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- SUMMARY -

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**STABILITY ANALYSIS OF UNDERGROUND
STRUCTURES AT THE CANTACUZINO
MINE, SLĂNIC-PRAHOVA SALT MINE**

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1. PURPOSE, OBJECTIVES AND RESEARCH METHODOLOGY OF THE DOCTORAL THESIS

Slănic Prahova is one of the oldest rock salt mines in Romania, with extraction documented since the seventeenth century and continuous mining of the present deposit since 1835. Across four successive mining stages, from the early bell-shaped excavations, through the large trapezoidal chambers of the Carol, Mihai and Unirea mines, to the modern room-and-pillar method of the Victoria and Cantacuzino mines, close to fifteen million cubic metres of salt have been removed. The surface above the workings continues to settle at measurable rates to the present day, while the pillars and the interlevel slabs between horizons close slowly under the action of salt creep. As part of the mine remains in tourist use, the long-term stability of the underground structures is a practical priority for the operator, not only a scientific problem.

Purpose of the thesis:

The thesis presents the first three-dimensional geomechanical model at the scale of the entire salt mine for Slănic Prahova, reconstructing the complete extraction history from 1835 to 2025 and forecasting surface and underground deformation to 2050. The model treats the salt massif, the overburden, the topography and the excavated voids of each historical sector as a single mechanical system, instead of analysing each stage in isolation.

Objectives of the thesis:

- Characterisation of the current stability state of the Cantacuzino mine, in terms of underground structural behaviour, surface deformation phenomena, and the zones affected by earlier extraction.
- Design of a methodology for building the geological model in Leapfrog Works, transferring it through Rhinoceros, then discretising it with Griddle and importing the geometry into the FLAC^{3D} code, while managing the interoperability problems that arise between modern systems and heterogeneous archival data.
- Calibration of the Norton power-law creep parameters at mine scale through back-analysis, using surface levelling measurements, underground displacement records and laboratory creep results together.
- Assessment of the current and future stability of the mine on the basis of forecast subsidence profiles, strength-to-stress ratios, the factor of safety, and the distribution of yielded zones across the full simulation period.

Research methodology:

The methodology combines reconstruction of archival data, three-dimensional modelling, numerical simulation and calibration against field data. Surface topographic maps from 1962 and 1992, archival plans of the Unirea, Carol, Mihai and Victoria mines, borehole logs and horizontal and vertical sections characterising the salt deposit, together with the monitoring of surface and slab subsidence at the Cantacuzino mine, were collected, digitised and brought into a common coordinate system. A continuous three-dimensional

geological model was built in Leapfrog Works using an implicit modeling method, exported to Rhinoceros for geometry repair, and discretized in Griddle as a graded mesh, with element sizes of 2 to 4 meters around the excavations and 10 to 15 meters towards the surface. The resulting grid, of approximately three million elements, was imported into FLAC^{3D}, where the long-term response was simulated with a Norton power-law creep model combined with a Mohr-Coulomb failure criterion. Each excavated object was tagged with its year of opening, so that the simulation activates the workings in chronological order across the 190 years of extraction. The creep parameters were first estimated from uniaxial laboratory tests, then refined through back-analysis against two independent datasets: the surface leveling records from 1994 to 2025 and the underground displacement records collected at the Cantacuzino mine from 2004 to 2019. Stability was assessed through the surface and underground displacements, the stress state, the strength-to-stress ratios, and a strength reduction method analysis used to locate the zones where a plastic mechanism would form first.

2. SYNTHESIS OF THE DOCTORAL THESIS

The doctoral thesis entitled *"Stability analysis of underground structures at the Cantacuzino Mine, Slănic-Prahova salt mine"* is structured in eight chapters, grouped into three parts. Part I covers the geological, hydrogeological, topographic, geomechanical, geophysical and mining foundations. Part II describes the stages of work for building the three-dimensional geological and numerical model. Part III presents the model calibration, the long-term simulation results and the assessment of protection measures.

Chapter 1, *Introduction*, establishes the research context. It reviews the creep mechanisms of rock salt and the constitutive models used to describe them, and summarises how numerical models have been applied to salt mines worked over time. The chapter identifies the two problems that motivate the work: the variability of the creep parameters between laboratory and field scale, and the computational difficulty of simulating the complex geometries of long-worked salt mines. It records that, despite three centuries of extraction, no three-dimensional creep model at the scale of the whole salt mine, covering all the extraction stages at Slănic Prahova, had previously been developed.

