# Assessment of induced seismicity impact on multi-level mining structures in underground salt exploitation

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**Abstract.** Underground salt mining frequently relies on blasting techniques that generate shock waves with seismic characteristics. These waves propagate through the geological medium and undergo significant transformations at the boundaries of elastic deformation zones, manifesting as seismic waves capable of inducing dynamic loads on multilevel mining structures. Under such conditions, the structural stability of these works depends on the rock mass's capacity to dissipate the transmitted energy without exceeding the residual deformation threshold. Modelling the rock mass behaviour under dynamic loading conditions is central to seismic risk assessment. Findings indicate that seismic wave fronts may induce stresses that surpass the elastic limit, resulting in plastic or residual deformations. Repeated exposure to such phenomena, due to sequential blasts, can lead to the accumulation of irreversible deformations, ultimately affecting the structural balance and overall stability. The research underscores the necessity of optimizing the blasting regime to ensure that dynamic loads remain below critical thresholds for residual deformation. This approach aims to safeguard the integrity of multilevel mining structures and support the continued safe operation of underground salt extraction activities. The paper evaluates the seismic risks associated with successive blasting operations in salt deposits and their effects on overlying mining structures.

## 1 Introduction

The exploitation of underground salt deposits through multi-level mining operations is a critical component of the raw materials industry, particularly for applications in chemical manufacturing, food processing, and road de-icing. However, such activities inherently alter the stress regime of the surrounding rock mass, often leading to induced seismicity small to moderate magnitude earthquakes resulting from human activities. In salt mining, the relatively ductile and creep-prone nature of halite can complicate predictions of rock mass behaviour, especially in complex, multi-level extraction environments where stress redistribution is highly nonlinear [1].

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Induced seismic events pose a significant risk to the integrity and stability of mining structures, including pillars, ceilings, and access corridors, potentially endangering both personnel and equipment. These events can also accelerate the degradation of mine infrastructure and increase maintenance costs. Therefore, a comprehensive assessment of the impact of induced seismicity is essential for developing effective risk mitigation strategies and ensuring the long-term safety and sustainability of underground salt exploitation.

This paper present research study results with the aim to evaluate the effects of induced seismicity on multi-level salt mining structures through a combination of field monitoring data, numerical modelling, and geomechanically analysis. By examining the spatial and temporal characteristics of seismic events in relation to mining operations and assessing the response of mining structures to dynamic stress changes, the research seeks to contribute to the development of improved design and management practices in salt mining under seismic hazard conditions.

# 2 The impact of blasting on underground excavations

## 2.1 Factors to consider while doing underground blasting operations

Attaining the intended blasting outcomes depends on configuring the blasting settings to facilitate the separation of rock from the massif, minimizing over profiling and fracture zones, achieving optimal granulometry, and limiting the dispersion of the blasted rock mass.This assumes that the parameters for drilling and blasting are established in relation to the physical and mechanical properties of the rocks and the thermodynamics of the explosives employed:

- physical-mechanical and elastic properties, respectively natural fragmentation (on micro and macrocrystalline scale) of rocks;
- the section of mining works in the excavation and the depth at which they are located;
- number of free surfaces of the blasting area;
- drilling and blasting parameters;
- type of explosives and initiation;
- type of explosive load;
- size and quality of stemming area.

In the case of shaping the mined space within the salt mine, it is essential to consider the self-bearing capacity of the massif, as well as the need to maintain the cohesion of the massif to prevent a loss of resistance. The uniform connections among salt rock particles facilitate the systematic execution of drilling and blasting operations. The potential for consistently executing fixed-pattern blasts supports the mechanization of drilling and blasting operations[1, 2].

The salt mass exhibits perforability that permits the drilling of large-diameter and long holes through rotary drilling within a brief timeframe. The performance of the drilling technique correlates with the requirements of the blasting technique.

## 2.2 Particularities regarding exploitation in salt deposits

Underground mining operations modify the original condition of main stresses inside the massif, resulting in their redistribution and concentration at certain spots around the perimeter of the excavated area. When the magnitude of the stresses exceeds the mechanical strength of the rocks, they begin to deform or even fail. Monitoring the stability of resistance elements in multiple-level structures inside salt mines is essential to ensure low-risk salt extraction.

