

FINITE ELEMENT MODELLING OF THE STABILITY OF UNDERGROUND MINING EXCAVATIONS AT OLD MINES – SLĂNIC SALT MINE

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Abstract: The underground mining of the rock salt deposit from Slănic started over 350 years ago, in bell-shape room (Ocna din Deal and Ocna din Vale) and in large trapezoidal rooms (Carol, Mihai and Unirea mines), until 1970, generating a volume of underground excavations of over 5.3 million m³. Over time, these large excavations have lost their stability (collapse of the mines to the surface and various degrees of instability of the Carol and Mihai mines), keeping only the Unirea mine in operation for tourist purposes. This article is a synthesis of the analysis with 3D finite elements, in elasto-plasticity, of the state of stress and strain developed around the excavations and highlighting the factors that led to the loss of their stability, focusing on the Unirea mine.

1. Generalities

The object of the stability analysis with finite element are the Old Mines, located in the center of the perimeter of the Slănic Prahova saline, which include: Ocna din Deal, Ocna din Vale, Principatele Unite (Carol) mine, Mihai (23 August) mine and Unirea mine (figure 1).

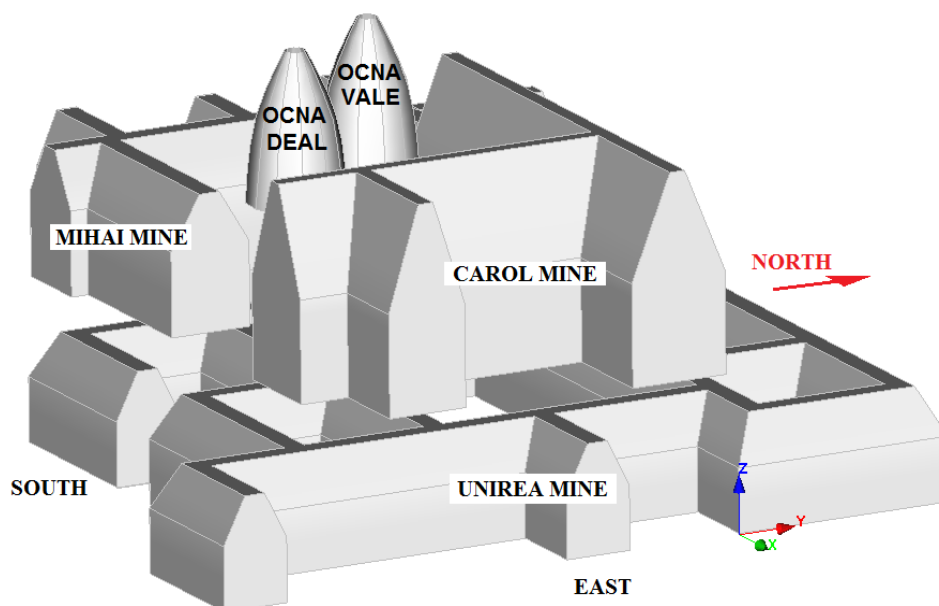


Fig.1. 3D overview of the Ocna din Deal, Ocna din Vale, Carol, Mihai and Unirea mines [6]

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Ocna din Deal was mined between 1819-1865 and Ocna din Deal between 1838-1865, then they were reopened for rock-salt extraction, being in operation between 1875-1881. Ocna din Vale reached a depth of 145m, with a diameter of 75m, at an excavated volume of 171.941m³, and Ocna din Deal had a depth of 96m, with a diameter of 68m, resulting in an excavated volume of 94.516m³.

The Carol mine was opened in 1881, the extraction was carried out downward, resulting at the end of the extraction, in 1935, an excavation with an ogival profile with a height of 97m and an opening at the floor of 48m. The area at the floor of the Carol mine is 24.672m², with an excavated volume of 1.703.396m³.

In 1912, the Mihai mine was opened, which was operated in rooms with a trapezoidal-rectangular profile, with dimensions of 12m, the opening to the ceiling, with walls inclined at 60°, a length of 30m, a height of 66m and an opening at the floor of 37m. The extraction was stopped in 1942, resulting in an excavated volume of 462.332m³, at a floor area of 12.500m².

Under the two mines, Carol and Mihai, which are positioned on the same level, under a safety ceiling of 28-31m of thickness, the Unirea mine develops in depth, opened and mined between 1942-1970. Unirea mine is a set of rooms with a trapezoidal-rectangular profile, arranged around a central pillar. The rooms have an opening at the roof of 10m, walls inclined at 60°, a length of 30m, an opening to the floor of 35m and a height of 56m. The rooms of the Unirea mine have a total area at the floor of 78.360m² and a total volume of excavated rock salt of 2.903.131m³.

After the cessation of the extraction at the Unirea mine, in 1970 the activity at the Victoria mine started, with small rooms and square pillars. Between 1993-2019, using the same mining method, the rock salt deposit was extracted from the Cantacuzino mine, then under an equalization pillar of 40m of thickness, the extraction continues on the entire surface of the deposit, at the New mine Slănic.

Table 1. Statistical situation of the volumes of rock salt (voids) extracted, over time, at the Slănic Prahova Saline

Period	Old Mine	Volume, m ³	Period	Mine	Volume, m ³
1668-1691 1800-1854	Baia Verde		1831-1935 1881 oficial	Mina Principatelor Unite (Carol)	1,703,396
1689-1691	Baia Baciului		1912-1942	Mina 23 August (Mihai)	462,332
1689-1691	Dorobănești		1943-1970	Mina Unirea	2,903,131
1800-1854	Grota Bârsei		1970-1992	Mina Victoria	7,379,128
1800-1854	Grota Miresei		1993-2019	Mina Cantacuzino	2,362,324
1819-1865 1875-1881	Ocna din Vale	171,941.0	Note: * The total volume of the resulted voids is estimated. To this must be added the volume of the voids related to Old Mines Baia Verde, Baia Baciului, Dorobănești, Grota Bârsei, Grota Miresei și Sistemica.		
1838-1865 1875-1881	Ocna din Deal	94,516.8			
1865-1875	Ocna Sistemica				
TOTAL*					15,076,768.8

Numerical models with finite elements in 3D, represented by the Old Mines, try to simulate the state of stress and strain produced by the extraction from the deposit of approx. 11,204,165 tons of rock salt, thus generating a volume of underground mining voids, with complex geometry, of approx. 5,335,317m³ (of which, over 54% is represented by the Unirea mine). As the Old mines are collapsed to the surface and the Carol and Mihai mines are inaccessible due to instability phenomena, produced over time, and the Unirea mine is the only one that will be in operation for a long time for tourist purposes, the stability analysis will be an overall one, but focused on the stability of this mine.

2. 3D finite element models for Old Mines – Slănic Saline

In order to analyze the stability of the Old Mines, a numerical model with 3D finite elements was build, with the dimensions: X = 1,390m, Y = 1,430m and Z = 460m (figure 2).

