The Influence of the Exploitation of the XIV Horizon on the Stability of the Cantacuzino Mine - Slănic Prahova Saline

Bogdan Postolachi¹, Ovidiu Marina¹, Dacian-Paul Marian¹* and Ilie Onica¹

¹University of Petroșani, Department of Mining, Surveying and Construction

Abstract. Salina Slănic Prahova continued its activity, during the period 1993-219, through the exploitation of the Cantacuzino mine, with rooms and square pillars of 16 m x 16 m and 18 m x 18 m, on 7 overstory levels, with a height of 16 m, during which 4 964 880 tonnes of rock salt were exploited. Over time, some ceilings between the levels, with a thickness of 8 m, began to crack, which required the monitoring of their movements through topographical methods. Although the exploitation of the Cantacuzino mine has ended, the last three levels are used for technical purposes. Therefore, the stability analysis of the resistance structures was imposed, under the conditions of mining with rooms and pillars of the XIV horizon, located at +145 m elevation. Between the last horizon from the Cantacuzino Mine and the XIV horizon, a 40 m crown pillar was designed. Analysis of the state of stresses and strains, respectively of the influence of voids resulting from the extraction of horizon XIV on the Cantacuzino Mine was realized by numerical modeling with finite differences, in elasto-plasticity, using FLAC 3D software.

1 Introduction

The continuity of operations at Salina Slănic Prahova has been effectively maintained through the establishment and subsequent exploitation of the Cantacuzino mine, opened in 1993. A mining method employing small rooms with square pillars was carefully selected for this endeavor [5]. Notably, the dimensions of the pillars were adapted proportionally to the mining depth, resulting in the following specifications: \( L_p = 16 \text{ m} \) for levels V to VII, \( L_p = 17 \text{ m} \) for levels VIII to X, and \( L_p = 18 \text{ m} \) for level XI [1].

Over the years, significant quantities of salt were extracted from the Cantacuzino mine, resulting in substantial void volumes within the underground space. As of 2019, the cumulative salt extraction from the mine amounted to approximately 4,964,880 tons, corresponding to an estimated empty volume of around 2,364,229 m³. The mining operations reached a depth of nearly 103 m, beneath a massive salt block and a layer of rock cover, the thickness between 102 m and 160 m, determined by the surface topography [1]. These general data provide crucial context for understanding the operational and stability conditions of the Cantacuzino mine.

* Corresponding author: dacianmarian@upet.ro

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).
Starting from 2020, the work began on opening and preparing the first slice with a thickness of 5 m, for the mechanized salt extraction, of the XIV Horizon. This new mining field was designed to be mined underneath the three existing mines, Cantacuzino, Unirea, and Victoria, under a crown pillar of approximately 40 meters. The proposed mining method to be applied is room and pillar, with the pillars having dimensions of 18x18 m and the opening of the rooms being 12 m to the west of the K5 - K47 alignment and 19x19 m to the east and rooms of 11 m respectively while the height of the rooms is 8 m. The exploitation of the XIV Horizon will be carried out at an average yearly production of 125,000 tonnes/year, which for the first slice of 5 m will last until 2045, and for the second slice until 2059.

To investigate the impact of XIV Horizon exploitation on the stability of the upper levels of the Cantacuzino Mine, a 3D numerical modeling approach was utilized. The numerical modeling was performed using the FLAC 3D finite difference software, assuming an elastoplastic behavior characterized by the Mohr-Coulomb failure criterion without hardening [2, 3]. Therefore, three distinct numerical models were created: 1) For the current state of the Slănic-Prahova Salt Mine (the year 2022); 2) With the first slice extracted (the year 2045); 3) With Horizon XIV fully extracted (the year 2059) - see Figures 1 and 2.

In the geostatically loaded models [4, 5], the following geomechanical characteristics were considered for the rock salt: apparent specific weight, \( \gamma_a = 0.021 \text{ MN/m}^3 \); Young's modulus, \( E = 2,450 \text{ MPa} \); Poisson's ratio, \( \nu = 0.28 \); Cohesion, \( C = 2.9 \text{ MPa} \); Internal friction angle \( \phi = 26^\circ \). For the surrounding rocks, the values adopted: \( \gamma'_{ar} = 0.022 \text{ MN/m}^3 \); \( E_r = 3,000 \text{ MPa} \); \( \nu_r = 0.21 \); \( C_r = 5.3 \text{ MPa} \); \( \phi'_r = 24^\circ \) [6, 7, 8].