Consequently, based on topographic measurements, geo-mechanical observations, and the adjustment of geo-mining conditions with depth, safety measures are formulated yearly, and the dimensions of resistance elements are adjusted to ensure their stability. It should be noted that in evaluating the stability of resistance structures, only the alterations in the primary tensions within the massif are considered, neglecting the additional stresses induced by the seismic effects of the blasting operation on the contours of the mine workings.During displacement caused by blasting, a shock wave is generated that transforms into a seismic wave in the peripheries of the elastic deformation zone, exerting dynamic stress on underground excavations. Dynamic stresses induced by seismic waves in the structural integrity of subterranean excavations may result in strains that might ultimately cause damage over time. The components of resistance are modified to ensure their stability [2,6,7,8].

The studies conducted in the area primarily aimed to establish a link between the accepted oscillation velocity of particles in a medium where seismic protection is attained and the permissible seismic impact for that purpose. By acknowledging a certain seismic impact for a defined goal, the maximum allowable velocity of particle oscillations in the medium where the subterranean excavation occurs may be determined. Damage. The components of resistance are modified to ensure their stability.

The determination of oscillation velocities in compact media, such as underground excavations, necessitates a thorough evaluation of the strain characteristics of the surrounding rocks. In such media, if the maximum tension at the front of the seismic wave exceeds the tension threshold for elastic compression and recovery of rock, remnant strain may arise in the medium. The cumulative residue strain from repeated blasting may compromise structural stability by altering the internal tension state. Conditions of remnant rock strain that exceed the thresholds of elastic strain often appear as a relative strain greater than 0.0003, which may be induced by recurrent seismic impacts from subterranean explosions [1,2,3].

Regarding salt seams, the plastic condition intensifies with depth, resulting in elevated stresses and strains within the mass of resistant components. At a pillar loading of $T_{ef} = 0.7\ T_{lim}$ (limit load), the resulting stresses may lead to a loss of load-bearing capability, potentially resulting in material failure. In addition to the features affecting the stability of multi-level structures, the temporal impact of seismic effects resulting from repeated blasting operations is also considered.

Upon detonation of explosives, a transient elevation in tension arises in the adjacent massif, directly proportionate to the quantity of explosives used, thereafter followed by a pronounced hyperbolic decline with increasing distance from the explosion's epicentre. Increased tensions accentuate the internal crystalline flow in salt, hence enhancing the convergence rate, leading to the formation of fissures and exfoliation of the contour [4,5].

In contrast to friable rocks, salt exhibits pseudo-plastic behaviour when subjected to blasting, necessitating different blasting process principles compared to stratified sedimentary or igneous rocks. It is also noteworthy that salt inhibits the thermodynamic characteristics of explosions, hence affecting their performance. Given these factors and the issues related to the stability of floors and pillars in salt mines using the room and abandoned pillar approach, it is deemed essential to investigate the seismic impact of blasting on subterranean excavations.

The main outcome of the research was to determine explosive charges that may be detonated underground without compromising the integrity of structural elements, such as pillars and flooring.

The link between the evaluation of primary stress state alterations in the massif and the seismic impact of blasting operations allowed the selection of optimal and safe methods for the coordination and advancement of excavations.

### 2.3 Allowable relative deformation

Rock strain conditions within elastic limits often occur at stresses of 0.0001 to 0.0004, dependent upon the duration of mining operations, and specifically in salt mines, on the length of time mining occurs at the level where blasting is conducted. Consequently, based on the elastic properties of the subterranean rocks and the permissible relative strain, the maximum allowable velocity of particle oscillation inside the medium of the resistance structures has been determined, according to the general relation (1), and (2 ), [6,7,8]:

$$v_{\max.adm} = v_{\max} \cdot k_f \quad (1)$$

Where:

- $V_{max}$ - maximum velocity of oscillation of the medium in multi-level resistance structures;
- $k_f$ - reduction coefficient of the frequency of stress at a certain place at maximum value of the maximum oscillation velocity function, (see Table 1).

**Table 1.** Correction factor $\mathbf{k_f}$ based on annual blasting frequency

| Annual Number of Blasts | Reduction Coefficient (Kf) |
|---|---|
| ≤ 10 | 0.99 |
| 11–50 | 0.95 |
| 51–100 | 0.85 |
| 101–250 | 0.80 |
| >250 | 0.75 |

As shown in Table 2, an underground structure's classification and permissible relative deformation ($\varepsilon_{rc}$) are determined by its anticipated service life.