The discretization of the 3D model from the Old Mines was performed with a total number of 48,400 nodes and a total number of 44,247 volume elements.

In the stability calculations, a law of elastic-plastic behavior without hardening was chosen.

To simplify the 3D numerical models, two regions with specific geomechanical characteristics were considered, corresponding to the surrounding rocks and the rock salt deposit [1, 2, 3, 4, 5]. The characteristics of the rock salt considered homogeneous and isotropic, were taken into account in the hypothesis of elastic-plastic behavior without hardening, Mohr-Coulomb type. Thus, a series of average characteristics were adopted, considered by us as representative for the in-situ behavior of the rock salt massif and of the surrounding rocks are synthesized in table 2.

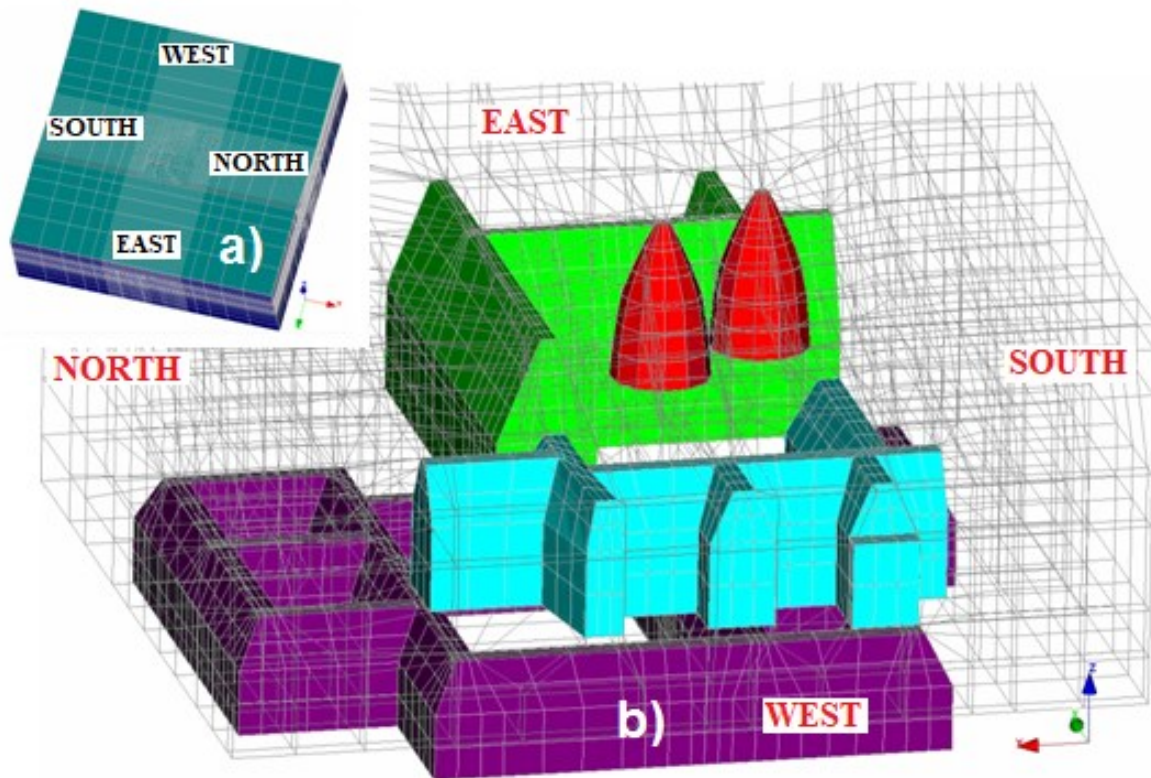


Fig.2. Discretization with 3D finite elements of the model related to the Ocna din Deal, Ocna din Vale, Principatele Unite (Carol), Mihai (23 August) and Unirea Mines [6]:
a) 3D model overview; b) View with the extraction rooms inside the 3D model

Table 2. The main average geo-mechanical characteristics of the rock salt massif and surrounding rocks taken into account in the finite element modeling [6]

Properties	UM	Value	
		Rock salt	Surrounding rocks
Density, ρ_a	kg/m ³	2 100	2 200
Apparent specific weight, γ_a	kN/m ³	21	22,0
	MN/m ³	0,021	0,022
Young modulus of elasticity, E	kN/m ²	2 500 000	3 000 000
	MPa	2 500	3 000
Poisson ratio, ν	-	0,28	0,21
Compressive strength, σ_c	kN/m ²	20 000	-
	MPa	20	-
Tensile strength, σ_t	kN/m ²	1 400	-
	MPa	1,4	-
Shear strength, τ_f	kN/m ²	2 300	-
	MPa	2,3	-
Cohesion, C	kN/m ²	4 000	5 300
	MPa	4	5,3
Internal friction angle, ϕ	°	30	24

In the analysis of the stability of the excavations and underground mining structures and of the surface from the Old Mines, Slănic Prahova salt mine, the CESAR-LCPC finite element software was used, with CLEO2D and CLEO3D processors [7].

The realization of the analysis with finite elements in 3D, for the model defined above, required the following stages: I) establishing the limits, the area of interest and discretizing the model; II) determination of the areas (regions), calculation hypotheses and introduction of geomechanical characteristics; III) imposition of the boundary conditions; IV) establishing the initial and loading conditions of the model; V) performing calculations and storing results [7].

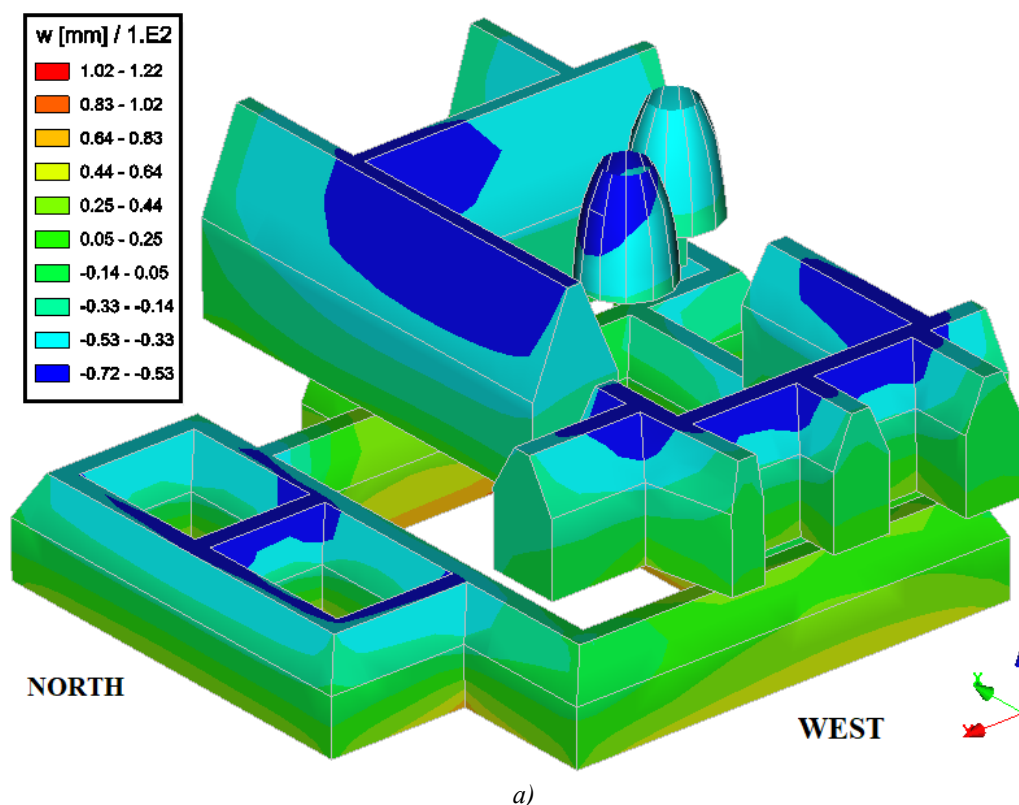
Based on the results obtained from 3D finite element modeling, a stability analysis of the Old Mines will be performed in the following, in correlation with the geomechanical phenomena of instability that occurred at this mine [8, 9, 10, 11].