![Fig.1. Compression safety factor FS = \( R_c / \sigma_c \) Slanic Prahova mine, year 2059](image1.png)

![Fig.2. 3D view of Cantacuzino Mine and Oriz.XIV. Maximum principal stresses, \( \sigma_1 \), in N/m²](image2.png)
2 The impact of XIV Horizon exploitation on level X at Cantacuzino Mine

The crushing and packaging of the rock salt produced at Salina Slănic Prahova are carried out on Level X of Cantacuzino Mine. Therefore, the stability of this horizon constitutes an object of analysis in the present study.

The horizontal displacements \( u \) along the x-axis are all negative, oriented from west to east, indicating the existence of lateral push stress from the eastern side of Cantacuzino Mine. The smallest values of displacements \( u \) within the western structure of the pillars reach a maximum of -0.064 m. At the eastern and western boundaries of the mining field, these values are reduce by half (to -0.32 m). The horizontal displacements \( (u) \) within the level floor demonstrate similar patterns. They experience a slight decrease in the year 2045 and then maintain relatively stable values in the year 2059.

The horizontal displacements \( (v) \) along the y-axis are oriented in the south-north direction, indicating a positive displacement trend. Negative displacements of -0.013 m are observed in the marginal pillars located in the northern part, as well as in the southern wall of the pillars in the eastern region of the mining field. Conversely, positive displacements \( (v) \) are recorded on the northern wall of the pillars, reaching a maximum value of +0.025 m, particularly in the southeastern quadrant of the Cantacuzino mining field. Following the exploitation of the first slice (in 2045), there is a relaxation in the \( v \) displacements, with maximum values of -0.012 m and +0.024 m, respectively. These values persist to a significant extent even after the complete extraction of the XIV Horizon.

The vertical displacements \( (w) \), depicted in Figure 3, exhibit sinking behavior in the eastern part of the floor, reaching a maximum depth of -0.046 m. Gradually, this sinking transforms into floor swellings, reaching a positive displacement of +0.01 m at the western boundary of the mining area. The vertical displacements of the pillars follow a similar trend to the ceiling, transitioning from upward displacements (+0.02 m) in the west to downward displacements (-0.03 to -0.05 m) in the eastern part of the mining field. These swelling values gradually decrease in intensity, while the subsidence of the pillars doubles after the extraction of the initial stage of Horizon XIV. However, in the second stage of exploitation, this phenomenon gradually diminishes.

![Fig.3. The vertical displacements \( w \) (along the \( z \) axis), in m, level XI, year 2059](https://doi.org/10.1051/matecconf/202438900025)

The load-bearing structures on level X experience exclusively compressive horizontal stresses \( \sigma_{x} \) in the southeastern area of the mining field at most of the pillars, and compressive stresses range from approximately -3,150 to -3,600 kN/m². Within the ceiling, the maximum stresses align with the south-north rooms, varying from -2,250 to -2,700 kN/m², while the corners of the east-west rooms exhibit minimum values of -45 to
-1,350 kN/m². These stress values persist during the initial stage of Horizon XIV exploitation and slightly decrease in the subsequent stage, where tensile stresses of +550 kN/m² appear in the east-west rooms.

Horizontal stresses, \( \sigma_{xx} \), in the ceilings, oriented from south to north, exhibit compressive values in the east-west rooms, reaching maximum values of -3,150 to -3,600 kN/m². This pattern is also observed in the central pillars of the eastern mining side, while the other pillars experience a maximum compressive stress \( \sigma_{yy} \) of -1,800 kN/m². In the ceiling, localized tensile stresses occur in the north-south rooms, with a maximum value of +613 kN/m².