Chapter 2, *Geology, hydrogeology, and extraction history*, describes the deposit setting. The Slănic Prahova salt body is a lenticular mass of Miocene halite, about 2,700 metres long, between 800 and 2,300 metres wide and up to roughly 500 metres thick, composed mainly of halite with thin intercalations of anhydrite, gypsum, polyhalite and dolomite. The chapter presents the stratigraphy and tectonics of the Slănic syncline, the hydrogeological regime that governs dissolution and infiltration, and the four extraction stages. These extend from the early bell-shaped excavations, through the large trapezoidal chambers of the Carol, Mihai and Unirea mines, to the Victoria mine, opened in 1970 with the room-and-pillar method, and the Cantacuzino mine, worked between 1990 and 2019. The geometry and age of each stage determine several assumptions later adopted in the

model, since the older chambers continue to load the overburden above the more recent workings at the Victoria mine.

Chapter 3, *Geomechanical and rheological characterization of the rock salt; creep parameters*, presents the properties of the rock salt obtained from many years of laboratory testing and defines the creep parameters used in the simulation. The three stages of salt creep, primary (transient), secondary (steady state) and tertiary, are described and related to the long-term closure of the excavations, with secondary creep identified as the stage governing convergence over the time scales relevant to the mine. The Norton power-law creep model, combined with a Mohr-Coulomb failure criterion, is introduced as the framework adopted for the long-term response of the salt.

Chapter 4, *Current state and stability of the Slănic mine: analysis through analytical methods and monitoring data*, reviews the earlier analytical, empirical and numerical assessments of the Slănic mine and describes the observed underground response: pillar deformation, convergence between mining levels, slab cracking and the local roof falls recorded in the eastern part of the Cantacuzino mine. The chapter then presents the two monitoring datasets that constrain the model. The surface levelling network has been measured since 1994 and currently comprises 105 benchmarks distributed over the Victoria, Cantacuzino and Old Mines perimeters. The underground network, installed on the floors of horizons V to X of the Cantacuzino mine in 2004, measures the vertical convergence of the pillars and of the interlevel slabs, which are about eight metres thick and carry the main load between levels. The two datasets respond differently to variations in the creep parameters, in particular to the stress exponent, so that their combined use constrains the calibration more tightly than either dataset taken on its own.

Chapter 5, *The geological model and the geotechnical grid: the Leapfrog → Rhinoceros/Griddle → FLAC^{3D} workflow*, describes the construction of the three-dimensional model from sources spanning almost two centuries and differing widely in accuracy, format and coordinate system. The chapter presents the implicit modelling procedure in Leapfrog Works, the object hierarchy of the geological model, and the one-way transfer of the geometry to the geotechnical model along the Leapfrog → Rhinoceros/Griddle → FLAC^{3D} path. The compatibility constraints encountered between these systems and the practical decisions taken to preserve the geotechnical attributes during transfer are discussed.

Chapter 6, *Construction and calibration of the numerical model*, sets out the geometry, discretisation and calibration of the FLAC^{3D} model. To avoid boundary effects distorting the results, the model edges were extended beyond the worked zone by about 100 metres, measured from the model boundaries; the total model dimensions are 1,700 metres by 1,000 metres in plan and 400 metres in height, with the excavations located inside the model. The mesh was optimised so that the computed results reflect the field reality. It is dense enough to capture the stress concentrations around the excavations and the gradual convergence driven by salt creep, while remaining tractable for simulations over 215 years. A graded discretisation was adopted, with finer elements in the worked zones, in particular the

chambers, pillars and their intersections, and progressively larger elements towards the far field and the ground surface. A sensitivity study compared three meshes; the adopted model contains approximately three million zones, with elements of two by two metres in the near field of the Cantacuzino sector. In the absence of in-situ measurements of the natural stress state, the geostatic state was defined through a stress field in which the vertical component derives from the weight of the overburden column, while the horizontal components were set through a lateral earth pressure coefficient $K_0 = 0.7$, chosen on the basis of a sensitivity study (range analysed from 0.43 to 1.66). The Norton power-law parameters were first estimated from uniaxial creep tests, then refined through back-analysis against the surface levelling records (1994 to 2025) and the underground convergence records (2004 to 2019). The calibrated values are a stress exponent of 2.03 and a creep coefficient of $3 \times 10^{-25} \text{ s}^{-1} \cdot \text{MPa}^{-n}$. At the underground monitoring stations, the vertical displacements computed by the model reproduce the measured values with a deviation between 1.4% and 9.0%, below the 10% threshold; at the surface stations the deviation is larger, because surface levelling captures the integrated, far-field response of the overburden, while the underground benchmarks record the convergence between chamber and pillars directly.