3. Analysis of the results obtained from the numerical modeling with finite elements of the Ocna din Deal and Ocna din Vale and of the Carol and Mihai Mines

In order to explain the geomechanical phenomena of loss of stability of the resistance structures appeared at the Old Mines, the stress concentration reports according to the coordinate directions and the maximum / minimum principal stresses can describe the stress imbalance and implicitly the possibility of failure phenomena [12]. A ratio as high as possible makes the circle of the principal stresses intersect the characteristic curve of the rocks, which has as a significance the development of some failure phenomena or the opening of some fissures or natural cracks in the massif. Also, from the stability point of view, the study of tensile and shear stresses is very significant, knowing that rock salt has very low tensile and shear strengths and most often the failure occurs due to exceeding these limits. The analysis of the values of vertical and horizontal displacements and the orientation of the vectors corresponding to them can suggest the amplitude and the sense of development of the deformation phenomena [6, 7].

3.1. Ocna din Deal and Ocna din Vale mines

Ocna din Deal and Ocna din Vale being located close to the surface underwent vertical displacements w of the larger vault at Ocna din Vale, of approx. 70 mm, and smaller ones at Ocna din Deal, of approx. 50 mm (fig. 3.a). The incidence of horizontal displacements u and v (fig. 3.b and 3.c) remains more important on Ocna din Vale, with higher values in the E-W direction, than N-S.



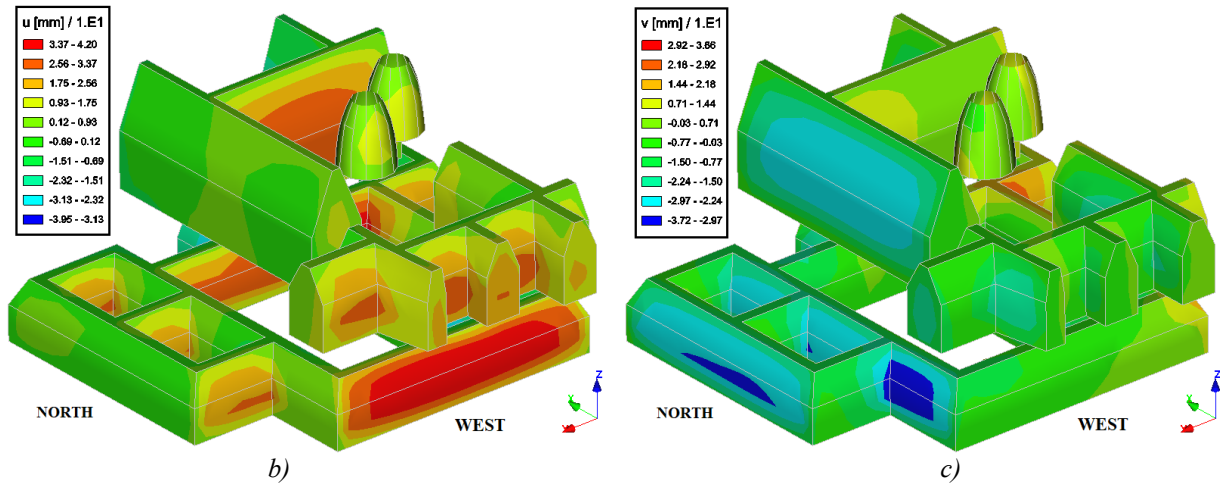


Fig.3. Vertical displacements w (a); horizontal u (b) and v (c), in mm [6]

There is a concentration of horizontal stresses σ_{xx} (fig. 4.b) and σ_{yy} (fig. 4.c) towards the entrance of the mines and at the walls, of approx. $-2,500 \text{ kN/m}^2$, non-hazardous in terms of compressive strength of rock salt.

The vertical stresses σ_{zz} (fig. 4.a) that charging the walls are around $-10,000 \div -14,000 \text{ kN/m}^2$, reaching $-18,000 \text{ kN/m}^2$, at the corner between the floor and the walls from the eastern area, approaching the compression resistance of the rock salt.

