MODIFICATION OF THE STATE OF STRESSES AND STRAINS AROUND THE CAVITIES RESULTED AFTER THE EXPLOITATION OF SALT BY DISSOLUTION CASE STUDY: OCNELE MARI EXPLOITATION

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Abstract
Due to the complex geological aspects, the stability and management of the caverns produced in salt by dissolution represent a very difficult task. The special properties of the salt – low conductivity, viscous-elasto-plastic behavior – made salt suitable for hydrocarbons and high-active waste storage in caverns produced by dissolution, beside the actual salt exploitation. At the same time, beside the location investigation made by various methods, it is necessary to evaluate by calculus the stability of the cavern in various exploitation conditions. Among the methods used for this, the numerical modeling presents undisputed advantages because is using all the existing information and permits the cavern behavior simulation in relation with the existing loadings.
The numerical modeling of the stress and strain around the salt dissolution caverns is intended to simulate the controlled collapse progress of the main cavern in Filed I – Ocnele Mari.
Key words: cavern, numerical modeling, monitoring, safety factor

1. Introduction

The exploitation of the Ocnele Mari deposit was performed by salt dissolution, a technology which involves the injection of sweet water flows that dissolve the salt by means of a well system. The outcoming brine is extracted by means of the same well system and it is delivered to the processing plants.
The exploitation of the salt deposit through solution mining results in the formation of caverns filled with brine under pressure. It is crucial to maintain the mechanical balance of the cavern during the exploitation of the system through brining. For this purpose, the exploitation technique involves the development of cylindrical caverns, centered around the well, maintaining a salt layer in the roof of the cavern, thick enough to ensure its balance. To the extent possible, the exploitation shall be performed outside the populated areas in order to avoid any serious consequences, in case of a potential collapse. At the same time, the system's behaviour is continously monitored, supervising the evolution of subsidence through surface measurements and the evolution of the cavern through cavernometric measurements. Lately, the monitoring system is supplemented by monitoring the cavern's induced seismicity, in order to highlight the stress concentration areas.
These requirements were not complied with in case of the exploitation of Ocnele Mari deposit, as the wells were dug at small distances one from another, thus determining an uncontrolled exploitation. Given the fact that the salt deposit base contains sterile gangue material, eroded due to the exploitation process, the individual caverns of the wells merged together, resulting in the formation of cavities of signifiant volume. Hence, in the Well Field II of Ocnele Mari, the common cavity had a volume of approximately 4.3 milion m^3. The accidents occurred during a period of 4 years, brought about unpleasant situations, having an impact both on the local community (many families had to relocate) and on the environment. Also, a cavern with a volume of nearly 1 milion m^3 was present in the Well Field I, such cavern being defused in 2009.
The evaluation of the cavern stability actually involves the calculation of the state of stresses and strains in the geological complex where the cavern was opened. Due to the complex geometry, the variation of the geomechanical properties, as well as due to the constitutive rock behavior laws, the analysis of the state of stresses presents a very high level of difficulty. The only method able to take into consideration all elements in case of unsteady loads is the numerical modeling.
This work has two objectives:
Analysis of the evolution of the state of stresses and strains during the defusing of the situation in the Well Field I of Ocnele Mari
Correlation of the integrated monitoring system results with the distribution of the state of stresses and strains, obtained through numerical modeling

2. Geological conditions

The Ocnele Mari salt deposit is located in the Lower Carpathians Hills of Oltenia, at a distance of about 10 km westwards from the municipality of Rm. Vâlcea.

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Masses from the Paleogene, Neogene and Cuaternary age are present in the area.
The Ocnele Mari salt deposit occupies the northern flank of the Govora – Ocnele Mari anticline (fig. 1), being limited by the Copacelu fault in the East and the Teiuş fault in the West. Also, the salt deposit is limited by the Stoeneşti fault in the North and the Bisericii fault in the South (fig. 2).