Chapter 7, *Numerical results and long-term stability analysis*, presents the outcome of the calibrated creep simulation over 215 years, for the period 1835 to 2050. Surface subsidence develops progressively from the earliest extraction stages and persists long after the excavations are completed, centred on the Victoria sector, with a deepening settlement minimum and an increasingly steep radial gradient towards the centre of the subsidence trough. For 2025, after the close of extraction, the maximum settlement above the Victoria sector reaches about $-1,640 \text{ mm}$, while the Cantacuzino sector shows much smaller magnitudes, with a peak of around -600 mm . By 2050, the maximum vertical displacement remains concentrated above the Victoria sector and reaches about $-2,060 \text{ mm}$, corresponding to a mean settlement rate of around -17 mm/year for the interval 2025 to 2050. The geometry and position of the subsidence trough remain relatively stable while its magnitude increases progressively and the affected area continues to expand laterally. The maximum above the Victoria sector cannot be attributed to the recent excavations alone: the massive trapezoidal chambers of the Unirea mine and the old mines produced a long-term stress redistribution that continues to load the overburden and to accelerate the creep-induced closure of the newer underlying and adjacent levels. Underground, the forecast closure follows a persistent west-to-east gradient: at horizon VII the vertical displacements increase from about -100 mm in the west to about -550 mm in the east in 2025 and reach about -780 mm by 2050, while at horizon VIII they increase from about -80 mm in the west to about -460 mm in the eastern zone in 2025 and reach about -700 mm by 2050, with the maximum values consistently located in the eastern sector. The strength-to-stress ratio (SSR) computed at the pillar monitoring stations stays consistently above 2.8, with a maximum of about 3.6, while the lowest values, around 1.7, are confined to thin bands along the pillar edges and near the roof and floor. The fact that large displacements coexist with a high strength-to-stress ratio at the monitoring stations shows that the pillars undergo a controlled rheological deformation rather than brittle failure, with the load-bearing cores redistributing the lithostatic load and

Mohr-Coulomb failure remaining confined to the pillar perimeters. A strength reduction method analysis locates the zone where a global plastic mechanism would form first, above the Victoria sector. The displacement magnitudes obtained in the unstable state of this analysis are not physical, since the solution no longer reaches equilibrium once the strength is reduced beyond the point of failure; only the location and shape of the yielding zone are meaningful.

Chapter 8, *General conclusions, personal contributions and recommendations*, synthesises the results, lists the author's contributions and sets out recommendations for monitoring, protection measures and future research. The chapter highlights the main limitation of the model, which treats the salt as a continuous, homogeneous and isotropic medium and therefore cannot reproduce the discrete fractures observed in the eastern sector of the Cantacuzino mine, where it tends to underestimate the measured displacements. The strength reduction method is presented as an optimistic, instantaneous measure of the stability of pillars and slabs that does not capture the progressive development of failure through creep, thereby complementing the creep simulation without replacing it.

3. PERSONAL CONTRIBUTIONS

Writing the thesis had to confront a problem of its own, the absence of a centralised mine-scale database. What exists for Slănic Prahova is scattered across decades of geological prospecting, partial maps, hand-drawn mine plans, old reports and laboratory results from different years. Some of this survived only on paper, other parts were digital but incomplete, and a good share carried no reliable date, which made it difficult to place within the extraction sequence and, all the more, to model. The rock mechanics side had a gap of its own. No one had built a creep model for a Romanian salt mine over its whole working life, so there was no calibrated parameter set to start from. Everything had to be brought together before any real analysis could begin. The laboratory data were part of this effort. Starting from the steady-state portions of the uniaxial creep curves, the author computed the parameters A and n and fitted them to the Norton power law, a first estimate later corrected through back-analysis against the field measurements.

The main contributions of the author of this doctoral thesis to the studied field are the following.

- Systematisation and integration of the geological, topographic, monitoring and mining records of the Slănic salt mine into a single, attribute-traceable geological model, intended for the stability analysis of the underground structures and the ground surface over the period 1835 to 2025;
- Compilation and structuring of the borehole database starting from the historical borehole logs, including preparation of the collar, survey and geology tables, which were imported into Leapfrog Works and used to build the lithological geometry of the geological model;