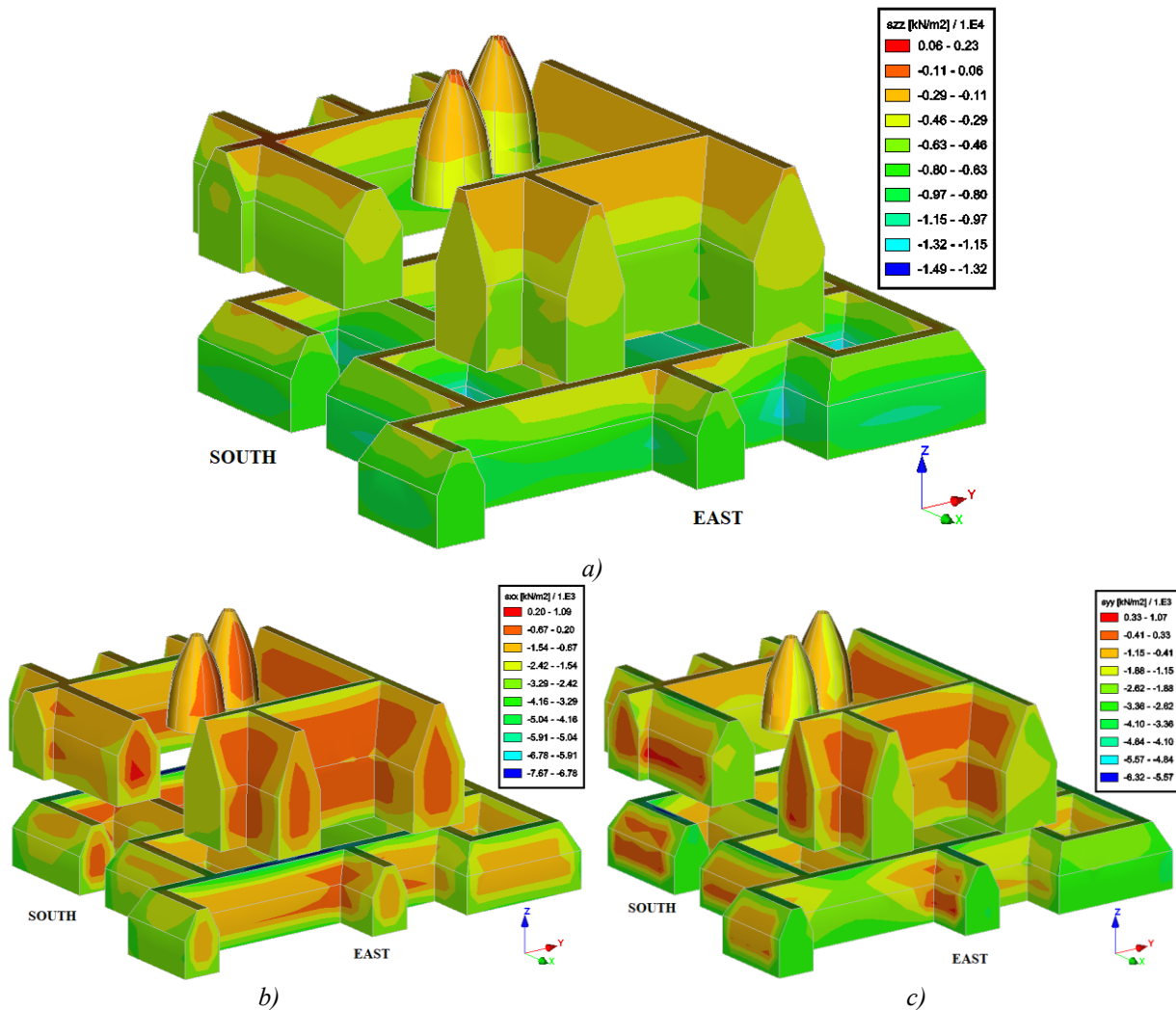


Fig.4. Vertical σ_{zz} (a) and horizontal σ_{xx} (b) and σ_{yy} (c) stresses, in kN/m^2 [6]

If, from the point of view of the maximum principal stresses σ_1 (fig. 5.a), most of which are compressive stresses, have not developed dangerous values in the walls of the Old Mines, however at the level of the ceiling, to the east, can be notified some values of the tensile stresses of over $+900 \div +1,000 \text{ kN/m}^2$ which, in the conditions of some local defects of the rock salt massif can become areas of loss of stability.

The minimum main stresses σ_3 the most dangerous, of compression, are also located at the intersection of the floor with the eastern wall and have values in the range of $-16,000 \text{ kN/m}^2 \div -18,000 \text{ kN/m}^2$ (fig. 5.b).

The highest values of the maximum shear stresses (fig. 6.a) are distributed on the contour of the floor of the rooms, mainly towards the eastern area, reaching over $+2,500 \text{ kN/m}^2$, more than the rock salt shear strength, which caused the walls to slide and the Old Mines to collapse.

The tensile stresses are very high in the floor of the rooms, concentrating towards their center, reaching over $+3,000 \text{ kN/m}^2$, at Ocna din Vale and over $+2,000 \text{ kN/m}^2$, at Ocna din Deal, both situations far exceeding much the tensile strength of the rock salt (fig. 6.b).

The distribution of the compressive stresses (fig. 6.c) follows the compressive values of the maximum main stresses and their concentration in the walls, towards the floor of the rooms.

As a conclusion, the destabilization of the Ocna din Deal and Ocna din Vale rooms took place, due to their positioning close to the surface and the low resistance of the covering rocks, starting with the collapse of the roof from the east and the detachment of the rock salt from the walls, from the base of the rooms upward.

3.2. Carol mine

The Carol mine consists of two trapezoidal (ogival) rooms arranged in an "L" shape, with the long sides approximately parallel to the N-S and E-W directions. To the east, two more short rooms were excavated, perpendicular to the N-S room, one in the extension of the E-W room and the other, towards the southern end of the long N-S room. The stability of the Carol mine was mainly influenced by the presence of the Old mines and then by the spatial position of the Unirea mine, under the Carol mine.

The N-S room undergoes some horizontal displacements u (fig. 3.b), which determined horizontal convergences of the walls over 80 mm, and the E-W room, displacements v (fig. 3.c) and convergences of the walls over 75 mm.

The vertical displacements w (fig. 3.a) are accentuated on the ceiling of the northern room, with values of over -70 mm, while the eastern room, of only -50 mm. The floor of the northern room suffers expansions towards the center of over +80 mm, and the one from the east, of over +60 mm; although on their contour, the floors have subsidence of over -50 mm.

The horizontal stresses σ_{xx} (fig. 4.b) and σ_{yy} (fig.4.c) act on the walls of the rooms with compression values of over -600 kN/m^2 , increasing more than 10 times towards the contour at the base of the rooms and at the ceiling of the preparatory working.

Starting from the preparatory working, then at the inclined walls, the values of the vertical stresses σ_{zz} (fig. 4.a) increase from approx. $-3,000 \text{ kN/m}^2$ to more than $-10,000 \text{ kN/m}^2$, in the vertical walls of the rooms, especially in those of the northern room.

The maximum principal compressive stresses σ_1 (fig. 5.a) are concentrated above the preparatory working, at the corners from the ends of the rooms of the Carol mine, at the intersection between the inclined ceiling and the vertical walls, towards the base of the walls and in the northern wall, at some non-dangerous values of approx. $-1,200 \text{ kN/m}^2$. Instead, dangerous tensile stresses of more than $+1,000 \text{ kN/m}^2$ develop in the floor of the rooms, reaching a value of more than $+3,200 \text{ kN/m}^2$, at the western end of the northern room.

The minimum principal stresses σ_3 (fig. 5.b) are concentrated in the vertical walls towards the floor, of the northern room and at the intersection of the walls of the two main rooms, at values of over $-10,000 \text{ kN/m}^2$. The center of the floor of the rooms is eased, from the point of view of the minimum stresses, increasing towards the walls at values of over $-8,000 \text{ kN/m}^2$.

The maximum shear stresses $\tau_{f \max}$ (fig. 6.a) increase from approx. 700 kN/m^2 , starting with the preparatory working, reaching over $2,000 \text{ kN/m}^2$ in the walls of the rooms, with an increase towards the floor, being a risk of their breaking by shearing stresses. On the contour of the floor, towards the corner with the walls, dangerous shear stresses of over $2,900 \text{ kN/m}^2$ develop, where the loss of stability can occur.

