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Salt exploitation by dissolution – an alternative method to reduce post-closure risks

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Abstract. During the last century, the mine closure frequency had significantly increased, therefore important environmental issues affect the public safety and the sustainable development process of the mining areas. The customary method of salt exploitation by dissolution uses the flooding of the formed caverns as the last step of the exploitation, which permanently isolates the caverns. In this case the rock-mass equilibrium inside the cavern changes, calamities such as seismicity, subsidence and collapse occasionally occur. Quite a few times, human settlements, civil buildings or industrial constructions located at the surface are affected. The present paper discusses adopting an alternative salt exploitation method by dissolution which offers the possibility to extract the entire salt deposit. This allows monitoring the stability factors linked to the exploitation process - the collapse that will occur as monitored represents the latter part of the method. It finally offers the opportunity to reclaim the water surface formed as a sustainable development goal and to reduce the long-term risks for calamities.

1 Introduction

Dissolution salt exploiting methods have been known since ancient times. The main source of obtaining salt solutions was the shallow wells, as well as the cracks from which the brine was extracted. Most chroniclers have described the method of dissolution mining in more or less detail, but what is essential to remember is that these methods remained unchanged for hundreds of years. Analyzing the evolution of these methods as well as their diversification, it can be appreciated that important changes have occurred in order to obtain maximum productivity, with minimum energy consumption. The first methods of exploitation by dissolution were based on the extraction of salt from concentrated solutions, already existing [1].

The classification of salt mining methods using dissolution requires taking into account the following criteria:

-Types of production columns (fixed or mobile);
-Dissolution mode (directed or undirected);
-How to raise the production column (in small or large steps);
-Wells grouping (individual, in battery).

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Following the results obtained with different exploitation methods, it can be appreciated that the only rational criterion for classifying the methods is the efficiency of the method, given by the way the dissolution process is carried out.

2 Mining methods

2.1 Mining methods with undirected dissolution

There are two main methods [2]:

a.) Column mining method. This method represents the first method used in salt mining through drilling and provides for the introduction of a single mining column up to close to the maximum depth of the well. Well with an ascending circuit or with a descending circuit are known, depending on the direction of circulation of the solvent (water).

b.) Descending circuit exploitation method. In this method, the contact zone of the fresh water with the salt is located at the level of the cemented column. The brine is extracted through the mobile (extraction) column, which descends close to the bottom of the well. The stratification of the brine by density is favored by the descending circuit. The ceiling is not subject to dissolution due to a cushion of air directed from the water. The shape of the dissolution chamber is a funnel, with a horizontal ceiling, which can reach a diameter of 100 m in a period of 2 years and which can give saturated solution continuously only at the end of the exploitation period.

2.2 Mining methods with directed dissolution

These methods are characterized by the possibility of controlling and directing the dissolution process. Two methods are used worldwide: salt exploitation methods with dissolution in large steps and in small steps. Both methods use three operating columns: for water, for brine and for insulating fluid. Mining with high dissolution stages is based on the increased dissolution rate that occurs successively from the core of the well to the periphery for each stage. The shape of the dissolution chamber that results from mining is a truncated cone, with each step resulting in the final shape being a succession of truncated cones with the large base up (Fig. 1).

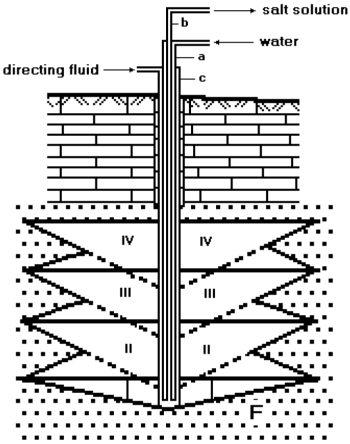


Fig. 1. The shape of the dissolution chamber with large step method [1].