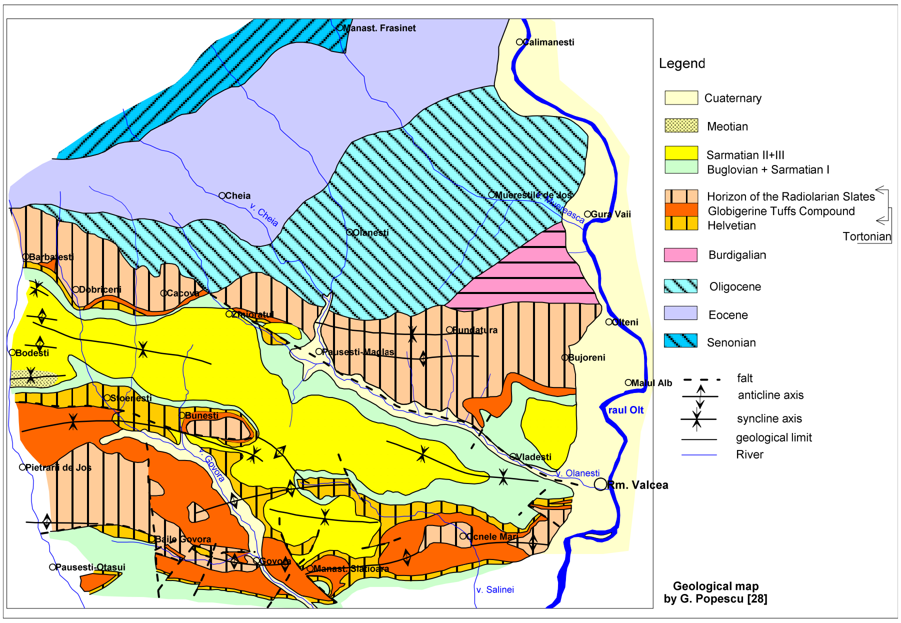

Fig. 1 *Geological layout of Govora - Ocnele Mari area*

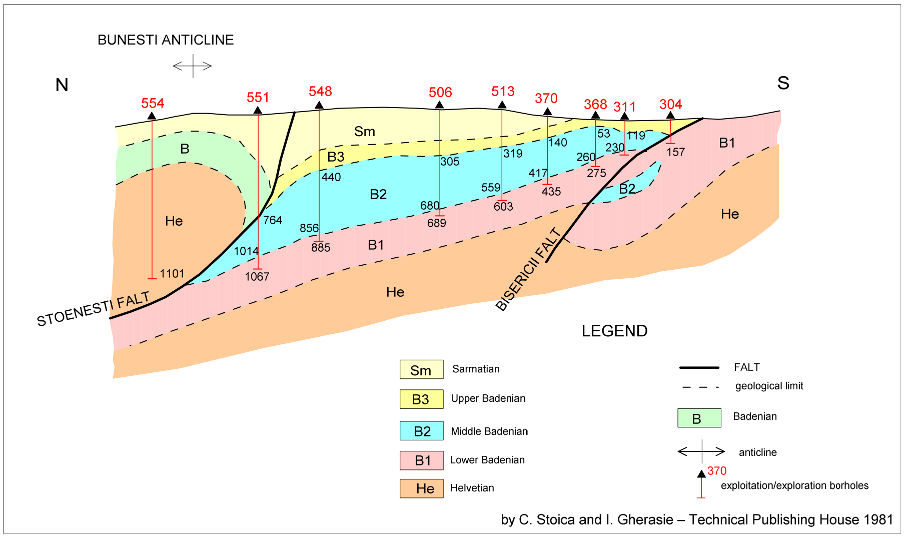

Fig. 2 *Geological section of the Ocnele Mari deposit*

The salt deposit is lens shaped, having a length of 8 km, a width of 3.5 km and a total surface of about 30 km^2. The masses in the deposit's roof belong to the Upper Badenian age and those in the floor belong to the Lower Badenian age. The NaCl content of the deposit is 98-99%. The thickness of the deposit varies from a few metres in the pinching-out area to 473 m. The average thickness of the deposit is of 250 – 300 m.
The exploitation of salt through solution mining at Ocnele Mari started in the 1960s and it was carried out in time by means of four well fields. Currently, the exploitation only continues in Fields III Lunca and IV, Fields I and II being decommissioned. Well Field I consisted of 10 wells (fig. 3). The exploitation of this field started in 1960 and went on until 1973. At the beginning of the exploitation, the wells were operating individually, but, due to the circulation of fluids through the interlayers of the salt deposit, the cavities of the wells merged together over the time.
In 2006, after the defusing of the situation in the Well Field II, having in view the influence of the phenomena occurred in this field over the Well Field I (the two fields were hydraulically communicating through the sterile interlayers within the salt deposit), the wells in Field I were cavernometrically measured. The performed measurements revealed the presence of a cavern of approximately 1 milion m^3 in field I.
Following the identification of this cavern, the systematic monitoring of this field was initialized.

The monitoring involved cavernometric measurements, topographic measurements, level measurements, as well as microseismic monitoring. During the 3 year period until the defusing of the situation, the salt ceiling above the common cavity of the wells in Field I, gradually crushed down. Hence, while in January 2006, the surface having a salt layer with a thickness of less than 10 m was of about 3600 m^2, in January 2009, the surface was of about 8000 m^2 (fig. 3).
The continuous moving-up of the cavern's ceiling is reflected in the evolution of the sinking, their gradient increasing from 1.1 cm/year in 1995 to 2.5 cm/year in 2007 and locally up to 9.1 cm/year - at the beginning of 2009.
These two elements – the moving-up of the ceiling and the continuously increased sinking, led to the conclusion of an imminent collapse of the cavern's ceiling.
In order to avoid the consequences of this process, the Research Department of Geology and Ambiental Geophysics proposed a project for the defusing of the situation in the Well Field I.
In 2007, when the ceiling segmentation process was speeding up, a measure of stabilization of the system was implemented, by introducing concentrated brine in the cavern and by maintaining a high level of the brine.

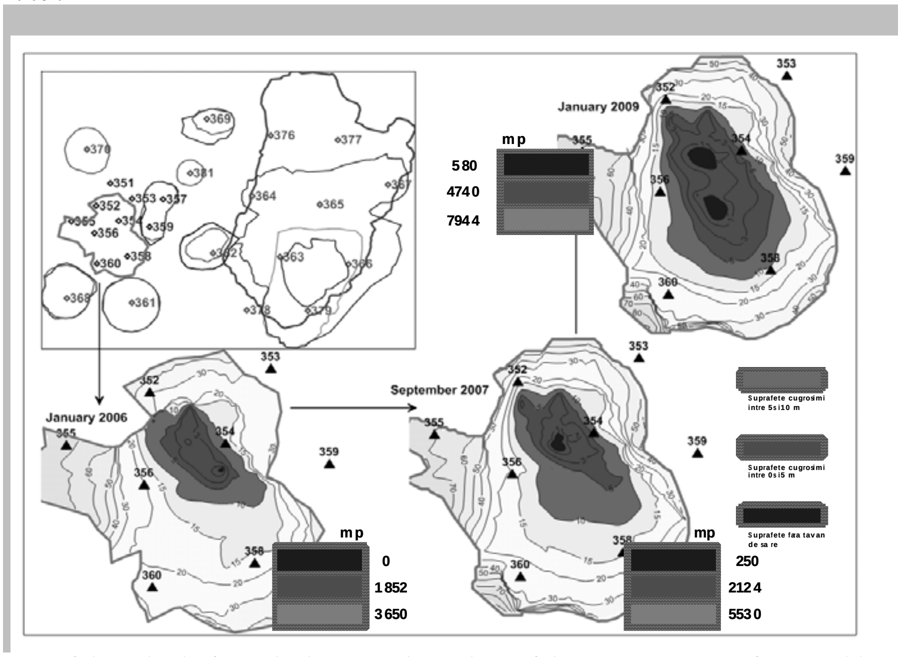

Fig. 3 *Evolution of the salt platform thickness in the ceiling of the common cavity from Field I –2006-2009*

The Research Department of Geology and Ambiental Geophysiscs– of which I am a member, operating within the Faculty of Geology and Geophysics of the University of Bucharest proposed a project for defusing the situation in the Well Field I. After the approval of the abovementioned project, the proposed works were initialized. Principle of the project: gradual reduction of the piezometric level in the cavern and the takeover of the brine volumes by the chemical plant. Firstly, a dam was built on Pârâul Sărat creek, which was intended for the takeover of the brine volumes pushed out from the cavern; connections were established between the wells and this dam; 3 pumps were installed in wells 361, 368 (wells belonging to Well Field II, situated in the South of Field I and 370 from Field II, situated in the North of Field I – the three wells establishing a hydraulic connection with the cavern consisting of the wells in Well Filed I); a buffer tank was installed on the route of the connection pipes between the wells where the pumps were installed and the brine duct.
In July 2009, it was decided to initiate the controlled collapse of the cavern in Well Field I. For starters, on July 14[th], the level was let free (no brine was introduced in the cavern), and later, on July 28[th] the reduction of the level through the three pumps was initiated.