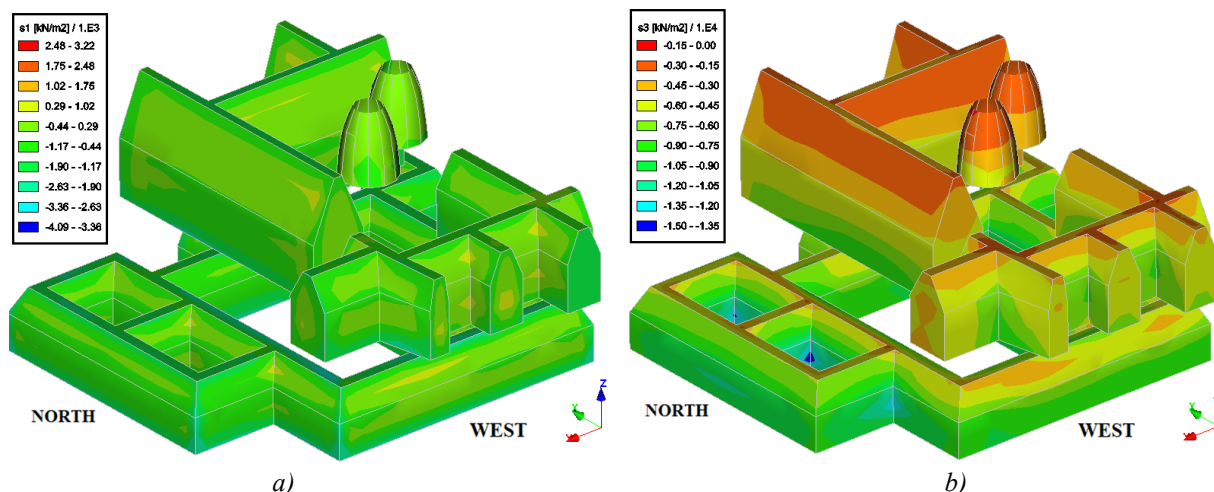


Fig.5. Maximum σ_1 (a) and minimum σ_3 (b) principal stresses, in kN/m^2 [6]

The tensile stresses σ_t (fig. 6.b) are concentrated at the intersection between the inclined ceilings of the rooms, exceeding the value of $+1,000 \text{ kN/m}^2$, tending to the value of the tensile strength of the rock salt. The most exposed for tensile stresses are the floors of the rooms, with values towards the center of about $+600 \div +2,000 \text{ kN/m}^2$, with maximums of over $+3,200 \text{ kN/m}^2$, towards the western end of the northern room.

The highest values of the compression stresses σ_c (fig. 6.c), of over $-10,000 \text{ kN/m}^2$, are in the vertical walls of the northern room, at their intersection with the eastern room and in the floor of the rooms, at the limit with the walls.

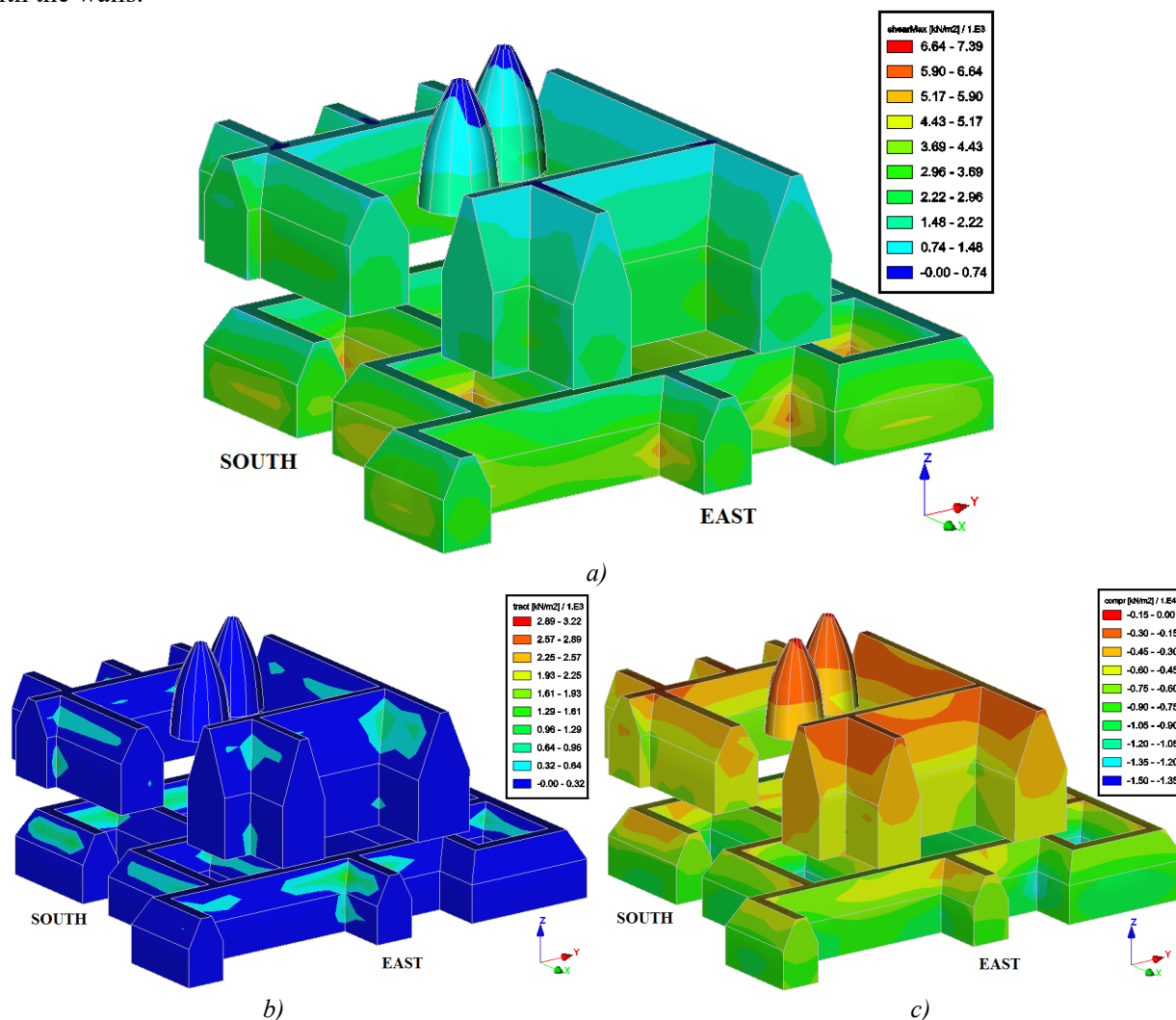


Fig.6. Maximum shear $\tau_{f_{\max}}$ (a), tensile σ_t (b) and compression σ_c (c) stresses, in kN/m^2 [6]

3.3. Mihai mine

Mihai mine consists of a main room, oriented N-S, from which derive 3 short rooms to the west, another short room placed to the northern end, excavated to the east, from which a short room was extracted to the north. The mine also has a secondary room, oriented E-V, intersected in "L" with the main one (see figure 1).