**Table 2**. Allowable relative deformation based on structure class and lifetime

| Class | Description | Service Life (years) | Allowable relative deformation ($\varepsilon_{rc}$) |
|---|---|---|---|
| I | Highly important structures | 10–15 | 0.0001 |
| II | Important structures | 5–10 | 0.0002 |
| III | Medium importance | 3–5 | 0.0003 |
| IV | Low importance | 1–3 | 0.0004 |
| V | Temporary structures | <1 | 0.0005 |

## 3 Evaluation of the seismic effect

### 3.1 Assessment of maximum permissible dynamic parameters

The seismic effect of blasting is evaluated based on the energy dispersed as seismic waves into the rock mass. The main assessment criterion is the particle oscillation velocity (V), which depends on several factors.

The maximum velocity of particle oscillation within the medium of resistance structures is dependent on the elastic characteristics of the perimeter of underground excavations, as described by the following general relation:

$$v_{\max} = f(v_L, v_T, \mu, \varepsilon_{rc}) \qquad (2)$$

Where:

- $V_L$ - propagation velocity of longitudinal waves, [m/s];
- $V_T$ - propagation velocity of transversal waves, [m/s];
- $\varepsilon_{rc}$ - relative deformation admitted function of the lifetime of mining at the level where blasting is performed;
- μ - Poisson's coefficient.

To ascertain the specific law governing the propagation velocity of oscillations resulting from the seismic effects of blasting operations, in relation to the geo-mining and technological conditions typical of the seams in salt mines, a series of underground measurements need to be performed. The measurements are conducted using seismometers that recorded the peak value of the longitudinal component of oscillation velocity.

The expression for particle oscillation in seismically protected structures can be represented as [6,7,8]:

$$v = f(Q, R, n, \Delta t, k, k_f, r_{em}) \qquad (3)$$

Where:

- Q - maximum amount of explosive per delay, [kg];
- R - distance from the explosion to the boundary of the elastic strain area, [m];
- n - number of delays;
- Δt - time delay between two successive delays, [s];
- k - a synthetic coefficient characterizing the geo-mining and technological conditions specific to each studied seam, determined via experimental methods. The average value of the determined coefficients is commonly employed in calculations for each experimentally determined measurement point. This value of the determined coefficients is typically used in calculations for each measurement point;
- $r_{em}$ - denotes the radius of the elastic strain area, measured in meters, (m).

Relations (4) and (5) present the factors that determine the distance from the explosion center to the boundary of the elastic strain area and the elastic strain radius.

$$R = f(h, l, r_{em}) \qquad (4)$$

Where:

- h = height of chamber, (m);
- l = width of chamber. (m);
- $r_{em}$ = radius of the area exposed to elastic deformations, (m);

$$r_{em} = f(V_L, Q_g) \qquad (5)$$

Where:

- $V_L$ = propagation velocity of longitudinal waves, (m);
- $Q_g$ = amount of explosive per hole, (kg).

Typically, blasts with micro delays are employed; therefore, the function f(n) for the reduction of the seismic effect must be considered. The equations for calculating the function f(n) are as follows:

$$f(n) = 1 - 12.9(\sum \Delta t)^2 \quad \text{for} \quad \sum \Delta t \le 0.15 \qquad (6)$$

and

$$f(n) = 0.275 / \sqrt{\sum \Delta t} \quad \text{for} \quad \sum \Delta t \succ 0.15 \qquad (7)$$

To obtain a precise assessment of seismic action, measurement points must be strategically positioned at the same level, above, or below the explosion center. This includes locations above and below the blasting operation level, along the axis of the rooms, at the base of the pillars, and, if feasible, in small pockets excavated at their base.

### 3.2 Determining the maximum permitted quantities of explosives

In determining the maximum allowable explosive quantities for detonation in salt mines, while considering the seismic protection of the inter-level floors and the abandoned pillars, the following factors were considered: the established maximum permissible seismic velocities, experimentally calculated synthetic coefficients k, dimensions of the rooms, pillars, and floors, as well as the duration of mining at the level where the blasting occurs. The mining duration is evaluated based on the development of each stage, depending on the interrelationship between production capacity, sales capacity, and market demand.

Based on the maximum permissible quantity of explosives and the length of mining at the level (refer to Table 2), the following performance requirements for the blasting operation can be defined:

- *suitable* for an up to ten-year mining of the level and *acceptable* for an over ten-year duration of salt mine activity;
- *suitable* for an up to five-year duration of mining of the level and *acceptable* for a five to one year duration, for salt mine activity;
- *suitable* for a one-year duration of mining of the level, *acceptable* or *relatively acceptable* for one to five years and, five to ten years respectively, for salt mines activity.