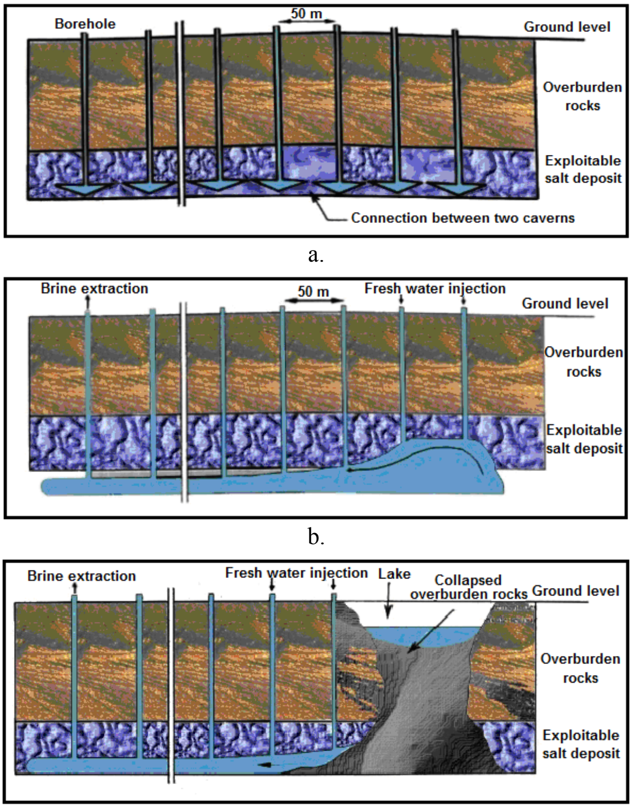
The mining method with small steps is applied exclusively in Romania, constituting a Romanian patent. Using small steps mining method, the phenomenon of vertical dissolution is used. The shape of the resulting dissolution chamber during operation is approximately cylindrical, closed at the top with a cut or pointed vault, depending on the speed of advancement of the dissolution to the ceiling.

2.3 "Column" or "battery" exploitation method

It is a well exploitation method in which a controlled collapse of the well field is carried out, or the intensive method. This method, introduced by the SOLVAY CARBONATE-FRANCE company in the Haraucourt concession in 1939 [3], has been gradually improved and makes it possible to achieve the following main objectives:

- Control and monitoring of the dissolution area;
- Maximum deposit recovery rate;
- Caused and directed collapse of cavities with precise localization. This makes it possible not to leave cavities that could later give rise to uncontrolled subsidence and collapse;
- Minimum ground impact area.

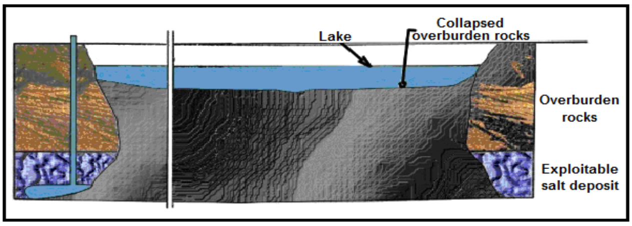
This method consists of an alignment of 20 to 30 boreholes, spaced 40 to 50 m apart, drilled to the base of the salt deposit. Each borehole is equipped with a cement casing that traverses the land in question. The foundations of the surveys are put into communication by creating a channel formed in salt by dissolving it. Briefly, the method is presented in Figure 2.



a.

b.

c.



d.

Fig. 2. Mining method applied at Cerville Buissoncourt – France. a) Stage 1 – Longitudinal section of a track at the connection between isolated borehole; b) Stage 2 – Development of the dissolution cavity due to freshwater injection, up to the top of the salt; c) Stage 3 – Collapse of the area around the well where the freshwater injected; d) Stage 4 – Longitudinal section of the collapse at the end of exploitation [3].

3 Characterization of the Gura Slanic - Târgu Ocna exploitation perimeter

3.1 Gura Slanic - Târgu Ocna deposit geology and hydrogeology

The rock salt deposit is located in the perimeter of the town of Târgu Ocna, on the lower course of the Vâlcica stream. Geographically, the Târgu Ocna region is located at the base of the eastern slope of the Eastern Carpathians. The uneven relief has elevations between 400 ÷ 600 m. The main water collector in the area is the Trotuş river [4].

Hydrogeologicaly, the rock salt deposit faces the effects of surface and underground waters. A real danger of water penetration on the salt deposit, inside the massif, is the old and new mining works that pierce the roof continuity. Another way for water to enter the massif is the old, abandoned and damaged drainage works.

