Prognosis of Ground Surface Deformation of the Victoria Mine – Slănic Prahova Saline

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Abstract. The Victoria mine, from Slănic Prahova Saline operated in the period 1970-1992 and was mined with small rooms and square pillars, on 11 overstory levels, of 16 m high. It resulted in a volume of mining voids of 7.4 million m³, which led to the pronounced degradation of the resistance structures (rooms and pillars) and to the deformation of the ground surface of the saline. Systematic, annual monitoring of ground surface deformation has been carried out since 2004, through geometric levelling, on certain representative alignments. The prediction of the time evolution of ground surface subsidence was carried out with some power approximation functions of prognosis and the future ground subsidence curves were established on the analyzed alignments. Also, 3D numerical modeling was used to estimate ground surface subsidence and displacements.

1 Introduction

The mining of the rock salt deposit at Slănic-Prahova was first carried out in the center of the deposit, between 1689-1691, through the bell-shaped chambers at Baia Bacilului. Being close to the surface, these old excavations created pits in which salt lakes formed: Baia Verde, Baia Baciului, Lacul Mare, Grota Miresei, and Baia Porcilor. Then, between 1800 and 1854, mining continued through the bell-shaped chambers at Bâile Verzi and Grota Miresei, which are partially filled in today. Between 1819 and 1881, the salt rock from Ocna din Deal and Ocna din Vale were extracted, first at a depth of 96 m and the second at 145 m. Between 1865 and 1875, a more evolved mining method was adopted, with multiple chambers, through the so-called Ocna Sistematica [1].

In addition to the salt mines presented above, the following old mines were operational in the central area of the deposit: The Principatelor Unite or Carol Mine, between the years 1831-1935; The 23 August or Mihai Mine, between the years 1912-1943; The Unirea Mine, during the period 1947-1971. In 1970, in the northern part of the deposit, the Victoria Mine was opened; the mining methods with small rooms and square pillars were applied. The inter-room pillars with a square horizontal section, with a length of 14-17.5 m and a height of 8 m, are arranged coaxially on all 11 mining levels of the mine. The extracted rooms have a square horizontal surface, with a side of 16-12.5 m and a height of 8 m [1]. The mining activity at the Victoria Mine was halted in 1992 due to safety concerns. The depth of the rooms from

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the first mining horizon varies between 49 m and 174 m, and the ones from the last floor XI is between 207-328 m.

In this mine, the rooms resulting from the deposit extraction generated an area of 922,391 m² and a void volume of 7,379,128 m³; thus, being close to the surface caused the collapse of this mine and severe damage to the surface.

Between 1990-2022, in the south part of old mines, the rock salt deposit at Slănic Prahova was extracted from the Cantacuzino Mine between horizons V and XI, using the same mining method with small rooms and square pillars. In the year 2022, a new mining level XIV was opened at an elevation of +145m, situated beneath a 40 m-thick equalization pillar that extended across the entire surface of the mining area below the old excavations.

Fig.1. The vertical displacements \( w \) (along the \( x \)-axis), in m, predicted by 3D numerical modeling

Following the extraction of a volume of rock salt from the deposit, the state of stress and strain in the massif changes, resulting in reduced stability of the surrounding rocks and, consequently, the surface terrain. The surface displacement results from the redistribution of stresses in the rock mass under the influence of underground excavations generated by mining activity.

Surface subsidence or disturbance can be continuous and discontinuous [2, 3, 4, 5]. Discontinuous subsidence is characterized by significant surface displacements over the surface area above the mined region and the formation of discontinuities on the surface profile. In the conditions of salt mining, it can be defined as discontinuous subsidence or deformation of the ground, displacement of the rocks after a sinkhole formed near the shafts, created due to dissolution or cave-in of bell chambers because of the collapse of the safety pillars. In general, all dissolution caverns of the rock salt mass that can lead to a sudden collapse of the rocks after such sinkholes. The continuous subsidence or cave-in proper category includes surface deformations that form a stretched profile of the dipping bed and expand progressively with the extension of the mined area.

Continuous subsidence results from the mining of coal seams with strike longwalls or the extraction of other valuable mineral deposits, such as sulfur or evaporite deposits, which are typically found in sedimentary formations. This is also applicable to rock salt deposits [2, 4, 5].

Depending on the degree of impact on the surface, troughs can be: subcritical \((L / H < \tan \xi')\), critical \((L / H = \tan \xi')\), and supercritical \((L / H > \tan \xi')\); where \(L\) is the length of the extracted area; \(H\) - the depth where extraction is located; \(\xi'\) - the angle of influence or limit. In the case of the Victoria mine, the subsidence trough is classified as supercritical.