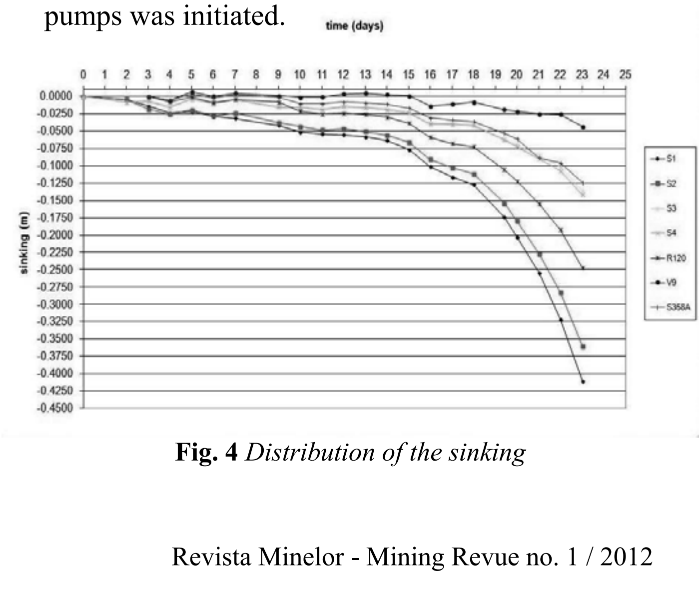

Fig. 4 *Distribution of the sinking*

During the period July 15th – August 7th, several land cracks were revealed (photo 1-2), suggesting a potential rupture area and the sinking recorded a maximum level of 42 cm (in the area of landmark S1) during this monitored period (fig. 4).

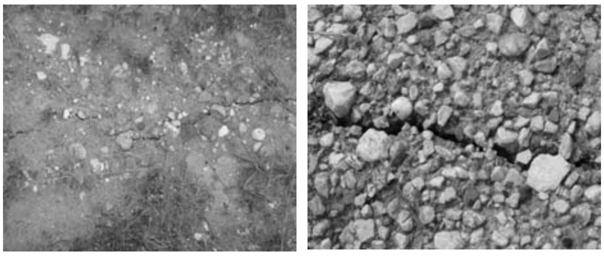

Photo 1-2 *Land cracks*

Photo 3 *Crater – August 8th, 2009*

On August 8, a land crease funnel was revealed in the area of well 358, situated in the South of the cavern. The crater extended until the evening of that day (photo 3).

Following the topographic surveys performed on August 11th, the surface of the crater lake was determined to be of about 1800 m^2 and the surface of the crater of 6900 m^2, while on September 3rd, upon the performance of additional topographic surveys, the surface of the crater lake was determined to be of about 9700 m^2 and the surface of the crater of about 25000 m^2 (fig. 5).

During the brine spill process, both gravitationally and by pumping it towards the barrier on the Pârâul Sărat creek, the flanks began to get stabilized and the level of the crater lake began to decrease.

The crater lake currently exists only due to rainfalls (photo 4). The natural sloping continues, however, the evolution rate is insignificant and is not very easily detected, at a visual inspection.

Practically, the cavern in the Well Field I was decommissioned and, at the same time, the common cavity of wells 357 and 359 (belonging to Well Field I) was filled with sterile.

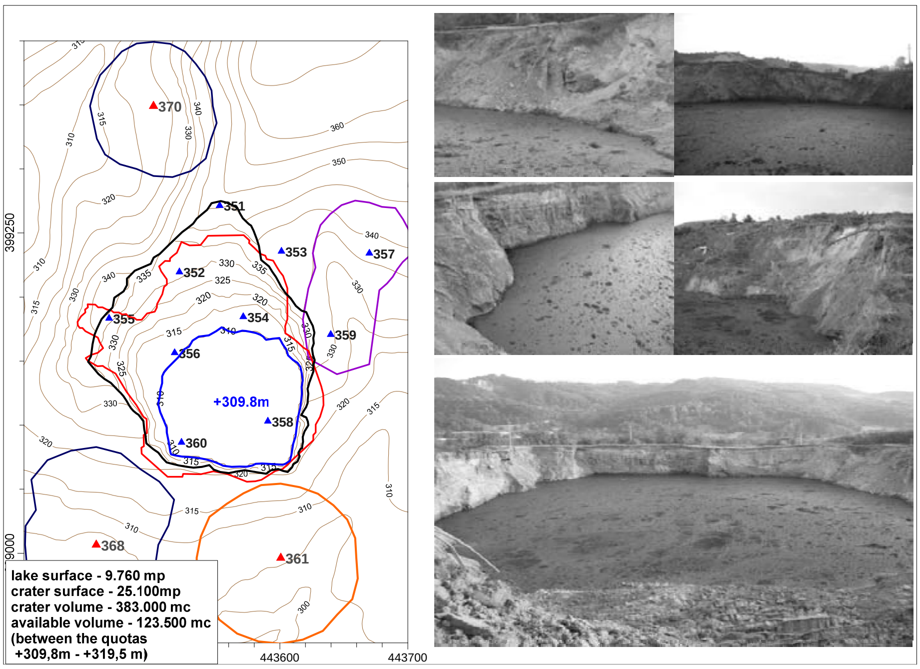

Fig. 5 *Evolution of the lake – September 3rd, 2009*

Due to the complex geological conditions, the stability and the management of the caverns created in salt deposits through dissolution represent a very difficult problem. The special properties of salt – low conductivity, the viscous, elastic and plastic behaviour, apart from the actual exploitation of salt, led to the creation of caverns by dissolution, for the storage of hydrocarbons or highly-active waste. At the same time, apart from the inspection of the site, performed by various methods, it is necessary to perform an evaluation by calculation of the stability of the cavern in different exploitation conditions. Among the familiar calculation methods, the numerical simulation presents undisputable advantages, as it incorporates all the existing information and it allows the simulation of the cavern's behavior according to the requirements.