3.2 Gura Slanic - Târgu Ocna deposit shape and position

The Târgu Ocna salt massif is part of a planing blade pulled from the Miocene of the western external unit and superimposed on the Helvetic deposits of the Pericarpathian unit in the Vâlcele window. In the area of the exploitation perimeter, the blade extends in the N-S direction for 1 km and in the E-S direction for approx. 700 m, having a thickness of 350 m in the central part.

In addition to the anthropic ways of water penetration into the massif, there is the possibility of their penetration along the faults, which affected both the roof formations and the deposit.

The dissolution processes produced in the roof and inside the salt massif determined the surfacing of some old mining works, arising of pits and funnels with openings on the surface of the land, arising of lakes, sinking processes recorded on the surface of the land. In order to determine or even stop these effects, works were undertaken to seal some depressed areas on the surface of the land with clay material, the systematic monitoring of sinking, the control of water circulation: the detection of infiltrations, the digging of dams, drains, canals and the maintenance of a constant hydrostatic level of the groundwater around the massif [4].

3.3 Qualitative characterization of Gura Slanic - Târgu Ocna deposit

Rock salt is granular, widely crystallized, compact, whitish gray or blackish gray in color. The texture of the salt is massive, compact. Inside the massif there are numerous sterile intercalations, with thicknesses between 10 ÷ 15 cm. [4, 5]

The rock salt consists of halite 85 ÷ 99%, next to which appears sylvinite, gypsum films and anhydrite with earthy marl-clay elements. From the point of view of chemical composition, Târgu Ocna salt contains between 92.37 ÷ 98.83% NaCl and 1.12 ÷ 4.30% insoluble materials.

It is also concluded that the depth of approximately 300 m represents a depth beyond which any dimensioning problem of resistance elements must be done with important caution.

3.4 Description of the present situation at Gura Slanic well field

On August 18, 1960 the well 363 and later on, the well 364 started their operation at Gura Slanic well field. The year 1966 saw the operation of two other wells: 365 and 366 and in 1970 there was performed a hydraulic joining of the wells 367, 368 and 369 [6]. Between 1977 and 1991 the wells 376 - 379 were drilled and initiated (Fig. 3).

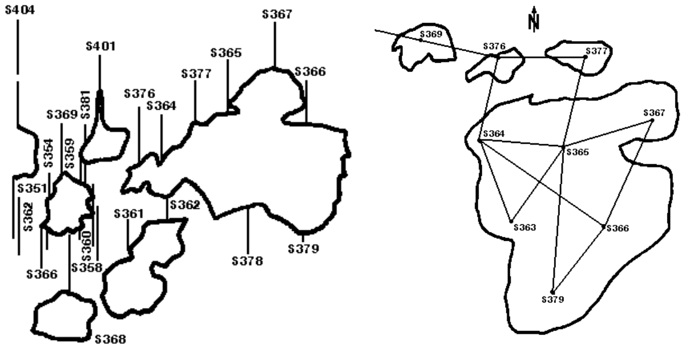


Fig. 3. Location of the Gura Slanic wells [6].

The total cumulated volume of the goofs connected to the wells in operation is of approx. 1,879,546 m^3. As for the shape of these voids it deviates a lot from the cylindrical shape, the dissolution radius suffering large deviations from the design radius. This aspect has been proved by underground measurements (Fig. 4).

Fig. 4. 3D representation of the Gura Slanic – Targu Ocna probe cavity.

Rock salt exploitation in our country using the method of kinetic dissolution well raises special problems regarding the stability of the massif of rocks in which an imbalance has occurred, due to the appearance of the dissolution chambers. Through the appearance of voids resulting from dissolution, the initial state of tension of the salt massif changes, creating a redistribution of tensions. This redistribution of stresses around the created gap implies the appearance of stress concentrations that reach the maximum value in the horizontal extremities of the gap. This stress concentration can cause cracks and falling blocks from the ceiling or walls in the dissolution cavity.

Maintaining the tension balance in the massif during exploitation, as well as after closure, requires the choice of appropriate methods of exploitation technology.