During the initial stage of Horizon XIV exploitation, both the ceiling and the pillars are predominantly subjected to compressive stresses. The east-west rooms experience maximum values ranging from -2,960 to -3,330 kN/m², while the north-south rooms range from -47 to -1,110 kN/m². The most stressed pillars are located in the eastern part of the mining area, with maximum values of -3,995 kN/m². In the second stage of exploitation, the stress distribution remains relatively similar.

Vertical stresses \( \sigma_{zz} \) are primarily compressive, with the eastern pillars reaching maximum values of -13,680 kN/m², while the western pillars range from -6,500 to -9,100 kN/m². In the ceiling, the highest vertical stresses occur around the pillars, ranging from -2,600 to -6,500 kN/m², while in the central rooms, they decrease to -16 to -1,300 kN/m². During the first stage of Horizon XIV exploitation, the pillars experience similar stress values with a slight decrease, and the middle of the ceiling floors transitions from compression to tension, with reduced values of +163 kN/m². In the final stage of Horizon XIV exploitation, the structures return to full compression, with stress values \( \sigma_{zz} \) slightly surpassing those in the initial stage (the year 2022).

The maximum principal stresses \( \sigma_1 \) (fig.4), in the initial stage (year 2022), are all compressive throughout the entire structure of Level X in the Cantacuzino mine. The central pillars in the eastern part experience values of -2,980 kN/m², while in the western part, the values reach -1,680 kN/m². In the ceiling, the minimum value is found in the center of the rooms, at -28 kN/m², increasing to -840 to -1,120 kN/m² in the vicinity of the pillars.

![Fig.4. Maximum principal stresses, \( \sigma_1 \), in N/m², level X, year 2059](image)

Exploiting the first slice of Horizon XIV leads to a slight decrease in stresses in the eastern pillars, with a maximum of -2,864 kN/m², and in the western pillars, with a maximum of -1,200 kN/m². In the ceiling, tensile stresses occur in the first directional room oriented north-south, starting from the boundary of the mining field, with a magnitude of +832 kN/m², in the middle of the room. In the remaining rooms, particularly at their intersections, there are tensile stresses of +400 kN/m², transitioning to compressive values of -400 kN/m² around the pillars.
Following the complete extraction of horizontal excavation XIV (in 2059), the maximum principal stress state $\sigma_1$, existing in the initial stage (in 2022) is restored.

The compressive stresses $\sigma_1$ experienced on the level X exhibit distinct patterns during its three chronological stages. In the eastern pillars, the minimum stresses reach their highest value at -13,860 kN/m², while the western pillars experience stresses of -7,800 kN/m². Compression stresses emerge within the ceiling structure at the rooms' intersection at -1,300 kN/m² but around the pillars, they range from -3,900 to -5,200 kN/m², with higher values observed towards the eastern region of the mining field.

During the initial exploitation phase of Horizon XIV, the stresses in the eastern pillars escalated to a maximum of -14,000 kN/m², while the western pillars maintain consistent stress levels. Likewise, the ceiling retains the same maximum stress values near the pillars. In the final mining phase of Horizon XIV, the pillars experience stresses $\sigma_1$ similar to those in the previous phase, with a relaxation of approximately 10% occurring in the middle of the room floor.

The maximum shear stresses $\tau_{f,\text{max}}$ (Figure 5) exhibit the highest magnitudes at the periphery of the pillars in the eastern zone of the mining field, ranging from 4,400 to 5,938 kN/m², which is more than double the shear strength of the rock salt (2,200 kN/m²). In the pillars towards the west, the maximum shear stress values range from 3,300 to 3,850 kN/m². Under these shear loading conditions, the outer surfaces of all pillars are susceptible to exfoliation, particularly at the corners and the base. In the ceiling, the shear stresses are highest around the pillars, ranging from 1,650 to 2,750 kN/m², while in the middle of the room floor, the values of $\tau_{f,\text{max}}$ decrease to 413.2 kN/m².

![Fig.5. Maximum shear stresses, $\tau_{f,\text{max}}$, in N/m², level X, year 2059](image)

During the second mining phase of level XIV, the shear stress values in the pillars remain relatively constant, decreasing to 365.4 kN/m² in the central part of the room floor. Once the reserves in level XIV are fully exploited, the shear stresses in the pillars remain similar to the previous phase, but the stresses in the middle of the rooms increase to 569.7 kN/m².