- Conversion of the historical contour maps of the Slănic perimeter from 1962 and 1992 from analogue to digital format and their integration with modern photogrammetric elevation data in a common coordinate system (Stereo70, Black Sea reference datum);
- Digitisation of the archival plans of the worked sectors (Victoria, Cantacuzino and the Old Mines group, made up of the Carol, Mihai and Unirea chambers) and conversion of all two-dimensional cross-sections and level plans into three-dimensional objects integrated into the geological and numerical model;
- Calculation of the initial creep parameters A and n from the steady-state segments of the laboratory uniaxial creep curves, fitted to the Norton power law;
- Development and documentation of a multi-stage methodology that links the implicit geological model to the FLAC^{3D} geomechanical model, organised as a two-way update loop, together with an explicit account of its interoperability limits;
- A mesh sensitivity study, comparing three discretisation variants of the model, with near-field element sizes of 4 by 4 m, 3 by 3 m and 2 by 2 m and approximately 1.6, 2.2 and 3.0 million zones respectively, which established the graded mesh adopted for the calibrated model as the balance between the resolution needed to capture the stress concentrations and the creep-driven convergence around the excavations and the computation time required for the 215-year simulations;
- A sensitivity study of the initial stress state, in which the lateral earth pressure coefficient K_0 was varied from 0.43 to 1.66 to evaluate its influence on the forecast surface and underground displacements, leading to the adopted value $K_0 = 0.7$ in the absence of in-situ measurements of the natural stress state;
- Implementation of a chronological excavation activation procedure, in which each excavated volume carries the year in which it was worked, so that the simulation activates the excavations in sequence and reproduces the 190-year extraction history of the mine;
- Calibration of the Norton power-law creep parameters for the Slănic rock salt ($n = 2.03$, $A = 3 \times 10^{-25} \text{ s}^{-1} \cdot \text{MPa}^{-n}$) through back-analysis against two independent field datasets, the precision surface levelling records (1994 to 2025) and the underground convergence records from horizons VII and VIII (2004 to 2019);
- Three-dimensional numerical modelling (FLAC^{3D}) of the stability of the underground structures and the ground surface affected by the Slănic excavations, reconstructing the staged extraction over the 190 years between 1835 and 2025 and forecasting the surface and underground displacements to 2050;
- Stability analysis of the chambers and the load-bearing structures (pillars and interlevel slabs) of the Cantacuzino mine through the calibrated three-dimensional model, based on a set of indicators (surface and underground displacement, strength-to-stress ratios and yielded zones) and a strength reduction method analysis that locates the zone where a global plastic mechanism would form first;

- Statistical analysis of the surface subsidence records measured above the Old Mines, Victoria and Cantacuzino sectors, and of the convergence records measured between horizons VII and VIII of the Cantacuzino mine, and their use as independent datasets for the calibration and validation of the long-term forecast;
- Analysis of how the mines interact and influence one another, made possible by the single integrated model, in which the Unirea, Carol and Mihai workings load the Victoria deformation centre from above, while the Victoria and Cantacuzino fields connect along their southern boundary;
- Production of surface and underground vertical displacement maps from the numerical model, for the current state (2025) and the 2050 forecast, which provide a sound basis for the land-use restrictions and for the General Urban Plan (PUG) of the town of Slănic Prahova.

4. RECOMMENDATIONS AND RESEARCH DIRECTIONS

The recommendations follow directly from the stability analysis and combine immediate operational measures with subsequent directions of study.

- The Victoria and Unirea mines should receive the highest priority, since the analysis identifies them as the sectors that govern the global factor of safety and as the locations where a plastic mechanism would form first. Monitoring, reinforcement and land-use restrictions should be concentrated here first, followed by the eastern sectors of the Cantacuzino mine, where the fracture network recorded since 2004 may affect stability over the longer term.
- The surface levelling stations and the underground displacement stations should be maintained and, where possible, extended to cover further parts of the mine. Future campaigns should include measurements of horizontal displacement alongside the vertical ones, since the lateral component provides information about the development of the subsidence and about the asymmetric behaviour of some pillars. The accumulated monitoring records could then support a data-driven forecasting model trained to predict future displacements and flag anomalous trends, thereby complementing the numerical analyses, while the numerical model would remain the physical reference framework for interpreting the deformation mechanisms.
- Additional laboratory tests on samples from a wider range of locations, in particular from the Victoria and Unirea mines, would improve the description of the long-term creep behaviour and help explain why some zones are less stable. Direct in situ measurements of the natural stress state are recommended, for example through hydraulic fracturing, so that the assumed lateral earth pressure coefficient of 0.7 can be replaced by an empirically determined value in future models. Beyond these measures, the work points towards modelling the interaction between creep and fracturing in the fault zones of the eastern Cantacuzino sector, where a continuum model alone cannot reproduce the local damage observed.

- One concrete direction in this respect is the use of hybrid modeling that explicitly represents fractures. Unlike the continuum model used in the thesis, a hybrid approach combines the continuum behaviour of the salt massif with a discrete representation of the discontinuities, namely the cracks, fractures and faults of the eastern Cantacuzino sector. In this way, the displacements and stress concentrations along the fracture planes could be reproduced directly, and the underestimation of displacements observed in the fractured zones could be corrected.
- A second direction is the application of submodelling, in which the coarse-mesh overall model of the mine is progressively reduced to a zone of interest with a much finer mesh. The boundary conditions of the submodel, that is the north, east, west, south, bottom and top faces in FLAC^{3D} terminology, are extracted from the results of the coarse overall model and imposed as edge conditions for the smaller submodel. The procedure allows the computational effort to be concentrated on a restricted portion, for example a group of pillars or a fractured zone, and more accurate results to be obtained in that volume, without rerunning the entire 215-year simulation at fine resolution over the whole domain.