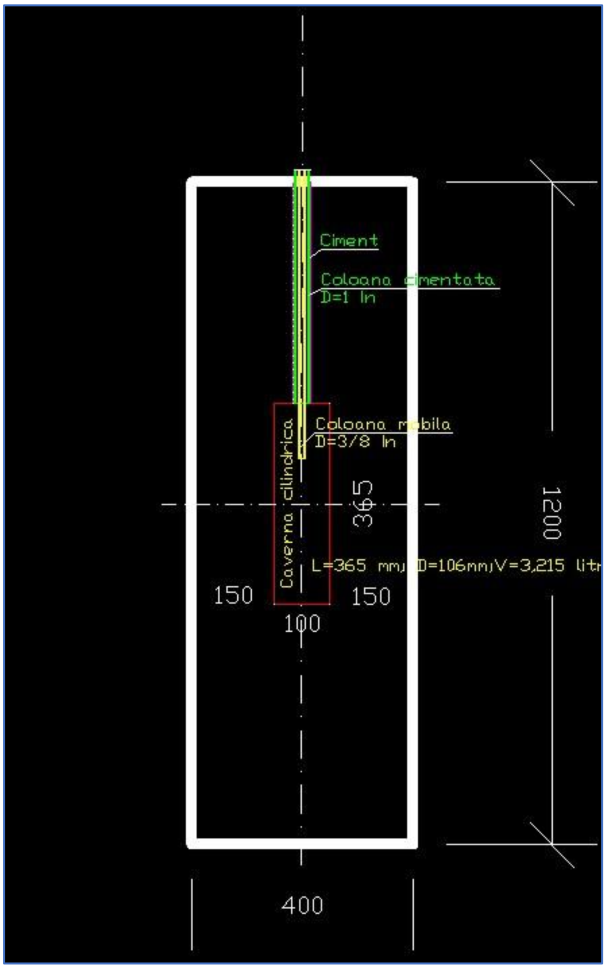

Figure 5. Construction and dimensions of the mini-cavern

In order to obtain by dissolution a cavern inside the salt prism, a hole was drilled with a length of 500 mm and a diameter of 1.5 inches, for the insertion and fixing of the dissolving device consisting of two concentric pipes, thus constituting the extraction column, respectively the operating column.

Extraction column (fixed-cemented) L= 400mm, θ=1.0 in,

Operating column (mobile) L= 500mm, θ=3/8 in.

Dissolving agent = drinking water (city network);

The temperature of the dissolving agent 22°C ;

The height of the cavern H=365 mm, the volume of the cavern V=3.215 litres (by removing the water from the cavern) were measured and the mean diameter of the cavern D=106 mm was calculated.

The interior of the cavern was researched with the help of an endoscope coupled to a computer, thus taking photos and even a video material for detailing the relief of the walls.

By performing the analysis of specific deformations, the average value of the deformity in the three directions was determined **Table** 1.

Table 1. The average tension values on the three directions

Col	Mean	StandardDev	Variation	Min
TER.1-dir.X	**33,14**	11,58	134,06	49,05
TER.2- dir. 45grd	**32,93**	13,18	173,81	67,31
TER.3-dir.Y	**26,91**	10,52	110,71	40,47

Using the previous calculation data, the direction of the main tensions can be represented **Figure** 64*6*.