The integrity of underground mine workings is maintained when the residual stresses do not exceed 0.0002, which corresponds to a mining period of 5 to 10 years [1,3].. In the instance of a salt mine, if operations at a level extend beyond 5 to 10 years, it becomes evident that consecutive blasting may compromise the safety and integrity of the floors and pillars over time.

## 4 Field tests and results

The method of evaluating the seismic effect induced during the execution of blasting works in salt deposits presented in this article was tested under the operating conditions of the Ocnele Mari salt mine, Rm. Vilcea.

Three blasting operations were carried out, using seven seismic equipment at the first two blasts and nine equipment at the third blasts, located at different distances from the explosion site, at the base of the pillars or in the middle of the chambers between the pillars, obtaining 23 values regarding the oscillation velocity of the particles in the environment specific to the salt deposit. The salt mine uses the descending mining method, with rectangular chambers and square pillars. The mine holes are drilled in rows, starting from the bottom up [9].

<u>Technical specifications:</u>

Drilling parameters:

- room with straight ceilings;
- height in the shaft: h = 8 m;
- width: l = 15 m;
- hole diameter: 42 mm;
- hole length: 2,7 m;
- hole spacing: max. 1,0 m;
- row distance: max. 1,0 m;
- no. of holes: max. 162;

- no. of rows: max. 10;
- stemming length: min.1/3 of hole length;
- formation of a secondary free surface by executing a cut at the chamber's base using a cutting machine, resulting in a slot of 0.15 m width and 2.7 m in depth..

Explosive materials:

- explosive used: Riomax XE;
- initiation means: MMSED electric detonators type (18 delays), with a delay of 30 ms between two successive steps;
- quantity of explosive/hole: 1,2 kg;
- quantity of explosive used at a blast: max. 152 kg.

## 4.1 Test results

### *4.1.1 Drilling and blast parameters*

***Blast no. 1** – Level + 190 W, room 10 I from S-N, between pillars 10 I – 11 I* [10,11].

- explosive: Riomax XE Ø 32 X 200 mm.;
- number of blasted holes: 162;
- quantity of explosive/hole: 1,2 kg;
- total quantity of explosives: 152 kg.;
- total number of detonators: 162;
- 10 rows of holes were blasted, as follows:
  - ✓ row 1: 16+2 holes, 21,6 kg Riomax XE, delay no. 1;
  - ✓ row 2: 16 holes, 16,4 kg Riomax XE, delay no.2;
  - ✓ row 3: 16 holes, 14,0 kg Riomax XE, delay no.3. ;
  - ✓ row 4: 16 holes, 14,0 kg Riomax XE, delay no.4;
  - ✓ row 5: 16 holes, 14,0 kg Riomax XE, delay no.5;
  - ✓ row 6: 16 holes, 14,0 kg Riomax XE, delay no.6;
  - ✓ row 7: 16 holes, 14,0 kg Riomax XE, delay no.7;
  - ✓ row 8: 16 holes, 14,0 kg Riomax XE, delay no.8;
  - ✓ row 9: 16 holes, 16,4 kg Riomax XE, delay no.9;
  - ✓ row 10: 16 holes, 19,2 kg Riomax XE, delay no.10;
- quantity of explosives per delay: 21,6 kg;
- number of delays: 9.

Measurement places, velocity metrics, and the planar distance from the explosion's epicentre to the associated blast location are the following:

- $L_1$ : Pilar 10H, west side; R = 37,16 m;
  $V_R$=8,06 mm/s; $V_T$=4,57 mm/s; V=11,75 mm/s;
- $L_2$ : Pilar 13G, South side; R = 100,74 m;
  $V_R$=2,03 mm/s; $V_T$=1,33 mm/s; V=2,86 mm/s;
- $L_3$ : Pilar 12G, South side; R = 80,66 m;
  $V_R$=1,46 mm/s; $V_T$=1,21 mm/s; V=2,16 mm/s;
- $L_4$ : Pilar 12F, South side, ; R = 106,35 m;
  $V_R$=1,27 mm/s; $V_T$=0,70 mm/s; V=2,16 mm/s;
- $L_5$ : Pilar 11G, South side; R = 70,0 m;
  $V_R$=1,91 mm/s; $V_T$=2,41 mm/s; V=3,18 mm/s;
- $L_6$ : Pilar 10F, West side; R = 91,80 m;
  $V_R$=1,84 mm/s; $V_T$=0,83 mm/s; V=0,95 mm/s;
- $L_7$ : Pilar 10I, West; R = 23,5 m;
  $V_R$=0,95 mm/s; $V_T$=1,33 mm/s; V=0,19 mm/s.