The horizontal displacements u (fig. 3.b) affected the main room with convergences of the walls of over 80 mm, and the horizontal displacements v (fig. 3.c), the secondary room with convergences over 70 mm.

The ceiling of all the rooms, especially of the main room, underwent some vertical displacements w (fig. 3.a), of over -70 mm. The floor suffered expansions, especially in the main room, at the intersections with the rooms from its ends.

The horizontal stresses σ_{xx} (fig. 4.a) have maximum compression values of approx. -3,200 kN/m², in the outer corners of the rooms, reaching maximum values of tensile stresses, of over 1,000 kN/m², at the ends of all rooms from east and west.

The horizontal stresses σ_{yy} (fig. 4.b) similarly subject to stress the walls of the rooms located to the north and south with tensile values of over 1,000 kN/m², which are close to the dangerous values of failure if, locally, the rock salt massif reduces its resistance. In the floor of the rooms, in the intersection areas, the tensile stresses approach the same value.

The vertical stresses σ_{zz} (fig. 4.c) increase progressively from the value of approx. -3,000 kN/m², at the level of the preparatory working, reaching -8,000 kN/m² -1,000 kN/m², towards the base of the walls, with concentrations of compression stresses at the intersections between the walls.

The maximum main stresses σ_1 (fig. 5.a) have compression values, up to -2,000 kN/m², concentrated in all the corners of the rooms, tensile up to +1,100 kN/m², at the intersections between the ceilings of the rooms, in the middle of the walls and in the middle of the ceilings. These areas are exposed to the failure by tensile stresses.

The minimum principal stresses σ_3 (fig. 5.b) developed around the mining excavations are only compressive stresses, reaching values of over -10,000 kN/m², at the intersections between the walls of the rooms and at their intersections with the floor.

In the vertical walls of the rooms, the maximum shear stresses $\tau_{f\max}$ (fig. 6.a) exceed a value of 2,500 ÷ 3,000 kN/m², and at the intersection between the vertical walls they can reach 5,000 kN/m², values at which there is a very high risk of loss of stability by failure, by shear stresses. In the floor of the rooms, on their contour, the shear stresses can reach values of 2,000 ÷ 3,000 kN/m².

The tensile stresses σ_t (fig. 6.b) are distributed towards the halves of the ceilings, at values of about +300 ÷ +700 kN/m², with a concentration at the intersections between the vertical walls and between the planes of the ceilings, towards +1,000 ÷ +1,300 kN/m², values that predispose to the risk of failure by tensile. Towards the center of the floor in most rooms, the tensile stresses reach values of +1,500- +2,000 kN/m², with maximum values of +2,500 +3,000 kN/m², in the short room situated in the north at Mihai mine.

Compression stresses σ_c (fig. 6.c) especially subject to stress the walls of the rooms, with values of approx. -7,000 -8,000 kN/m², with a concentration of stresses at the intersection between the walls that can exceed the value of -10,000 kN/m². In the floor, the compression stresses can exceed the value of -8,000 kN/m², at the limit between the contour of the rooms and the walls.

4. Analysis of the results obtained from the numerical modeling with finite elements of the Unirea mine

The Unirea mine consists of a complex of rooms developed around a large central pillar P_{3.4.11.14}. On each of the northern and southern sides of the pillar, parallel rooms are arranged around two other smaller pillars, thus resulting 4 pillars (P_{1.2.3.15.16}, P_{14.15.16.17}, P_{5.6.7.8} and P_{7.8.9.10}). From the long eastern room C_{11.18}, oriented N-S, two other short rooms C_{12.13} and C_{18.19} were extracted to the east (fig. 7).

The horizontal displacements u (fig. 8.b) affects the chambers arranged in the N-S direction with convergences from walls of approx. 80-100mm, and the horizontal displacements v (fig. 8.c), affects the chambers arranged in the E-W direction, approximately with the same values of convergence.

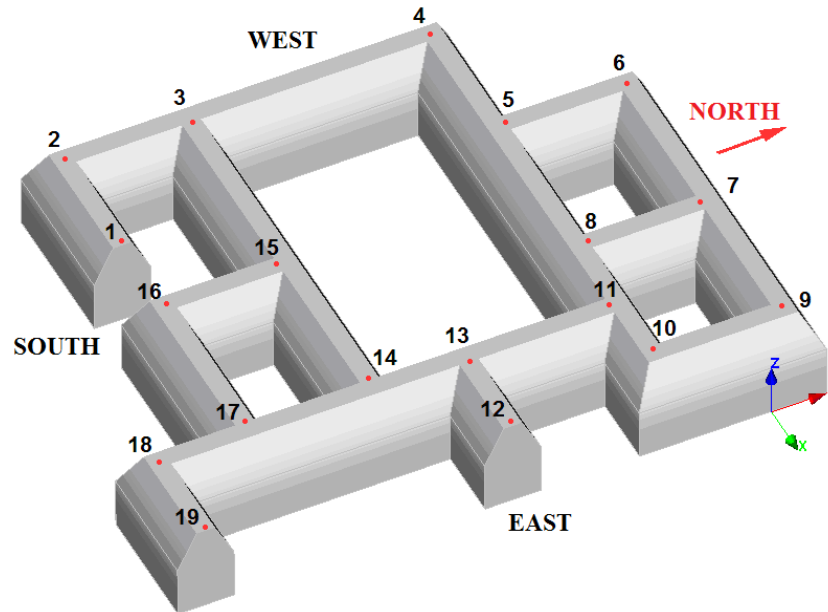


Fig.7. 3D overview of the Unirea mine [6]

The vertical displacements w (fig. 8.a) are represented by subsidence of over -70 mm, of the ceiling of the rooms arranged around the small northern and southern pillars, and by expanding of the walls up to $+80$ mm, towards the floor of the rooms. For most of their length, the main rooms from east and west undergo vertical ascending displacements along their entire structure, with a maximum of $+100$ mm towards the floor. The floors of all rooms are involved in expanding phenomena that can exceed $+120$ mm, which are the highest values of the entire structure.