According to Brauner [3], continuous subsidence occurs at every point along the subsidence trough. It is characterized by five significant variables: vertical subsidence, displacement, inclination, the curvature of the subsidence trough, and horizontal compressive and tensile strains (fig.2). Each influencing factor brings on specific types of damage to the surface terrain and structures located above it.
The phenomenon of degradation over time of the surface stability at Victoria Mine has been similar to that at the Cantacuzino Mine. The difference is because, having extracted a volume of almost 3.12 times the excavation volume from a mining perimeter with almost twice the surface area and with an annual mining decline rate almost three times higher, the degradation of the support structures (pillars and ceilings) was much more intense. Consequently, the local destruction of the support structures led to the Victoria mine becoming inaccessible to personnel from 1992 onwards.

The instability phenomena at the Victoria mine arose primarily because of the substantial volume of the mining voids (at present, this volume represents almost half of the total underground empty space at the Slănic salt mine). Then, because of the large depths at which the last three mining levels are located, where the salt rock has entered the elastoplastic behavior domain. Thus, because of the small distance of the first horizon from the surface and the undersized roof pillar for such a deep mine extension. All this bottlenecks facilitated water seepage through fractures in the overlying rocks and the central roof pillar. The ground surface has also been correspondingly affected, preserving the continuous character of surface deformation.

2 Monitoring and prognosis of ground deformation at the surface of the Victoria Mine

The experts at Slănic salt mine have conducted ground monitoring works since 2003, respecting the fundamental principles presented in the paper [6].

The topographic measurements on the surface terrain relief were intended to monitor the vertical displacements (subsidences) of several significant topographic landmarks. These landmarks, located in the area influenced by the Victoria, Unirea, and Cantacuzino mines, exhibited representative subsidences of the analyzed perimeter. For this purpose, a series of fixed points with control coordinates were established, to which points with time-varying coordinates were reported, for which the actual monitoring of the ground surface subsidences was carried out.

The information about the subsidence of the land, located in the influence zone of each analyzed mine, is based on the values measured over time of the coordinates of the monitored points, supported by the fixed coordinates of the points, and from the difference of the coordinates, the relative values were obtained, defined over time, of the deformation parameters such as the vertical displacements, subsidence speeds, inclinations, and displacement orientations.
In the case of the Victoria Mine, 60 landmarks were used to monitor surface deformation, located on the following five alignments (Fig. 3): B74-V21 (at the south-western boundary of the mine perimeter); V10E-10G (at the north-western edge - in the fourth quadrant); N3-N12 (in the south-western area - in the third quadrant); L1-L15 (in the middle of the Victoria Mine perimeter, in the north-south direction); T1-T15 (in the middle of the Victoria Mine perimeter, in the east-west direction). The first three alignments were monitored annually, starting from 2003, and are significant from the point of view of the study on the deformation of the surface of the Victoria mine, while the last two (T1-T15 and L1-L15) only start from 2021.

Out of a total of 60 landmarks located on the surface of Victoria Mine, for 31 landmarks the approximation equations of the subsidence evolution follow logarithmic low, while the remaining 29 follow power low. These equations have been determined with high accuracy, as evidenced by the determination coefficients ($R^2$) ranging from 0.90 to 0.99, except for a few exceptions. Moreover, the measured values indicate minimal deviation from the predicted values:

$$S_{(x=1;i)} = a_{(x=i)} \cdot t^{(x=i)}; \quad S_{(x=2;i)} = a_{(x=i)} \cdot \ln t - b_{(x=i)}$$

where $i$ represents the landmark with a certain position $x$ on the alignment.

The prognosis laws described by equation (1) indicate that land deformation attenuates over time, which can also be explained by the decreasing trends in subsidence speed, as depicted in the figures below.
By utilizing the approximation equations (1), the subsidence values and, consequently, the subsidence rates have been projected for all landmarks over 23 years (until 2045, assuming the complete extraction of the first slice) and 37 years (until 2059, after the total extraction of horizon XIV). In the initial phase of the calculation, this analysis of predicting displacement and subsidence speed is conducted under the assumption that land deformation continues without the extraction of horizon XIV (i.e., with the idea that the mining activities are stopped for a continuous period of 37 years).

Initial deformation amplification ratios were calculated to estimate the displacement and subsidence rates for two scenarios, the I slice extracted (after 23 years) and at the end of slice II extracted (after 37 years). These coefficients consider the ratio of the volumes of salt extracted during the initial period (until 2022) and after 2045 and 2059, respectively. These coefficients were calculated based on the estimated average annual production of 125,000 tonnes/year at the Slănic Prahova Mine. For slice I, (thickness of 5m), the coefficient $K_{\text{VICT} \, FI}$ was determined to be 1,077. After the extraction of slice II, (thickness of 3m), the coefficient $K_{\text{VICT} \, F1+II}$ was found to be 1,123.

Figure 4 provides a summary of the measured and predicted subsidence parameters, by alignment, for the year 2022 and those predicted for 2045 and 2059, after the staged extraction of the XIV horizon.