The compression safety factor $FS$ (Figure 6) exhibits a value exceeding 1 across all resistance structures of level X. In the pillars facing west, the safety factor exhibits values within the range of 1.7 to 3.4, decreasing to below 1.7 in the values from the eastern side. At the intersection of the rooms, the $FS$ is between 5.1 and 7.65, while around the pillars, it ranges from 2.55 to 5.1. To conclude, the two phases of extracting horizon XIV have an insignificant influence on the increase of safety factor values in the structures of level X from the Cantacuzino Mine.
3 The impact of XIV Horizon exploitation on level XI at Cantacuzino Mine

Until the operational commencement of the fourteenth level, rock salt will continue to be extracted from the XI level, and the underground spaces of this level will be used as an interim salt deposit. For this reason, and because the bedrock of this level is part of the upper surface of the crown pillar, the stability of the underground structures at this level will also be analyzed.

The horizontal displacements ($u$), along the $x$-axis, at the current mining stage of the XIV Horizon are all negative values, oriented from east to west, with maximums in pillars, western wall, from -0.056 to -0.063 m. At the floor, maximum values are located in the northeastern quadrant of the mining field.

After the extraction of the first slice from the XIV Horizon, the displacements ($u$) extend across the floor's surface, at values of -0.049 to -0.056 m, with maximums of -0.063 m, towards the northern boundary. In the second stage of exploitation, the horizontal displacements ($u$) remain approximately the same, with a slight but insignificant increase.

The horizontal displacements $v$, along the $y$-axis, are oriented from south to north, with positive values on the northern faces of the pillars, max. $+0.014 +0.024$ m, and negative values on the southern faces, ranging from -0.003 to -0.010m. In the floor, the displacements $v$ have positive values, up to a maximum of $+0.014$ m. After extracting the first slice of the XIV Horizon, the horizontal $v$ displacements show a slight increase, followed by an insignificant relaxation in the last stage 2059.

Vertical displacements $w$, along the $z$-axis (fig.7), are characterized by pillar sinkages in the northeastern quadrant, ranging from -0.014 to -0.089 m, and pillar elevations in the southeastern quadrant, from $+0.014$ to $+0.028$ m. The rooms floor undergo swelling in the range of $+0.014$ to $+0.053$ m. The highest swelling values are located at the center of the room in the southeastern quadrant of the mining level.

Following the extraction of the first slice of the XIV horizon (in the year 2045), both the pillars and the rooms floor undergo upward vertical displacement phenomena. The pillars with $v$ displacement values of $+0.009$ to $+0.054$ m, while the floor, with swelling of $+0.045$ to $+0.075$ m. After the complete extraction of this horizon (in the year 2059), load-bearing structures at level XI relax and return to the distribution of vertical displacements in the current situation (from the year 2022).
Horizontal stresses $\sigma_{xx}$ present positive values within the load-bearing structures of the XI-th mining level. The lowest compression values are located in the northern and southern faces of the pillars, with a maximum in the eastern part of the mining area of -2,700 to -3,600 kN/m² and -1,800 to -2,250 kN/m² in the western part. Within the confines of the floor structure, particularly surrounding the pillars, stresses manifest within a range of -1,350 to -2,700 kN/m², while at the center of the rooms, predominantly at intersections, horizontal stress $\sigma_{xx}$ values of -1,350 to -2,700 kN/m² can be observed. In the center of the rooms, primarily at intersections, the stresses are -77 to -900 kN/m².

Upon the extraction of the first segment of the XIV horizon in 2045, a detension process is experienced in all stresses $\sigma_{xx}$, both in the pillars, with a range of -2,000 to -3,000 kN/m², and in the floor, where it is manifested by traction with maximum values of +717 kN/m². After the second phase from 2059, there is a return to the initial state of stress $\sigma_{xx}$ from 2022, but less intense.