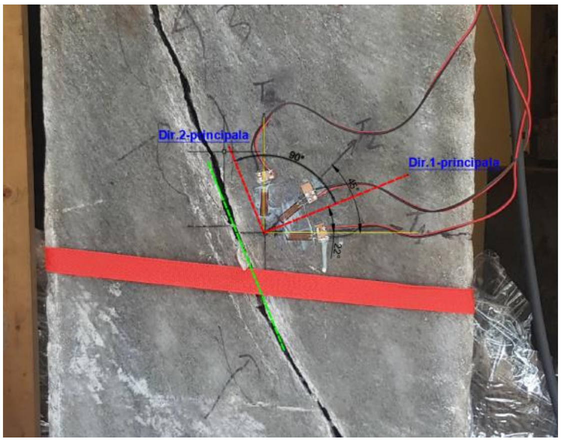

Figure 64. Determination of the main breaking directions

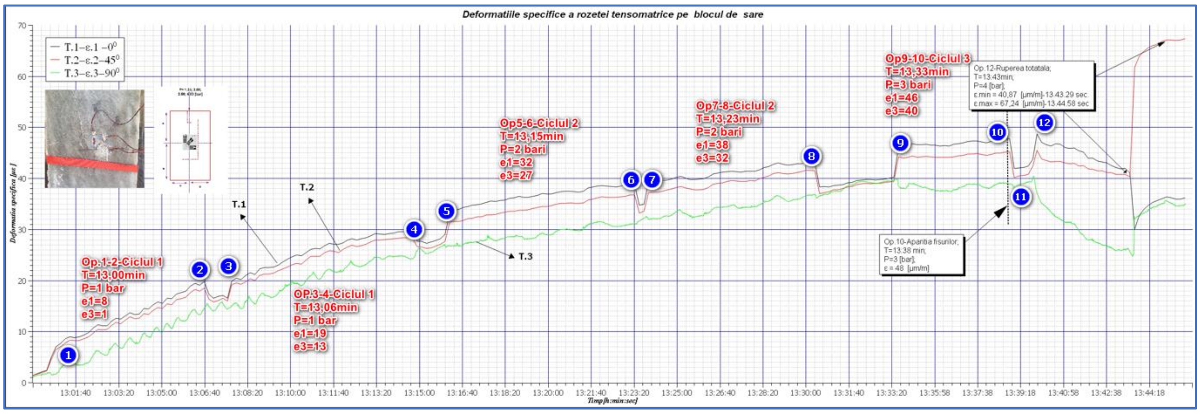

Figure 75. Recording and interpreting results from measurements

The values resulting from the MEF analysis were compared with those resulting from the measurements using the tensiometry method with resistive stamps applied to the experimental model built at the 1:500 scale, the latter validating the first. In conclusion, the application of the modelling-analysis-calculation methodology (MAC), through a double method of calculation and verification, is valid and gives conclusive results, which is why we recommend it as a complete and safe methodology in the design work.

The main personal contributions are the following:

- ✓ I carried out a vast bibliographic study on the geo-physical and mechanical characteristics of the salt masses in Romania, by presenting the geology, physical, mechanical and rheological properties, as well as the exploitation methods, especially of salt deposits with solution mining, with the recommendation of the salt deposit from Tg.Ocna, Bacău county;

- ✓ I analyzed the methods of salt exploitation through the lens of Romanian engineering practices. I presented the technical aspects regarding the construction and operation of the salt dissolution wells, as well as the verification of the tightness of the anchor columns;

- ✓ I made a synthesis of the technical characteristics as well as the standard tests needed to evaluate the tightness of the caverns. The study is based on specialized literature from countries where the storage of various gases or hydrocarbons is used. I have identified mechanical integrity tests for salt storage caverns that are used to determine the condition of cavern access wells and the integrity of the fluid or gas storage system.

- ✓ I presented the theoretical basis regarding the stability of the salt massif with particularization for the TG salt deposit. OCNA - Gura Slănic perimeter. Research has shown that rock mechanics/geoengineering problems are highly related to the insufficiency of site-specific data. I have therefore solved this problem through artificial intelligence (AI) based prediction methods. In the paper I have presented, in addition to some theoretical aspects, and examples of application;

- ✓ For the cavern stability analysis, I have used the FLAC 3D model for the radial creep problem of an infinitely long cylinder with thick walls with the analytical solution presented in the relations (84), and for the creep problem the single component power constitutive law was chosen (83). $\dot{\varepsilon}_{cr} = A \cdot \sigma_c^{n}$ (Where A=3.9 × 10^{-7} [$MPa^{-4.9}$ $year^{-1}$] and n=4.9-experimentally obtained parameters).

- ✓ I simulated, based on the measured data, the distribution of stresses in the salt massif in the vicinity of the cave, in the two limiting situations of pressurization at a pressure of 2.928 MPa (29 bars), respectively depressurization at 0.29 MPa (3 bars). In conclusion, setting the maximum admissible pressure at the standard value 80÷85% of the lithostatic pressure (the weight of the rock column) is valid and therefore acceptable for the Tg.Ocna Salt Mine;

- ✓ I made a 3D scale model for measuring deformations on the outer walls of a pressurized cavern. The construction of the 3D model and the measurements took place in the Rock Mechanics Laboratory of the Faculty of Mines, University of Petroșani, between November 2021 ÷ July 2022 and started with the purchase of two salt prisms (400x400x1200mm), weighing approx. 500 kg each, taken from the Trotus mine, Salina Tg.Ocna, Bacau;