Still in the design phase of the dissolution exploitation, it is imposed from a geomechanically point of view, in order to maintain the tension balance, the judicious establishment of the height of the dissolution chambers as well as the plan position of the wells. These two characteristics of the exploitation suppose to have safety pillars between the dissolution chambers, which if optimally designed and provide stability without risk and for a long period of time [5].

The problem of tracking the movement and deformation at the surface under the influence of the caverns resulting from the process of dissolution salt exploitation has special implications for surface protection. We will continue to deal with one of the methods of determining the displacement and deformation parameters of the surface and we can evaluate the amplitude of the phenomenon. The database used was obtained through topographical and cavernometric measurements carried out over a long period of time. The main purpose of the conducted research is the most efficient forecasting of the phenomenon, forecasting to prevent the occurrence of ecological catastrophes [7]. The areas of land affected by the influence of mining operations are expanding more and more as a result of the abandonment of salt dissolution exploitation, and sometimes turn out to be unprofitable. Currently, mine fields abandoned by dissolution wells constitute a real danger, through the uncontrolled process of dissolution that generates caverns with safety floors, whose thickness no longer corresponds in terms of bearing capacity [8]. Insufficient knowledge of the problems related to the dissolution salt exploitation can lead to the loss of control over the dissolution and implicitly to the destruction of the intercameral pillars. Studying the phenomena that can occur in the displacement process, as an effect of the destruction of these pillars, the particular importance is delimiting the dangerous areas.

In our country, the research and evaluation of these phenomena is done by specialized institutes, which have the appropriate equipment for topographical and cavernometric observations. The fair appreciation of these factors in the evolution of a mining exploitation immediately leads to the reduction to the minimum and even to eliminate the negative effects, through the developed study we will highlight the phenomenon of displacement and deformation of the surface under the influence of underground voids.

4 Checking the roof thickness and stability at the Gura Slanic mine

4.1 Theoretical considerations

Considering the geological and hydrogeological parameters, salt strength and deformation features and the field measurements performed at surface and in underground we have tried to check the roof salt stability and give a prognosis on their destruction [9].

Considering the current situation, for the roof salt thickness, the diameter of the dissolution cylinder we used the equation (1) to check the roof thickness [1, 10].

$$h_{pl} = \frac{n \cdot \gamma \cdot l^2}{2B \cdot \sigma_{rt} a}\left[1 \pm \sqrt{1 + \frac{4B \cdot a \cdot \sigma_{rt}}{n \cdot l^2 \cdot \gamma_a^2}\left(q_s - P\right)}\right] \tag{1}$$

Where:

-q_s – strain put over the table by the roof rocks;

-l – maximum opening of void;

-B – shape coefficient, with values ranging between 2 and 8, depending on the shape of the table; for the case of a circle or elliptic table, B = 3 ÷ 5.33;

-n – safety coefficient;

-σ_{rt} – salt resistance to traction;

-P_n – leonine pressure.

Based on this equation, there resulted a minimum roof thickness of $h_{pl} = 48$ m.

As drillings have proved, this thickness is generally observed.

The maximum recorded sinking is much lower than the calculated maximum sinking of 2.5 m from which the uncontrolled rupture process begins.

The forces created by the weight of the floor and the covering rocks exceeds in some cases, in deep wells, the long-term resistance to compression and traction of the salt in the floor. From the laboratory measurements and tests, it follows that the breaking of the floor will be smooth, being preceded by a high value of the sinking. Regarding the Burlacu Lake, the lake formed in 1974 which is located in the Magura park, the sinking do not exceed 0.6634 m, respectively a maximum sinking speed of 2.23 cm/year. For the dangerous (risk) area, respectively for the wells in this area, the maximum sink does not exceed 0.7832 m, respectively a sinking speed of 2.65 cm/year. For the area of wells 369, 376 and 377, the maximum sinking do not exceed the interval 0.3683 ÷ 0.8954, respectively a sinking speed between 1.88 and 3.17 cm/year [10].

From the analysis of the forecasting relations of sinking and according to the determined sinking speed, it follows that the dangerous sinking of 1.5 m will be reached after a period of activity between 40 and 50 years from the date of the measurements and laboratory experiments. So, it can be said that for no one well in the Gura Slănic field there are no dangerous sinking, which would endanger the exploitation of the well and the stability of the surface for the time being.