Horizontal stresses $\sigma_{yy}$ are oriented in a south-north direction. There are the compression (negative) values in all pillars, along the eastern and western faces of these pillars, with maximum values of -2400 -3761 kN/m² in the eastern part of the mining area and values of -1200 -2400 kN/m² in the pillars on the western side. In the floor, negative stress values occur around the pillars, ranging from -780 to -2340 kN/m². After the extraction of the first slice of the XIV Horizon, the stress decreases slightly in the pillars and the rest of the structures. Following the complete extraction of the XIV Horizon, the stress in the pillars is slightly reduced, but in the center of the rooms, tensile stresses appear, with a maximum value of +198.8 kN/m².

Vertical stresses $\sigma_{zz}$ are compressive throughout the resistance structure of the mining level in the model related to the year 2022. In the pillars towards the east, the stress $\sigma_{zz}$ values range between -7800 and -13800 kN/m², and in those on the western part, from -3900 to -9100 kN/m². In the floor, around the pillars, there are stresses ranging from -2600 to -6500 kN/m², and in the middle of the rooms, from -45 to -1300 kN/m². In the model for 2045, the values of the vertical stress in the pillars do not undergo significant changes, with slight decreases in the values in the eastern pillars. In the model for 2059, we witness a certain increase in the stresses of all pillars on the eastern side of the XI-th level.

The maximal principal stresses $\sigma_1$ (Figure 8) are compressive throughout the entire structure of the XI-th level at the Cantacuzino Mine. In the pillars of the eastern area, the compressive stresses range from -1,680 to -2,999 kN/m², while in the western part, they reach...
from -840 to -2,240 kN/m². On the floor, the stresses vary from -1,120 kN/m², at the boundary with the pillars, to the lowest value of -31.5 to -280 kN/m².

Upon extraction of the first slice from Horizon XIV, there is a slight reduction in the stresses within the room floor. Full extraction of Horizon XIV results in a negligible reduction in stresses within the pillars of the eastern part of the XI level and a significant decrease in the stresses \( \sigma_1 \) from the western side of the mining region. Tensile stresses occur across the entire floor of Horizon XI, reaching values of +370 to +777 kN/m².

The minimum principal stresses \( \sigma_3 \) are compressive across the entire level. In the pillars of the eastern part, the values of compressive stresses range from -10,400 to -13,940 kN/m², while in the western part, they range from -3,900 to -10,400 kN/m². On the floor, the minimum principal stresses \( \sigma_3 \) manifest at -3,900 kN/m² to the edges of the pillars and between -197 and -1,300 kN/m², while in the center of the rooms, they range from -197 to -2,600 kN/m². In the numerical model for the year 2045, all values of stresses have decreased insignificantly.

The maximum shear stresses \( \tau_{max} \) (Figure 9) have the highest values in the pillars, towards their external surface, in the eastern part of the XI-th level, ranging from 3,300 to 5,910 kN/m². In the pillars of the western part, these values range from 2,750 to 3,300 kN/m². On the floor, around the pillars, the maximum shear stresses \( \tau_{max} \) have values between 2,200 to 2,750 kN/m², and in the center of the rooms, the values range from 77 to 2,200 kN/m².

The compression safety factor, \( FS \), exhibits values exceeding 1.024 across all load-bearing structures at the eleventh floor of the Cantacuzino Mine, ranging between 1.024 and 2.550 in pillars, and 5.1 to 10 in the floor. These values remain approximately consistent during the second stage of operation at horizon XIV.

The maximum shear strain \( \tau_{Hmax} \) in the western part exhibits values between 0.180 and 0.300, with peak values of 0.643 located in the northeastern corner of the floor.

Furthermore, an in-depth analysis was conducted to assess the impact of exploiting the XIVth horizon on the current excavations (as of 2022) situated above it. This analysis involved the development of two-dimensional finite element models and the use of CESAR-LCPC software for computation. The model was executed at an elevation of +193m, specifically at the boundary of the XI-th mining level floor with the crown pillar, underneath the Cantacuzino mine. Subsequently, a comparison was made between the safety factor distribution of the current mining situation (2022) and the distribution after the introduction of excavations at the +145m horizon (2059) - refer to Figure 11.