On the V10E-10G alignment (Fig. 4), significant subsidence values were observed for landmarks B74, V2, V3, and V4 located at the south-western edge of the Victoria Mine. In 2022, the measured subsidence values for these landmarks ranged from 231 mm (landmark B74) to 368 mm (landmark V4), with corresponding subsidence rates of 0.702 mm/yr and 1.114 mm/yr, respectively. At landmark V4, the predicted displacement for 2045 and 2059 were 982 mm and 1,433 mm, with corresponding predicted subsidence rates of 1.620 mm/yr and 1.851 mm/yr, respectively. Although landmarks V11, V12, and V14 are located along the northeastern boundary of the mining perimeter, have measured subsidence values between 285 mm and 222 mm and subsidence speed between 0.863 mm/yr and 0.674 mm/yr.

![Fig.4. The variation of measured and predicted subsidences (years 2045 and 2059) without the extracting the XIV horizon and with the extraction of the XIV horizon (in stage I and II), by landmarks – Alignment B74-V21, Victoria Mine.](image-url)
Fig. 5. The variation of measured (year 2022) and predicted subsidences (years 2022, 2045 and 2059), by landmarks – Alignment B74-V21, Victoria Mine

Fig. 6. The variation of measured (year 2022) and predicted subsidence rate / speed (years 2022, 2045 and 2059), with the extraction of the XIV horizon (in stage I and II), by landmarks – Alignment B74-V21, Victoria Mine

The landmarks on alignment V10E-10G (fig.7) are located within the north-eastern quadrant of the Victoria minefield, following the sloping boundary of the mining perimeter. All benchmarks have very high subsidence values, from 986 mm (V10G landmark), to 644 mm (V10E landmark), with subsidence rates of 4.738mm/year and 3.096mm/year. In the year 2059, after the both stages will be completed of extraction (5 m and 3 m) at the level of these landmarks, the highest potential subsidence which will be reached, is 2,981mm, for landmark V10G and of 5,914mm, for landmark V10E. As can be seen from the analysis of predicted subsidence speeds, ground deformation is one with a continuous upward trend in the area of the Victoria Mine.
The variation of measured (year 2022) and predicted displacement (years 2022, 2045 and 2059), by landmarks – Alignment V10E-10G, Victoria Mine

Figure 8 provides a graphical representation of the time evolution of subsidence for the landmarks along the N3-N12 alignment, situated in the southeast quadrant of the mining perimeter. The highest values measured of subsidence in 2022 on the N3-N12 alignment were observed at the N12 landmarks (481 mm) and N4 landmarks (365 mm). For these landmarks, the prognosis for the year 2059 is 1,448 mm, respectively 1,268 mm. The predicted rates of subsidence show a slightly declining trend.

Analyzing the values of the landmark subsidence along the L1-L15 alignment at the Victoria Mine, could be conclude that there are no displacement greater than 55 mm. Although the L1-L15 alignment stretches along the perimeter of the Victoria Mine, around its mid-section, in the north-south direction, the measured values of the subsidence (starting from the year 2021) are pretty minimal, a maximum of 45 mm (landmark L14) and are not representative for the scale of excavation volume at the Victoria Mine. The subsidence rates are relatively low, reaching a maximum of 1.77 mm/year at the same landmark. This transforms the initial surface deformation phenomenon into a process of relative attenuation.
As can be determined from the cumulative subsidence values at the landmarks along the T1-T15 alignment, they reach a maximum value of 148 mm, at the landmark T2, in 2022.

The minimal values can be attributed to the limited number of measurement campaigns, which only began in 2021. Consequently, the current estimation of land deformations on alignments L1-L15 and T1-T15 for the years 2045 and 2059 is not sufficiently reliable or representative of the Victoria Mine, given the early stage of the monitoring process.

3 Analysis of subsidence at the surface of the Victoria Mine, based on results from 3D numerical models

The numerical modeling was carried out using the finite difference software, FLAC 3D, under the assumption of an elastoplastic behavior without hardening, characterized by the Mohr-Coulomb failure criterion [7, 8]. Consequently, three numerical models were developed: 1) for the current situation of the Slanic-Prahova Salt Mine (the year 2022); 2) with the first stage mined from horizon XIV (the year 2045); 3) with the entire horizon XIV fully mined II stage (the year 2059). In the geostatically loaded models, the following geomechanical characteristics were incorporated for rock salt: apparent specific weight, $\gamma_a = 0.021 \text{MN/m}^3$; modulus of elasticity, $E = 2,450 \text{ MPa}$; Poisson's ratio, $\nu = 0.28$; cohesion, $C = 2.9 \text{MPa}$; internal friction angle $\phi = 26^\circ$. For the surrounding rocks, the incorporated values were: $\gamma_a = 0.022 \text{ MN/m}^3$; $E_r = 3000 \text{ MPa}$; $\nu_r = 0.21$; $C_r = 5.3 \text{ MPa}$; $\phi = 24^\circ$.