To estimate the stability of pillars and roof at the Gura Slănic well field, a stress state simulation method based on numerical methods with boundary element analysis was used [11]. We used the EXAMINE 2D software to assess the stress-strain state and establish the resistance factor of underground structures, displacements and deformations suffered by pillars and floors [12].

4.2 Experimental results for 365 well

Taking into account the data from the cavernometric measurements made, we simulated the state of tension around well 365 with the help of the Examine 2D software, taking the almost circular shape of the well, according to its horizontal section (Fig. 5).

In the vertical section, the images of the maximum graph and the average diameter graph are superimposed. For 365 well, the data taken from the cavernometric measurements are reproduced in Table 1. Thus, the safety coefficient of the circular excavation with an average radius of r = 7 m located at a depth of H = 228 m was calculated under the conditions of the gravitational stress field, the isotropic environment of the rock massif, applying the Mhor-Coulomb failure criterion [13]. The boundary element is constant and the analysis is plane strain type. The summarized information of the project is shown in Table 1.

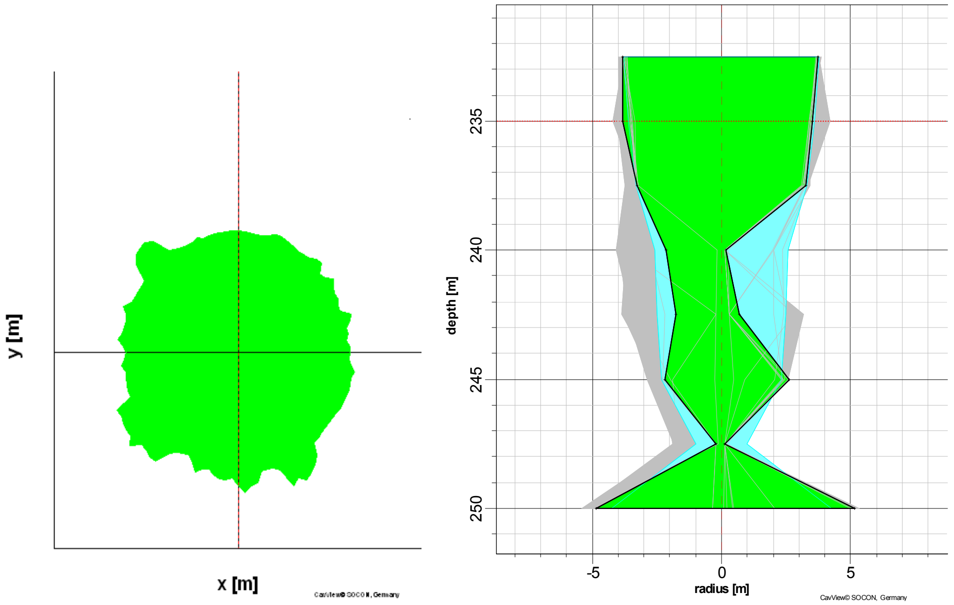


Fig. 5. Horizontal and vertical section through 365 well.

Table 1. Measurements for the 365 well [4].

Well 365	**Geometric data and Volume**
Volume	488698 m^3
Depth limits	228 m <--> 250 m
Maximum radius	7 m
Depth	228 m
Direction	180°

The results obtained for 365 well are presented in Fig. 6 (left) for the simulated main stress and in Fig. 6 (right) for the resistance coefficient.

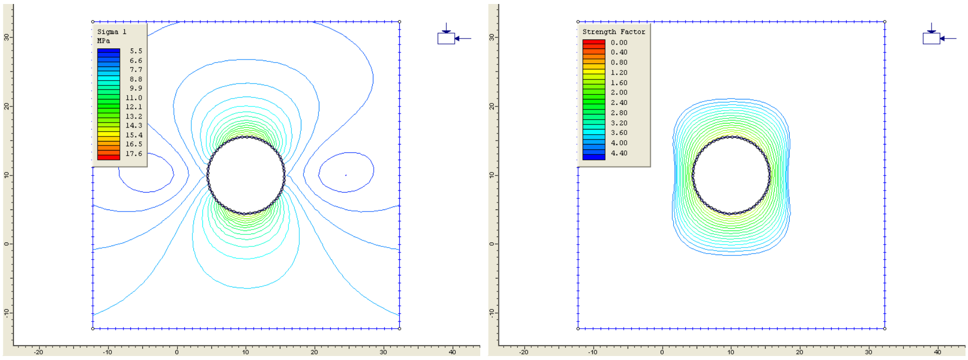


Fig. 6. Maximum main stress and the resistance coefficient.