Photo 4 *Chimney collapse – June 2010*

3. Numerical modeling of Well Field I evolution

The numerical modeling of the state of stresses and strains around the caverns resulted due to the dissolution of salt through solution mining, aims at simulating the evolution of the controlled collapse of the cavern in Well Field I – Ocnele Mari. The simulations were performed through PLAXIS 7 program, which calculates the distribution of the state of strains and stresses in the rock masses, using the finite elements method in elasto – plastic behaviour.

The simulations was made by Finite Element Method, in plane-strain conditions. This approach is frequently used in engineering practice, because it involves an infinite development of the caverns on the perpendicular direction, the results being secured. The domain was developed with an equivalent value of the cavern extension, on the both lateral sides (left and right) and also in the bottom of the section.

The particularities of this program are the following: the use of certain 15 nodes triangular finite elements and a wide range of constitutive laws, as well as a system for easy data entry and information processing.

The advantage of this method is that it enables the determination of the general stability factor of a section, as well as of the stability factor of each point in the section (determined as the reverse of the relative shearing stress).

The program calculates the stability factor by the *phi-c reduction* method. This method entails the successive increase of the stability factor, the recalculation of the resistance parameters and the recalculation of the maximum stresses and strains up to the moment when the resistance parameters begin to decrease, thus leading to the failure of the structure. The rupture is indicated by the non-convergeance of the solution, after a large number of steps.

Four sections, intersecting with the common cavern in Field I, were selected for the simulation of the controlled collapse process. An analysis of the distribution of the state of stresses and strains is performed for each section, in three different stages of the collapse process:

- July 15th, 2009, when the level of the brine was maximum, namely 285 m. This is the start moment of the controlled collapse process, characterized by discontinuation of the artificial supply;
- July 28th, 2009, when the level of the brine was of 278 m. This moment corresponds to the lowest level registered by the brine in free spill;
- August 7th, 2009, when the level of the brine was of 252 m, the moment prior to the collapse occurred on August 8th and during which the last settlement measurements were performed.

For each of the abovementioned moments, the following calculations are performed for each of the four sections: distribution of the displacements, of the main and shearing strains, the distribution of the main effective stresses, of the deviator and of the relative shearing stress. The evolution of the stability factor is also calculated.

The geomechanical parameters introduced in the model were taken from the determinations made available by SEM Vâlcea. The average values thereof were taken into consideration for the samples analyzed in the area of Ocnita (in the area of Well Field I), the designing of the model being performed according to the correlations between the absolute land displacements measured during the period June 14th – August 8th, 2009 and the absolute displacements calculated through modeling by the finite elements method, during the same period.

The geomechanical parameters resulted after the designing of the model: **for salt** $E = 1.075 \cdot 10^7$ kN/m^2, $\mu=0.3$, $c = 2000$ kN/m^2, $\varphi = 40^o$, $\sigma_t = 1000$ kN/m^2, $\gamma_u = \gamma_s = 22$ kN/m^3, **for sterile** $E = 7.5 \cdot 10^5$ kN/m^2, $\mu=0.25$, $c = 250$ kN/m^2, $\varphi = 25^o$, $\sigma_t = 100$ kN/m^2, $\gamma_u = 19$ kN/m^3, $\gamma_s = 21$ kN/m^3.

The performed analyses were used to determine the instability of sections 1 and 4, for which reason I am going to highlight the results obtained after the numerical modeling performed for these two sections (fig. 6 and 7).

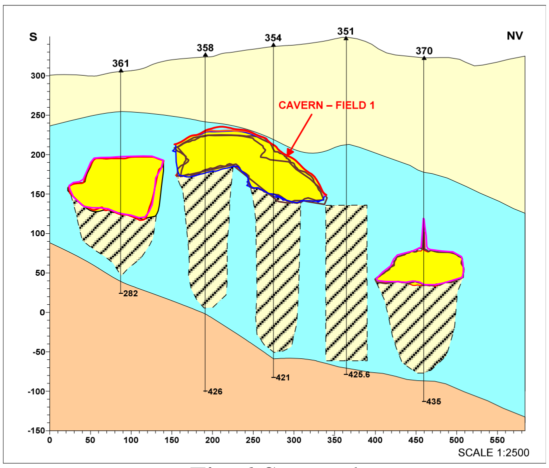

Fig. 6 *Section 1*

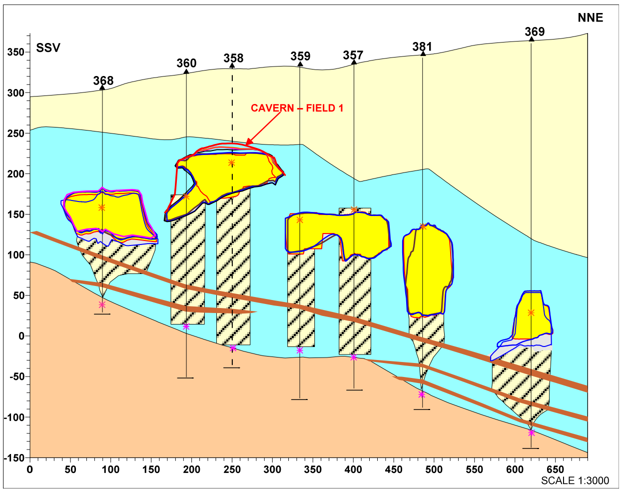

Fig. 7 *Section 4*

After analyzing the results, the following conclusions are drawn:

- among the analyzed sections, sections 1 and 4, particularly section 4, present the largest settlements, approximately 1.27 m, when the level of the brine is of 252 m (fig. 8 and 9). These sections intercept the apex of the cavern, in the area where it is in direct contact with the sterile;
- the distribution of the displacemnets is concentrated in the area of the future chimney, the curves of equal displacement having the shape of balance arches; this distribution represents an additional confirmation of the conceptual model used within the controlled collapse project (fig. 8 and 9).