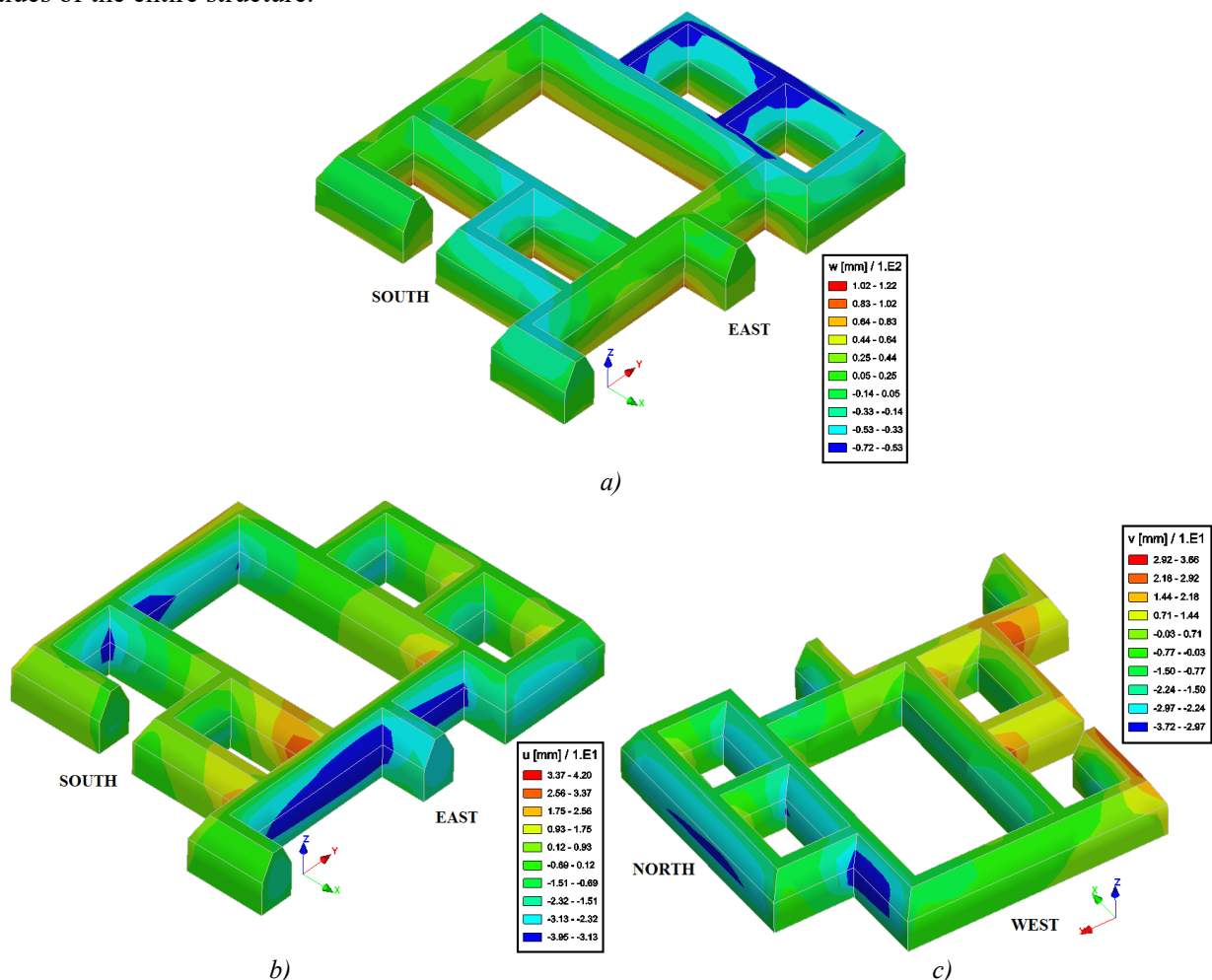


Fig.8. Vertical displacements w (a); horizontal u (b) and v (c), in mm [6]

Horizontal stresses σ_{xx} (fig. 4.b) affects the preparatory workings of the main eastern and western rooms, with compression values of over $-7,500 \text{ kN/m}^2$ and the intersection of the walls with the floors of all the rooms, with values of over $-5,000 \text{ kN/m}^2$.

The horizontal stresses σ_{yy} (fig. 4.c) bring under stress, in the same way and with close values, all the rooms oriented according to the E-W direction.

The vertical stresses σ_{zz} (fig. 4.a) develops progressively with the descent in depth, starting from the values of approx. $-3,000 \div -5,000 \text{ kN/m}^2$ at the level of the preparatory working, then at about $-13,000 \text{ kN/m}^2$, in the middle of the walls, exceeding locally $-15,000 \text{ kN/m}^2$, in the intersections between the walls of the rooms around the small pillars.

The major main stresses σ_1 (fig. 9.a) have maximum compression values, starting from approx. $-3,500 \text{ kN/m}^2$, at the level of the preparatory working and the intersection area of the walls with floor, reaching tensile values of approximately $+300 \div +1,000 \text{ kN/m}^2$, at the middle of the ceiling of the rooms, with their concentration at the intersection between the inclined planes of the ceilings. The floors of the rooms are subjected to the same values of the tensile stresses, towards the center of the rooms around the small pillars and to compression values of approx. -450 kN/m^2 , towards the limit with the walls and in the floor of the main rooms, oriented N-S.

The minimum main stresses σ_3 (fig. 9.b) are compressive stresses and stress the middle of the room walls and the corners between the walls and floors, with values above $-13,000 \text{ kN/m}^2$ and with stress concentrations above $-15,000 \text{ kN/m}^2$, at the intersections of the walls around the small pillars.

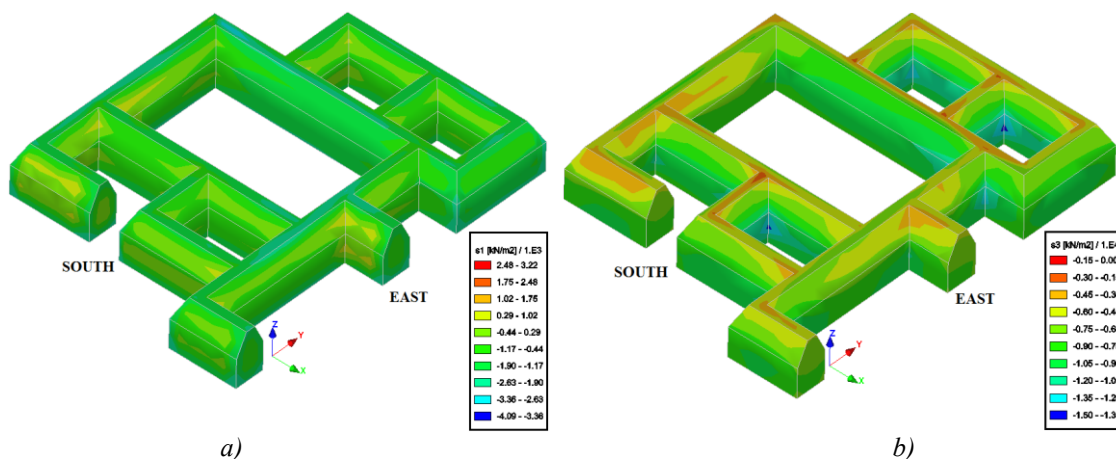


Fig.9. Main maximum σ_1 (a) and minimum σ_3 (b) stresses, in kN/m^2 [6]

The maximum shear stresses $\tau_{f \max}$ (fig. 10.a) with the most important values in the middle area of the walls or the rooms, with averages between $4,000$ and $5,000 \text{ kN/m}^2$, in the walls from the limit of the mining field and in the walls from the central pillar. The concentration of shear stresses is in the walls of the rooms around the small pillars and at the corners of all the pillars, at values of over $6,000$ - $7,000 \text{ kN/m}^2$. All these values far exceed the limit of the shear strength of the rock salt, these areas being the most predisposed to loss of stability by failure, by shear stresses.