Even though the computed stress state derived from the numerical models presents values that can be accepted for explaining real geomechanical phenomena, the obtained displacements (especially those on the surface) are significantly underestimated. The maximum subsidence values resulting from the numerical models for the Victoria Mine, determined under the current conditions of the Slanic-Prahova Salt Mine and under the conditions of mining of horizon XIV (staged, in slices), are synthesized in Table 1 and Figures 9 and 10.

| Table 1. Values of maximum vertical displacements (subsidence) $S_{\text{max}}$ ($w_{\text{max}}$–3D midelling), 3D numerical modelling results - Victoria Mine |
|---|---|---|
| Without oriz.XIV | Stage I, oriz. XIV | Stage I+II, oriz. XIV |
| $S_{\text{max}}$, mm | $S_{\text{max}}$, mm | $S_{\text{max}}$, mm |
| Year 2022 | Year 2045 | Year 2059 |
| 131,5 | 164,5 | 180,0 |

The amplification factor of subsidence and the percentage impact index, calculated based on the ratio between the subsidence values generated by the current displacements and the prospective ones (after the extraction of level.XIV), are presented in Table 2.

| Table 2. Amplification factor of the subsidence phenomenon and the percentage impact of mining level XVI on the surface following the ratio of vertical displacements resulting from 3D numerical modelling - Victoria Mine |
|---|---|---|---|
| Without oriz.XIV | Stage I, oriz. XIV | Stage I+II, oriz. XIV |
| Year 2022 | Year 2045 | Year 2059 |
| Infl. Factor $K$ | Impact, $I$, (%) | Infl. Factor $K_{FI}$ | Impact, $I_{FI}$, (%) | Infl. Factor $K_{FI+FI}$ | Impact, $I_{FI+FI}$, (%) |
| 1 | 0 | 1,25 | 25 | 1,36 | 36 |

$K_{FI} = S_{\text{max}FI}/S_{\text{max}}$; $K_{FI+FI} = S_{\text{max}FI+FI}/S_{\text{max}}$; $I_{FI} = (K_{FI} - 1) \times 100$; $I_{FI+FI} = (K_{FI+FI} - 1) \times 100$
The maximum vertical displacements, derived from the 3D numerical models, qualitatively represent the displacement of the surface as summarized in Table 2 very well. However, to quantitatively articulate the impact of horizon XIV on the surface, an equivalence can be drawn between the deformations derived from the 3D model and those observed in the field. For this purpose, the current highest measured vertical displacement in 2022 at the Victoria Mine, is 986 mm (landmark V10F), will be taken into account. This will be compared with the value of the maximum vertical displacement of 131.5 mm derived from the 3D numerical model in its current stage, within the Victoria Mine region. This comparison
suggests that for every 1 mm of maximum vertical displacement in the 3D numerical model, there corresponds an equivalent maximum surface subsidence of 7.5 mm.

By amplifying the value of the maximum vertical displacement of 986 mm with the specific factor to the 3D numerical modeling results, as listed in Table 2, the predicted values of the maximum displacement could be calculated for the year 2045 (after extracting the first slice of Horizont XIV) and for the year 2059 (after the completing the II stage extraction at the horizon XIV). These values are presented in Table 3.

Table 3. Predicted values of maximum equivalent subsidence, obtained from 3D numerical models - Victoria Mine

<table>
<thead>
<tr>
<th>$S_{max}$ – 3D model, year 2022, mm</th>
<th>$S_{max}$ – 3d model, predicted year 2045, mm</th>
<th>$S_{max}$ – 3d model, predicted year 2059, mm</th>
</tr>
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<tr>
<td>986</td>
<td>1233</td>
<td>1341</td>
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4 Conclusion

The Victoria Mine, situated north of the rock salt deposit, operated from 1970 to 1992, extending across 11 mining levels the mining method small rooms and square pillars were applied. It is the largest mine in the Slanic Prahova Mine complex.

The reduced depth compared to the surface and the very large volume of the underground excavations, over 7 million m$^3$ lead to a maximum surface subsidence of 1m.

Monitoring of land subsidence was carried out by topographical methods, by geometric leveling, on several landmarks arranged on preferential alignments. The database obtained was used to prognose land subsidence in two stages (I slice of 5 m and II slice of 3 m) on XIV horizon, located at $Z + 145$m.

Therefore, in order to predict the implications of the XIV horizon's extraction on the stability of the ground surface, three comparative numerical models were developed. These models represented various stages of Victoria Mine's during the years 2022, 2045, and 2059, employing the finite difference software FLAC 3D for this purpose.

References

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