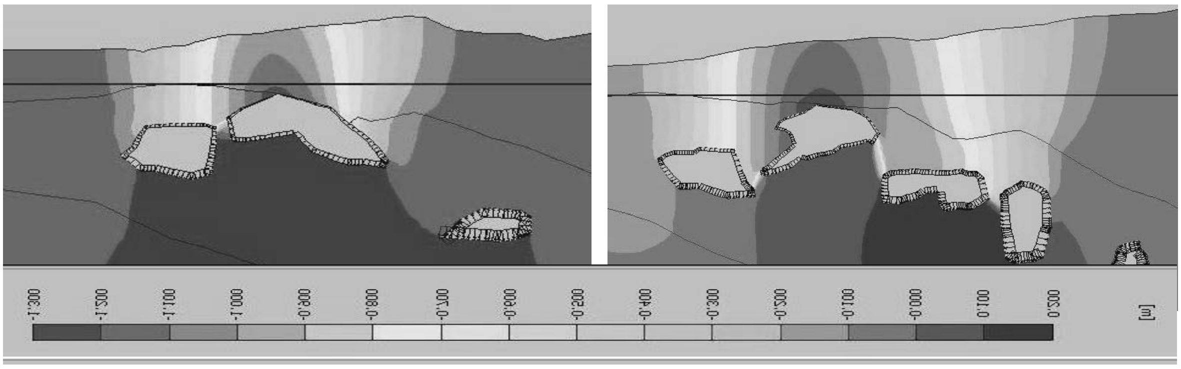

Fig. 8 *Section 1 –displacements calculated on August 7th, 2009*

Fig. 9 *Section 4 – displacements calculated on August 7th, 2009*

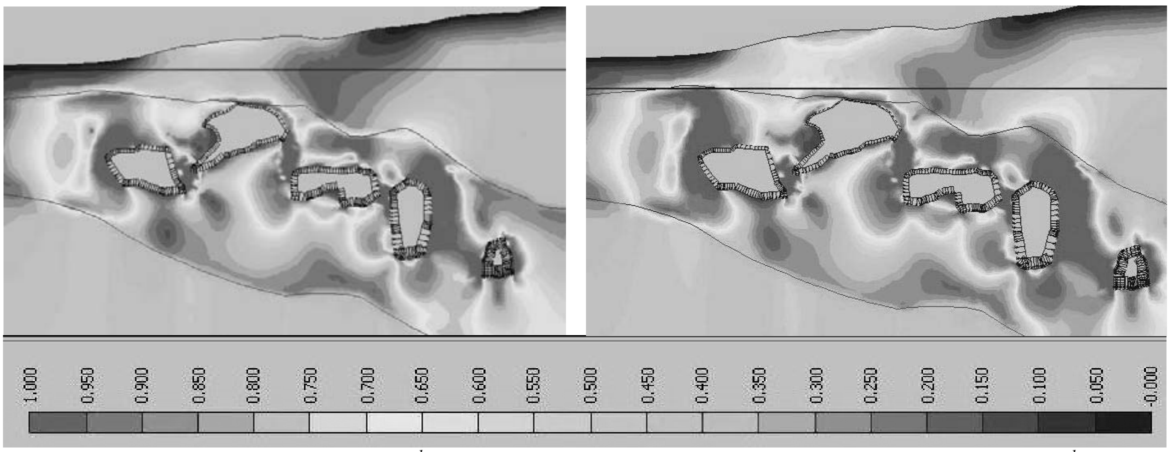

Fig. 10 *Section 4 – deviator June 14th, 2009*

Fig. 11 *Section 4 – deviator August 7th, 2009*

- the deviator is concentrated in the area of the inter-chamber pillars and in the cavern's arches, up to the sterile-salt contact; the shape of the distribution is maintained for all level values, however, its value increases simultaneously with the decreasing of the level (fig. 10 and 11);
- if, unsurprisingly, the main efforts have maximum values in the area of the inter-chamber pillars, in sterile, above the main cavern (fig. 12), the maximum main stress is a tensile force suggesting the segmentation of the material, after surpassing the tensile strength.

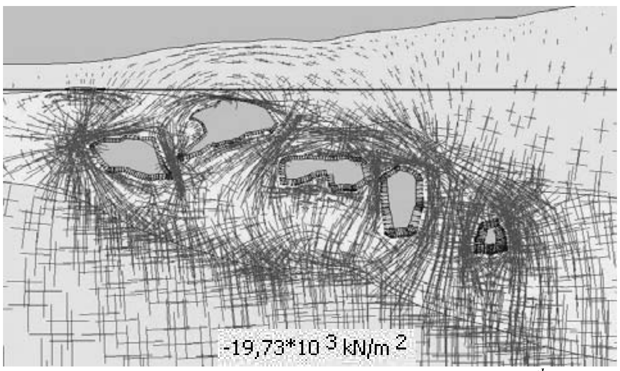

Fig. 12 *Section 4 – total main stresses – August 7th, 2009*

For sections 1 and 4, the stability factor decreases down to values adjacent to the unit F=1.075, for section 1, namely F=0.964, for section 4, when the brine reaches a level of 252m, indicating the cavern's roof collapse. This represents in fact, the altitude at which the main cavern's roof collapse in Well Field I began.