***Blast no. 2** – Level + 190 W, room 11 I from S-N, between pillars 11 I – 12 I* [10,11].

The drilling and blasting data were similar to test blast no.1. Measurement places, velocity metrics, and the planar distance from the explosion's epicentre to the associated blast location are the following:

- $L_1$ : Pilar 10H, West side; R = 65,30 m;
  $V_R$=3,81 mm/s; $V_T$=3,68 mm/s; V=4,64 mm/s;
- $L_2$ : Pilar 10G, West side; R = 86,10 m;
  $V_R$=4,45 mm/s; $V_T$=3,30 mm/s; V=4,19 mm/s;
- $L_3$ : Pilar 13G, South side; R = 88,30 m;
  $V_R$=1,97 mm/s; $V_T$=1,78 mm/s; V=2,10 mm/s;
- $L_4$ : Pilar 12G, South side; R = 77,20 m;
  $V_R$=1,91 mm/s; $V_T$=1,33 mm/s; V=1,78 mm/s;
- $L_5$ : Pilar 11G, South side; R = 76,50 m;
  $V_R$=1,59 mm/s; $V_T$=1,91 mm/s; V=2,60 mm/s;
- $L_6$ : Pilar 10F, West side; R = 110,75 m;
  $V_R$=1,59 mm/s; $V_T$=0,83 mm/s; V=1,97 mm/s;
- $L_7$ : Pilar 10I, West side; R = 53,70 m;
  $V_R$=4,76 mm/s; $V_T$=2,86 mm/s; V=6,73 mm/s.

***Blast no. 3*** *– Level + 190 W, room 12 H from S-N, between pillars 12 H-13 H* [10,11].

- explosive: Riomax XE Ø 32 X 200 mm.;
- number of blasted holes: 162;
- quantity of explosive/hole:max. 1,2 kg;
- total quantity of explosives: 128 kg.;
- total number of detonators: 137;
- 9 rows of holes were blasted, as follows:
  - ✓ row 1: 15+2 holes, 20,4 kg Riomax XE, delay no. 1;
  - ✓ row 2: 16 holes, 13,6 kg Riomax XE, delay no.2;
  - ✓ row 3: 16 holes, 12,8 kg Riomax XE, delay no.3. ;
  - ✓ row 4: 16 holes, 12,8kg Riomax XE, delay no.4;
  - ✓ row 5: 16 holes, 12,8 kg Riomax XE, delay no.5;
  - ✓ row 6: 16 holes, 12,8 kg Riomax XE, delay no.6;
  - ✓ row 7: 16 holes, 12,8 kg Riomax XE, delay no.7;
  - ✓ row 8: 16 holes, 12,8 kg Riomax XE, delay no.8;
  - ✓ row 9: 16 holes, 18,0 kg Riomax XE, delay no.9;
- quantity of explosives per delay: 20,4 kg;
- number of delays: 9.

Measurement places, velocity metrics, and the planar distance from the explosion's epicentre to the associated blast location are the following:

- $L_1$ : Pilar 10H, West side; R = 83,65 m;
  $V_R$=2,54 mm/s; $V_T$=3,37 mm/s; V=5,02 mm/s;
- $L_2$ : Pilar 10G, West side; R = 87,80 m;
  $V_R$=5,21 mm/s; $V_T$=3,40 mm/s; V=7,62mm/s;
- $L_3$ : Pilar 11F, South side; R = 78,72 m;
  $V_R$=5,59 mm/s; $V_T$=5,08 mm/s; V=17,53 mm/s;
- $L_4$ : Pilar 13G, South side; R = 38,45 m;
  $V_R$=5,78 mm/s; $V_T$=7,68 mm/s; V=17,21 mm/s;
- $L_5$ : Pilar 12G, South side; R = 37,10 m;
  $V_R$=14,10 mm/s; $V_T$=6,35 mm/s; V=21,34 mm/s;
- $L_6$ : Pilar 12F, South side; R = 67,30 m;
  $V_R$=6,35 mm/s; $V_T$=4,13 mm/s; V=13,27 mm/s;
- $L_7$ : Pilar 11G, South side; R = 57,43 m;

$V_R$=7,94 mm/s; $V_T$=4,38 mm/s; V=14,29 mm/s;
- $L_6$ : Pilar 10F, West side; R = 100,30 m;
  $V_R$=4,70 mm/s; $V_T$=1,84 mm/s; V=6,92 mm/s;
- $L_7$ : Pilar 10I, West side; R = 89,54 m
  $V_R$=2,98 mm/s; $V_T$=2,98 mm/s; V=8,57 mm/s.