Broadly speaking, a progressive decline in the safety factor \( FS \) is evident from west to east. In the present mining scenario, the \( FS \) ranges from 5 to 6 towards the western side and gradually reduces to 4 - 5 towards the eastern side, specifically at the rooms floor. Notably, the \( FS \) experiences a significant increase to values exceeding 6 to 7 in the first row of rooms, starting from the western boundary. In contrast, beneath the pillars, the safety factor diminish relatively uniformly, reaching approximately 2, with localized reductions to 1.5 at the boundary between the pillars and the rooms floor.

After the complete extraction of the XIV Horizon, there is an expected moderate decrease of approximately 5 to 10% in the calculated safety factor values within the floor of the rooms. However, it is anticipated that the values will remain relatively stable in the areas beneath the pillars. Therefore, it can be concluded that the exploitation of the XIV Horizon has a minimal impact on the upper limit of the crown pillar beneath the Cantacuzino mine.
In 2045, following the extraction of the first slice from Horizon XIV, a reduction in the shear stresses in the eastern pillars occurs to a maximum value of 5,800 kN/m². This process also generates a state of relaxation of the shear stresses in the room's floor.

By 2059, the maximum shear stresses will be maintained approximately at the same level, with an insignificant decrease.

The compression safety factor, or $FS$, exhibits values exceeding 1.024 across all load-bearing structures at the eleventh floor of the Cantacuzino Mine, ranging between 1.024 and 2.550 in pillars, and 5.1 to 10 in the floor. These values remain approximately consistent during the second stage of operation at horizon XIV.

The maximum shear strain $\varepsilon_{\text{f, max}}$ in the western part exhibits values between 0.180 and 0.300, with peak values of 0.643 located in the northeastern corner of the floor.

![Fig.10. Maximum shear strain $\varepsilon_{\text{f, max}}$, level XI, year 2059](image)

Furthermore, an in-depth analysis was conducted to assess the impact of exploiting the XIVth horizon on the current excavations (as of 2022) situated above it. This analysis involved the development of two-dimensional finite element models and the use of CESAR-LCPC software for computation. The model was executed at an elevation of +193m, specifically at the boundary of the XI-th mining level floor with the crown pillar, underneath the Cantacuzino mine. Subsequently, a comparison was made between the safety factor distribution of the current mining situation (2022) and the distribution after the introduction of excavations at the +145m horizon (2059) - refer to Figure 11.

Broadly speaking, a progressive decline in the safety factor ($FS$) is evident from west to east. In the present mining scenario, the $FS$ ranges from 5 to 6 towards the western side and gradually reduces to 4 - 5 towards the eastern side, specifically at the rooms floor. Notably, the $FS$ experiences a significant increase to values exceeding 6 to 7 in the first row of rooms, starting from the western boundary. In contrast, beneath the pillars, the safety factor diminish relatively uniformly, reaching approximately 2, with localized reductions to 1.5 at the boundary between the pillars and the rooms floor.

After the complete extraction of the XIV Horizon, there is an expected moderate decrease of approximately 5 to 10% in the calculated safety factor values within the floor of the rooms. However, it is anticipated that the values will remain relatively stable in the areas beneath the pillars. Therefore, it can be concluded that the exploitation of the XIV Horizon has a minimal impact on the upper limit of the crown pillar beneath the Cantacuzino mine.
4 Conclusions

To assess the impact of mining the XIV horizon on the upper functional levels X and XI of Cantacuzino Mine, a numerical modeling approach using FLAC 3D software was employed.

Three computational models were created to capture the current state of the Prahova Salt Mine (as of 2022), and the stages with the first slice extracted (in 2045) and with the XIV Horizon fully exploited (in 2059).

Through a comparative analysis of stress and deformation at level X and XI of Cantacuzino Mine, it was observed that after the extraction of the first slice, there was a relaxation of stresses and deformations, followed by a partial restoration towards the initial state upon full extraction of the XIV Horizon. These findings indicate that the impact resulting from the exploitation of the XIV Horizon on the Cantacuzino Mine is deemed insignificant.

References