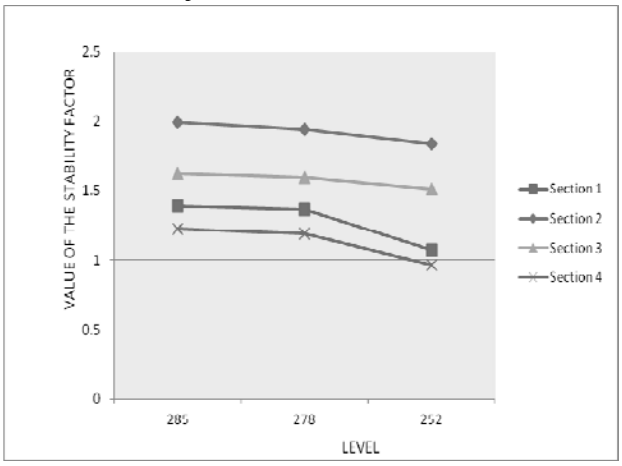

Fig. 13 *Variation of the stability factor for the 4 analyzed sections*

From the point of view of the determined vertical displacements, the maximum levels registered for the four sections were present at the level of the cavity's ceiling, which were slightly decreasing towards the surface. Hence, the maximum displacements registered at the level of the cavity's ceiling were revealed for sections 1 and 4, at a level altitude of 252 m, having values of 0.47 – 0.52 m, turned into absolute values – starting July 14th – at a level altitude of 285 m (fig. 14).

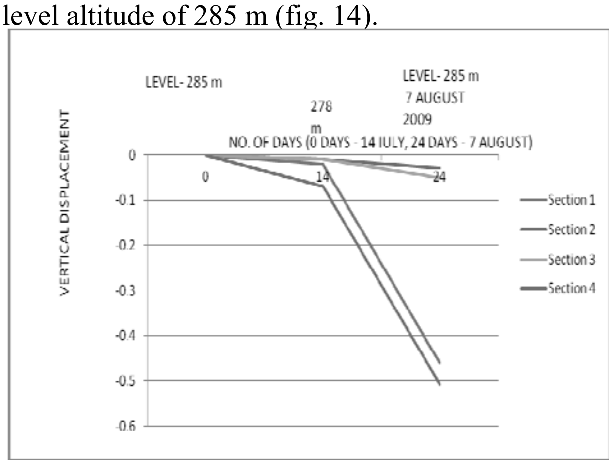

Fig. 14 *Variation of settlements at the level of the cavity's ceiling for the 4 sections*

After extracting the tables with the distribution of the vertical displacements, calculated in the nodes of the elements and upon the representation of these displacements for the geologic sections, the displacements calculated at the surface of the land, for the four sections, at the three different analyzed moments, were thus identified.

The maximum values, thus determined, are correlated with the maximum values of the displacements, determined after the topographic surveys performed on the field, a maximum value of 41 cm being determined for section 4.

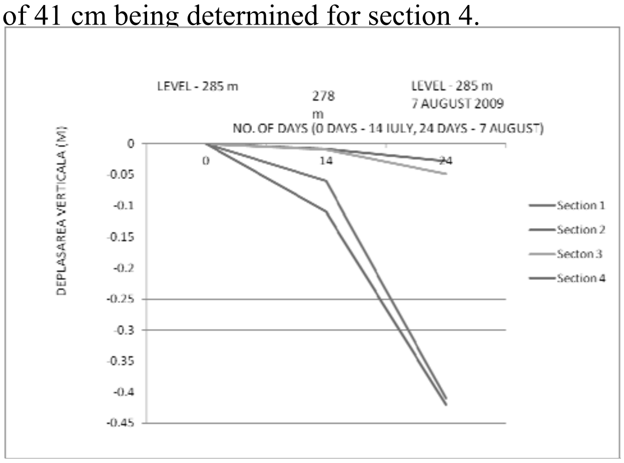

Fig. 15 *Variation of settlements at the level of the land surface for the 4 sections*

The correlation of the integrated monitoring results with the modification of the state of stresses and strains, aimed at creating a coherent image of the geomechanical behaviour of the Well Field I, according to the measurements and the numerical simulation. Four types of measurements were analyzed within the monitoring system assembly: cavernometry, level, evolution of settlements and induced seismicity.

Due to their accuracy, the cavernometric measurements are essential for the characterization of the system geometry evolution. Hence, the cavernometric measurements performed by using the SOCON German company's equipment and technology, enabled the outline of the common cavern, as well as its connection with the caverns and the cavities of the nereby wells. Following the periodic performance of the cavernometric measurements, a decrease in the thickness of the salt layer was revealed in the main cavity's ceiling and, since September 2006, of an area where the salt on the ceiling completely disappears, the cavern being in direct contact with the sterile. The total volumes of the masses fallen down from the ceiling were also evaluated, from 10000 m^3 at the end of 2006, to 90000 m^3 in January 2009 (fig. 16 and 17).

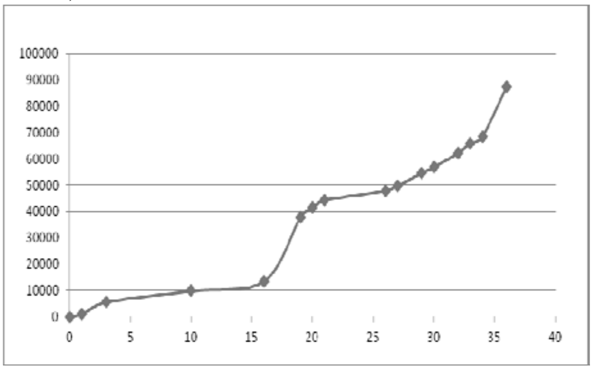

Fig. 16 *Evolution in time of the volumes detached from the salt ceiling*

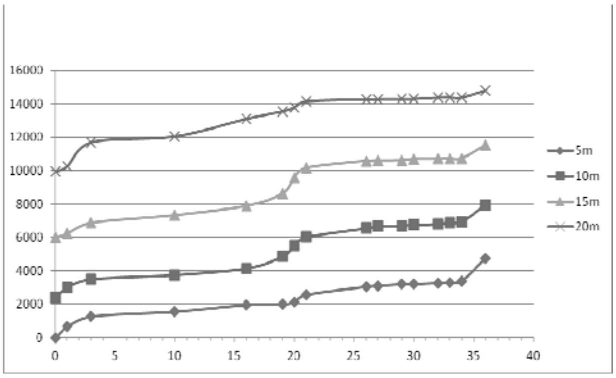

Fig. 17 *Evolution in time of the salt ceiling surfaces with thicknesses below 5 m, 10 m, 15 m and 20 m*

For example, during the period July – October 2007, the occurrence of a series of events towards the end of August (fig. 18) was ascertained, such events occuring at the level of the salt on the cavity's ceiling. After the occurrence of this series of events, the cavernometric measurements determined the detachment from the salt ceiling of a mass with a volume of 25000 m^3 (the inflexion point in fig. 16 and 17, correlated with the time interval corresponding to the occurrence of the microseismic events in fig. 18).