In the analyzed case, it is observed that the resistance coefficient R is above unity $R > 1$, that is, the rock resistance is higher than the breaking stress.

In conclusion, it can be stated that the analyzed excavation is stable, there is no danger of fracturing (breaking) of the resistance elements.

5 Results and discussions

For a proper monitoring of the diving phenomena, the existence of a monitoring station must be taken into account and the density of the sensors must be optimal. The number and location of the sensors are determined according to:

-the shape of the deposit;
-the properties of the covering rocks;
-properties of salt
-configuration of exploited areas;
-the evolution of the phenomenon in certain areas;
-the existence of some restrictions regarding the location due to the constructions or existing waters on the surface.

The strong development of techniques and technologies has led to the emergence of integrated IT systems, in which the processing and memorization of measurement data, analytical and graphic processing, the organization of databases, as well as the transmission of information between different levels is carried out by means of interconnected electronic equipment that use specialized software products.

Using the software Examine 2D, the state of tension, deformation was simulated and the resistance coefficient of each cavern determined for dissolution salt exploitation method was calculated. The geometrical data of the excavations are taken from the cavernometric measurements and the elastic and resistance properties of the salt massif were determined by the laboratory tests performed on the samples from the Gura Slănic mining field. Analyzing the resistance coefficient for the excavations, it can be stated that the analyzed excavations are stable and there is no danger of breaking the resistance elements.

Drawing a parallel with the method described and used by SOLVAY CARBONATE-FRANCE, it can be stated that these problems related to the stability of voids resulting from the exploitation of salt in solution are eliminated from the very beginning of the planning of the start of exploitation and last throughout the exploitation without posing the problem of the appearance of risks for the population and the environment.

In order to make a more precise prevision of the phenomenon, a prevision that could be made not only on statistical grounds but could also take into account the existing and future exploitation in the area, it would be necessary to calculate the horizontal displacements and the specific horizontal displacements, the calculation of the inclination , calculation of curve, overviews of dips, horizontal displacements, inclinations and curves, determination of connection functions between surface deformation/displacement.

We can make a brief description of the surface effects of the main brine production methods:

•"stable caverns": ground surface movements are negligible during and after mining. The long-term stability of the caves is certain;

•"deliberately collapsed caverns": all created caverns are deliberately collapsed during the operation period;

•"unstable caverns": caverns are neither completely collapsed nor all definitely stable in the long term;

•"wild brining": the origin of the clean water required for dissolution is not controlled.

In addition to the public safety, groundwater and environmental protection issues it may raise, the unstable cavern method creates, for any further use of the surface by the community, a constraint that cannot be considered acceptable.

The "stable cave" method is today the most frequently used method for the dissolution salt exploitation. It is universally considered an acceptable mining option, provided that techniques that meet current best practice are used during the creation, exploitation and abandonment of caverns. This method is now the only one accepted in Germany and the Netherlands.

Methods involving deliberate collapse of the ground surface are not widely used around the world, where the collapse of the ground surface is often considered an undesirable consequence of mining activity.

6 Conclusions

In conclusion, the so-called "stable cave" method is the brine production method considered worldwide as the most desirable. This method, if properly implemented, subject to an examination that takes into account the particularities of each operation, in the long term induces only negligible risks for safety and environmental protection.

The "deliberate collapse" or "intensive method", which has the advantage of a high exploitation rate, creates constraints on the future use of the land surface, in addition to the safety, hydrogeological and environmental protection issues it raises. In order for this method to be implemented, it is necessary that the collapses can be predicted with certainty, that no damage can be caused to the drinking water resources, that there is no risk of accidentally pollution with dissolution water after the collapse and that the abandonment caverns does not need any work that requires permanent maintenance.

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