The tensile stresses σ_t (fig. 10.b) are concentrated in the middle of the ceiling, in the intersection areas between the planes ceilings of the chambers, where their value exceeds $+1,000 \div +1,300 \text{ kN/m}^2$, dangerously approaching the value of the tensile strength of the rock salt. In these areas, where locally the rock salt has much lower resistance, there are created conditions for the occurrence of collapses by failure, by tensile stresses.

The highest values of compression stresses σ_c (fig. 10.c) are in the walls of the rooms, they are generally between $-6,000$ and $-10,000 \text{ kN/m}^2$, with significant increases in the corner areas of the small pillars, towards the middle of the walls of the rooms, at values of approx. $-13,000 \div -15,000 \text{ kN/m}^2$. If locally, the rock salt has strength below the maximum value of these stresses, then it is possible the occurrence of the phenomena of failure by compressive stresses of the corners of the small pillars.

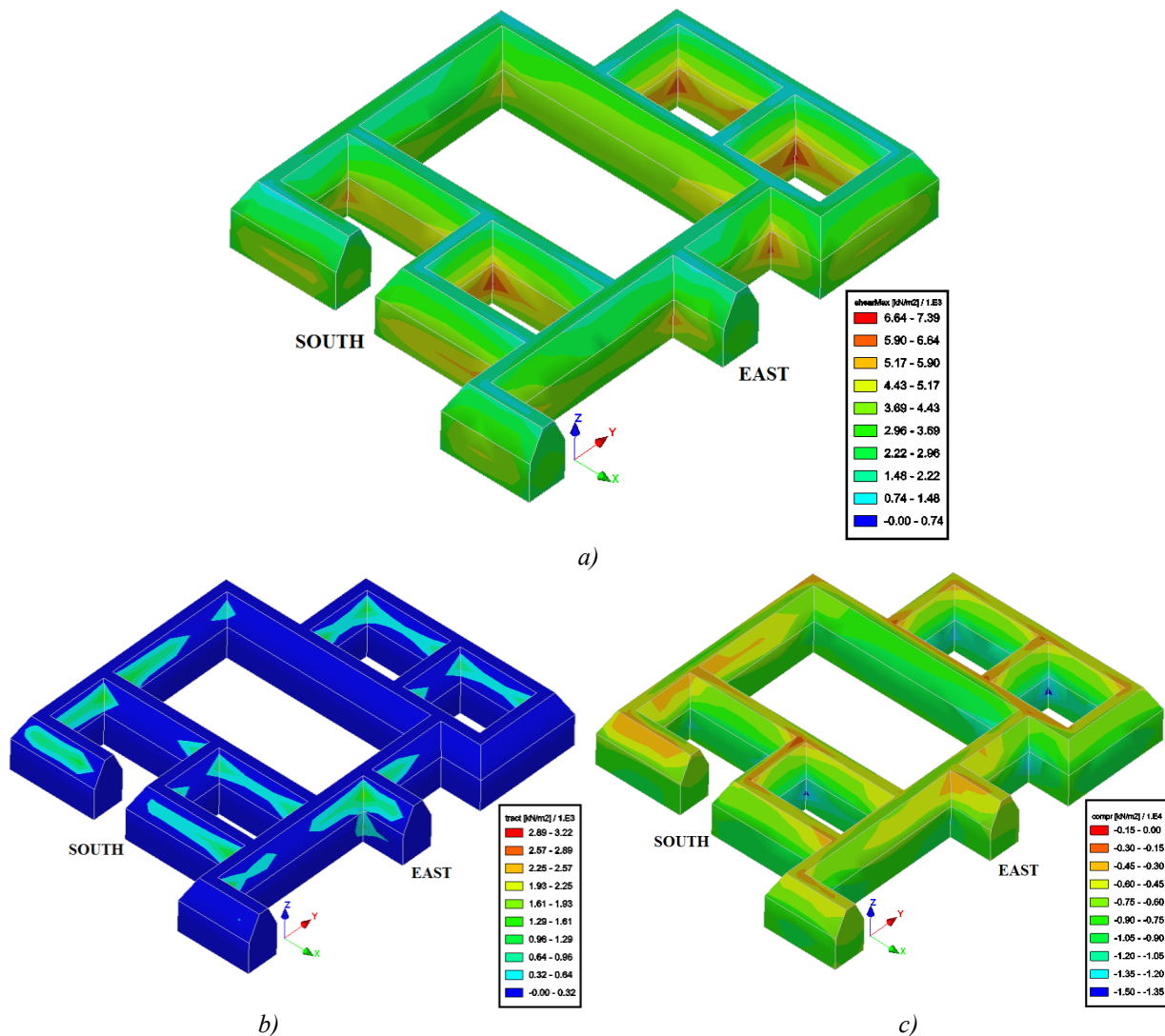


Fig.10. Maximum shear $\tau_{f_{max}}$ (a), tensile σ_t (b) and compression σ_c (c) stresses, in kN/m^2 [6]

5. Conclusions

The underground mining of the rock salt deposit from the Slănic salt mine started over 350 years ago, through bell-shape rooms (Ocna din Deal and Ocna din Vale) and continued with large trapezoidal rooms, in the Carol, Mihai and Unirea mines. By 1970, a volume of rock salt of over 5,3 million m^3 had been extracted from the Old Mines. The large volume of excavations and their positioning close to the surface determined the complete collapse of the Old mines and the degradation of the large trapezoidal chambers in different degrees, with the decommissioning of the Carol and Mihai rooms and certain areas of the rooms from the Unirea mine.

In order to establish the causes that led to the instability of the large excavations in the Old Mines, located in the center of the deposit, was performed a numerical modeling with 3D finite elements, in elastic-plasticity, using the CESAR-LCPC software.

With the aid of numerical modeling, the state of stresses and deformations of the entire model was analyzed, with the focus of interest on the Unirea Mine, which is in operation for tourism purposes.

In the analysis, both vertical and horizontal displacements were taken into account.

Also, in the stability analysis of the resistance structures, the distribution of stresses along the three axes, the distribution of the principal stresses, maximum shear stresses, tensile and compressive stresses were taken into account, which were compared with the specific strengths of the rock salt deposit.

In areas where the stresses in the resistance structures have exceeded the specific strengths of the rock salt, it has been assumed that a series of geo-mechanical phenomena of loss of stability have occurred, with various degrees of intensity, such as swelling of the floors and convergence of the chambers, the appearance of fractures in certain areas of the ceiling of the rooms and the breaking of the corners of the pillars.

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