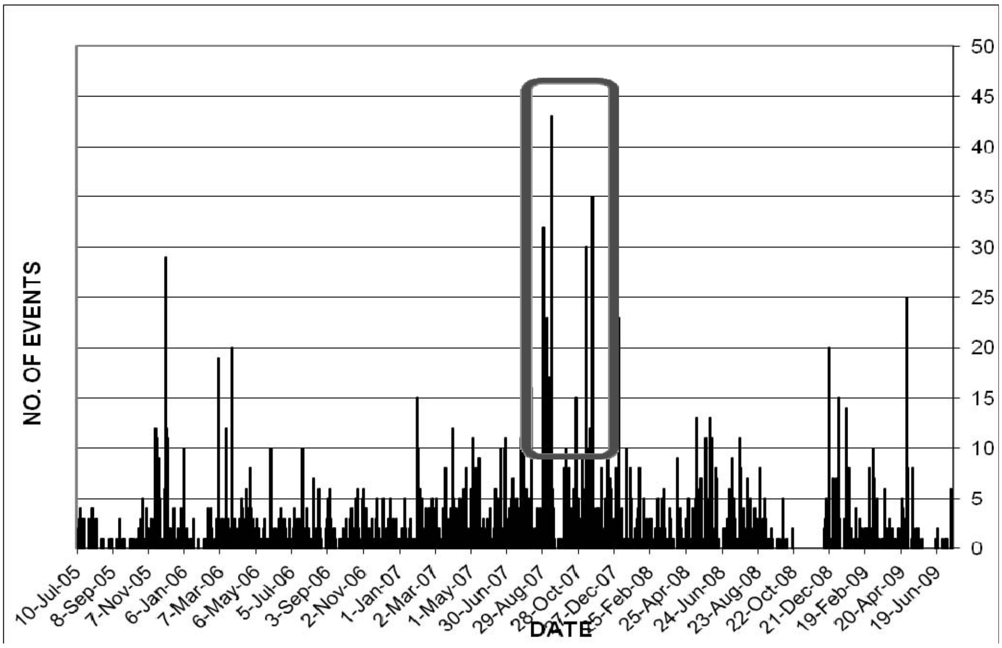

Fig. 18 *Frequency of microseismic events in Well Field I - 10.07.2005 – 15.07.2009*

The relations between the parameters measured or determined by calculation were presented from the perspective of the cavern's evolution in Well Field I, however, taking into consideration the influence of the SOCON cavern defusing, such cavern belonging to Well Field II and being defused in 2005. The influence of the SOCON cavern defusing may be observed at the level of the settlements recorded in Field I, immediately after its collapse.

The relative correlations between the microseismic events and the other parameters resulted after the monitoring, were performed for time intervals corresponding to certain evolution peaks, quantified by massive material falls from the cavern's ceiling in Well Field I, or for cavernometric measurements intervals performed for the determination of the cavity's geometry in Well Field I.

At time intervals common to measurements, the occurred microseismic events (Figures 19 and 20) were projected on the four geological sections (at a distance smaller than 10 m). The occurrence of the microseismic events, preeminently concentrated in the area of the inter-chamber pillars and in the area of the ceiling cavity pillar, corresponds to the distribution of the state of stresses and strains, determined through numerical modeling with finite elements.

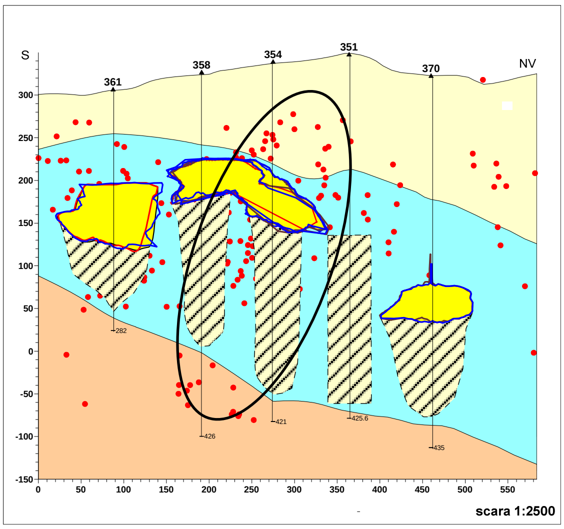

Fig. 19 *Projection of microseismic events for section 1 (April-July 2008)*

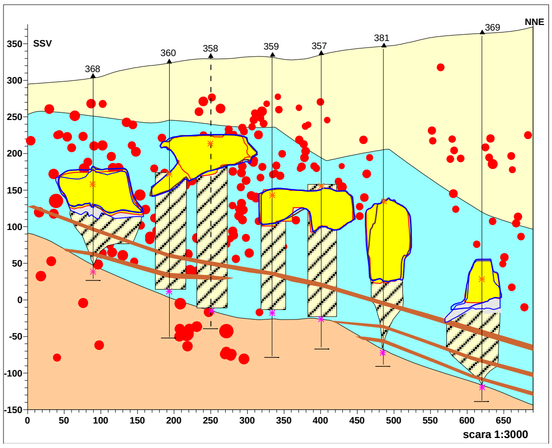

Fig. 20 *Projection of microseismic events for section 4 (April-July 2008)*

The microseismic activity is related both to the cavernometric measurements and the redistribution of stresses pursuant to the evolution of the caverns' geometry. Thus, by correlating the volumes detached from the cavern's ceiling with the frequency of the occurrence of the microseismic events, it was pointed out that the detachments from the ceiling are always preceded by an increase in the frequency of the events (fig. 21). The induced seismicity, in this case, represents a precursor of the cavern's evolution.