- ✓ I measured the deformations in the three directions with the author of some original schemes for placing the tensometric stamps and with solutions for placing them on the salt sample, which is a wet sample;

- ✓ In order to measure the deformations in the cave walls at different pressures, I have designed a flexible and easy-to-use circuit: gas cylinder (CO2 or Helium - we opted for these non-explosive gases, for safety reasons) under a pressure of 200 bars, pressure reducer max. 30 bars, pressure hose for connection to the cavern, valve with exhaust valve for depressurizing the cavern. I have set the pressurization of the cavern in pressure steps of 1-5 bar, and 3 rounds of 5 minutes each. More precisely, the first pressure step of 1 bar, the cavern was pressurized for 5 minutes, after which the source (cylinder) was closed and the cavern was depressurized. 3 cycles of 5 minutes each were performed, after which it was switched to a higher pressure step. The recording of the measurements was done with the help of a module and specialized software correlated by me;

- ✓ The geological storage of CO2 is an innovative method but, due to the complexity of the capture and storage process, health, safety and environmental risks may arise, and because of the caverns, understanding these risks becomes of fundamental importance. That is why I have carried out a complex analysis of the risks of CO_2 storage in salt caverns, as well as their management;

- ✓ In order to have a clearer picture of the evolution of the caverns of the analyzed probes, we performed cavernometric measurements in the probes from Tg. Ocna – Gura Slănic, resulting in their shape and the maximum contour of the cavern;

- ✓ Regarding the monitoring of land deformation phenomena in the case of salt pans, these being discontinuous deformation phenomena, they are difficult to monitor and forecast, because they appear suddenly and at hard-to-define time intervals. Therefore, the only forecasting possibilities are provided by modeling with numerical methods, and periodic cavernometric measurements to monitor the deformations in the walls of salt caverns under conservation or as underground deposits.

Salt caverns can be used for temporary storage of CO_2 or to use CO_2 for other commercial purposes. These structures are considered to be less suitable for long-term CO_2 storage because they could be used for other applications (CCUS-carbon capture for its use and storage).

In the world, caverns of this type are used for storing various products of hydrogen, natural gas, carbon dioxide, up to crude oil or nuclear waste, which requires caverns to be sealed.

In our country we are witnessing a situation in which mining operations have been and are progressively closed, even abandoned, without paying sufficient attention to the possible technical consequences and on the environment in the medium and long term. On the other hand, I know individuals and institutions from the private and state environment, who support and conduct research activities aimed at developing technologies for a clean environment. As far as I am concerned, I propose that future research work should be directed toward the three main axes: To better understand, analyse and model elementary phenomena and the various mechanisms that can intervene and interact in predicting and preventing technical, security and socio-economic consequences.

Storing CO_2 in salt caverns is an innovative method but because of the complexity of the capture and storage process, risks to health, safety and the environment can occur, and therefore understanding these risks becomes of fundamental importance.

Achieving climate goals will require a transformation of global energy systems of unprecedented scale, speed and ambition. CCUS technologies are expected to play a critical role in supporting this transformation as part of a portfolio of technologies and measures with minimal cost.

The storage of CO_2 in salt caverns is an area that has not been thoroughly researched, which requires further research in:

- modelling tools to predict the long-term response of rock mass to salt flute and its impact on the integrity of the cavern;
- regional storage capacity and costs must be estimated.

As future projects, I will consider the following studies:

- Further research on underground works in salt masses. Modelling the geometric evolution of an underground cavity (dissolving and transport mechanisms, breaking mechanism, rock-brine interaction;
- Analysis (forecast) of the influence of underground exploitation on the surface of the land from the day (respectively, determination of the main deformation parameters) and the stress-deformation state of the covering rock massif - under the conditions of salt deposits exploited by dissolution;
- Optimizing the geometry of cavern and operating pillars in case of extraction of deposits salt jam ;
- Analysis (forecast) of the stability of the protective pillars of underground voids, located in the influence area of other cavern, or their dimensioning in the design phase;
- Dimensioning of underground cavern and analysis of its stability under the conditions of static or / and dynamic stresses generated by natural or induced earthquakes;
- Thermo-mechanical analysis of the stress-deformation state and the stability of underground mining excavations under the influence of thermal emissions generated by radioactive waste deposited in underground spaces;

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