### 4.2 Establishing the amounts of explosives based on the allowable seismic level

Utilising seismic measurements related to peak particle velocity, the physical and mechanical parameters of the salt massif were determined: longitudinal wave velocity (VL) is 3300 m/s, transversal wave velocity (VT) is 1760 m/s, and Poisson's ratio (μ) is 0.3. The permissible deformation for a mine level's operational duration of 5 to 10 years is 0.0002. The reduction coefficient based on the number of blasts is $K_1$ = 0.9, and the elastic deformation radius is $R_{em}$ = 6.1 m. Consequently, the synthetic coefficient K was established at 120.7, alongside the maximum allowable peak particle velocity (Vmax) of 16.4 cm/s, ensuring the structural integrity of underground mining constructions (inter-chamber pillars and floors) against seismic impacts from blasting activities [10,11].

Considering the aforementioned parameters, the permissible maximum explosive charges for blasting, which guarantee the seismic protection of inter-chamber pillars and floors between levels, were determined under the conditions of utilising Riomax-type explosives and electric detonators with a 30 ms delay between successive stages in the Ocnele Mari Salt Mine for rooms featuring a straight ceiling with a width of 15 m and a height of 8 m, as presented in Table 3.

**Table 3.** Permissible maximum explosive charges blasted instantly and per delay

| $Q_{max.inst.}$ | $Q_{max.per\ delay}$ , [kg], depending on the duration of the blast ( the total amount of delays ∑Δ t, ms ) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kg E TNT] | 30 | 60 | 90 | 120 | 150 | 180 | 210 | 240 | 270 | 300 | 330 | 360 | 390 | 420 |
| 52 | 34 | 33 | 31 | 28 | 25 | 22 | 21 | 19 | 18 | 17 | 16,5 | 16 | 15 | 14 |

Where:

- $Q_{max.inst.}$ - the maximum amount of explosive allowed to be blast instantly – 52 kg.;
- $Q_{max.\ per\ delay}$ - maximum amount allowed to be blast per delay (34÷14 kg) corresponding to the duration of the blast (30÷420 ms)
- ∑Δt, is determined by considering the start of the blast as the first stage in the blasting circuit, regardless of its number, to which the value of the delay intervals between the following successive stages is added.

The use of the data in Table 3 is done as follows: for firing 10 rows of holes, using 10 delay steps (9 intervals) with a 30 ms delay between two successive steps, the result is a total duration of the blast of 270 ms, which corresponds to a maximum amount of explosive allowed to be used per delay of 18.0 kg. TNT equivalent.

## 5. Conclusions

The seismic protection of interconnected structural elements in salt mines may be accomplished by appropriately sized explosive charges to ensure oscillation velocities remain below the deformation threshold.

The suggested approach enables predictive assessment of seismic risk and optimization of blasting operations. Establishing maximum permissible dynamic parameters enables the secure extension of mining boundaries without compromising excavation stability. The methodology enhances safety standards, reduces maintenance expenses, and optimizes blast management.

The research presented in this paper revealed the complex link between generated seismicity and the stability of multi-level mining structures in underground salt extraction environments. The results indicate that seismic occurrences, even of low to moderate size, may substantially impact the integrity of structural components such as pillars, floors, and inter-level connections owing to cumulative stress redistribution and dynamic loading on the salt rock mass.

Induced seismicity should be regarded not just as a secondary effect of mining activities but as a principal consideration in design and operations. Consistent micro seismic monitoring, coupled with predictive numerical simulations, is crucial for the early identification of instability signs and the prompt execution of mitigation strategies.

In accordance with the study findings, the salt mines committed to each second year assess the seismic impact of blasting activities on the underground support structures to maintain their integrity and prolong the mines' operational lifespan.

In summary, including seismic hazard assessment into the design and management of underground salt mines may significantly improve operational safety, mitigate the risk of structural collapse, and prolong the operational lifecycle of multi-level excavation systems.

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