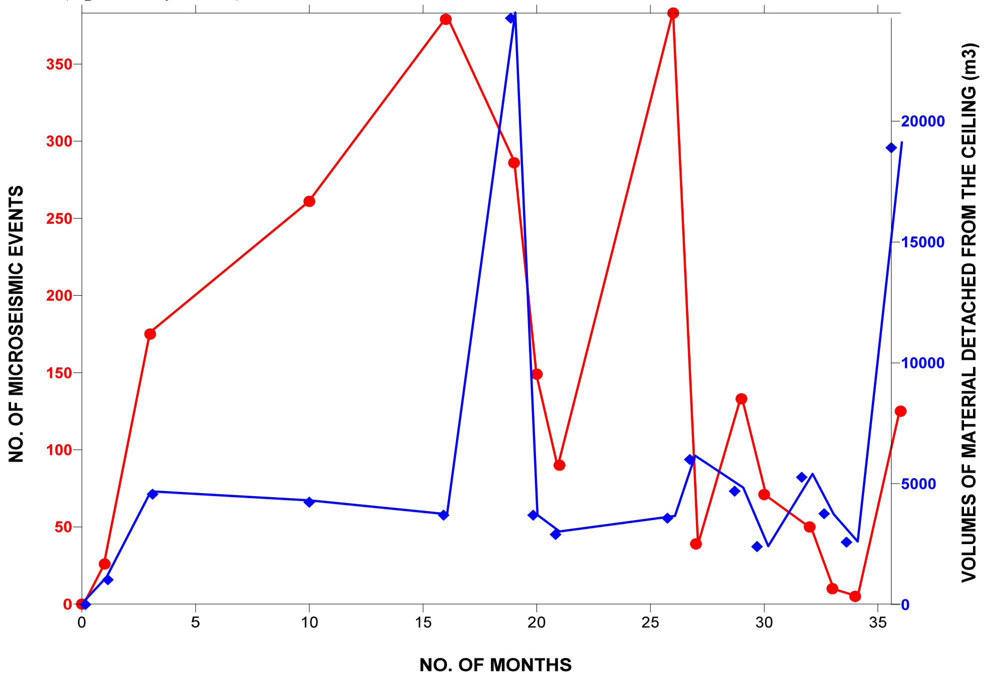

Fig. 21 *Correlation of the volumes detached from the salt ceiling with the frequency of the microseismic events*

After analyzing the distribution of the microseismic events in the sections where the distribution of stresses was calculated, their grouping was presented, during the period April – July 2008, in the inter-chamber pillars and in the cavern's salt ceiling. This concentrations lap over the areas of maximum distribution of the deviator, which leads to the conclusion that the source of the microseismic events is determined by shearing dislocations (Figure 22). On the contrary, in the period August 2008 - July 2009, the events are mainly concentrated in sterile: due to the loosening of the inter-chamber pillars, the loads are taken over by the competent sterile layers, which were thus fragmented.

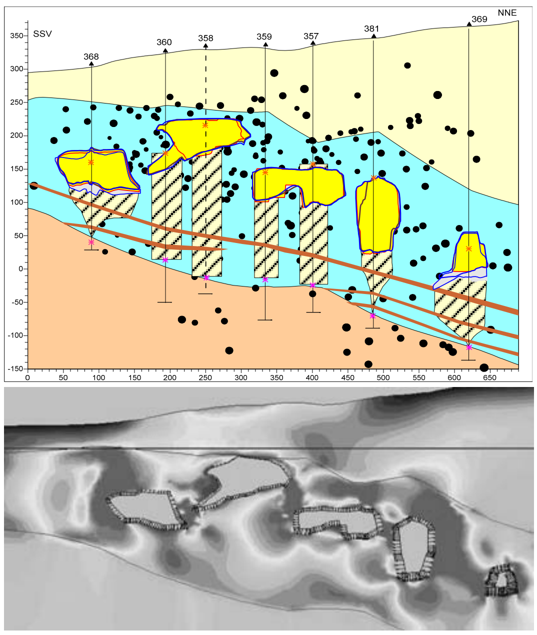

***Fig. 22** Section 4 – Correlation of the microseismic events (2008) with the distribution of the relative shearing stress*

4. Conclusions

Pursuant to the analysis performed for the geotechnical evolution of the cavern in Well Field 1 and for the cavities of the nearby wells, the following conclusions are drawn up:

- a cavern with a volume of approximately 1 million m^3 resulted after the merger of six wells in Well Field 1;
- gradually, the salt ceiling of the common cavity's roof crushed down and, in 2009, it completely disappeared on a significant surface, thus leading to a short term limit balance;
- The correlation of the integrated monitoring results, in the period 2006 – 2009 (topographic, level, cavern metric, micro seismic measurements) suggests the instability of the cavern in the Well Field 1, as well the implications generated by a sudden collapse, which would have involved serious consequences, firstly for the local population and then for a significant brine pollution of the environment, of Pârâul Sărat creek in particular, which flows into the Olt river.
- the results of the micro seismic monitoring, apart from the fact that they were able to be considered within the performed correlation, proved to be a real aid in anticipating the modification of the state of stresses and strains around the common cavern and the nearby cavities.
- the numerical modeling with finite elements enabled the determination of the stability factors for the analyzed sections, highlighting the future rupture area, also pointing out the rupture model taken into consideration for the elaboration of the cavern's controlled collapse project.
- the correlations performed between the measured land displacements (topographical surveys) and those calculated through modeling with finite elements, enabled the creation of a viable model, which can also be used in other areas of salt exploitation through dissolution, such areas being geomechanically unstable.

The phenomena registered at Ocnele Mari mark the beginning of a period during which we shall face similar situations in other salt exploitation mining areas, as well. The ongoing phenomena, registered at Ocna Mureș, confirm the abovementioned statement. Consequently, we are entitled to consider this inherent analysis as a role model for similar situations.

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