Revista Minelor – Mining Revue
ISSN-L 1220-2053 / ISSN 2247-8590
vol. 29, issue 3 / 2023, pp. 14-25

THE INTERACTION PRINCIPLE IN THE ASSESSMENT OF PILLARS' SECONDARY STRESS-DEFORMATION STATE

Mihaela TODERAȘ[1*], *Cristian IOSIF*[2]

[1]University of Petrosani, Romania, toderasmihaela@yahoo.com
[2]University of Petrosani, Romania, cristiiosif72@yahoo.com

DOI: 10.2478/minrv-2023-0020

Abstract: *In the field of mining, one of the exploitation methods that is still the most used in rock salt, potassium, and magnesium salt deposits is the method with the room and abandoned pillar. The salt mining method with rooms and pillars represents a unique spatial system for which the establishment of an optimal correlation between the parameters of the room, pillar, and rock massif is required in any given situation. Thus, the dimensioning of the most requested element in the system is followed, and depending on its parameters, the other parameters of the system are established. Considering the exploitation method with rooms and pillars, the pillars are certainly the elements that are subjected to the greatest loads. In the situation where the deep exploitation of salt is done with square pillars, the evaluation of the optimal parameters of the elements of the exploitation system requires: establishing the loads that appear in the surrounding salt massif (the natural stress state); the qualitative-quantitative determination of the way of distribution of the secondary stress state in the pillars; evaluating the bearing capacity of the pillars; and establishing their geometric elements. Solving this problem can be achieved by different methods: based on the theory of limit equilibrium, taking into account the effective stress in the pillars; methods of the mechanics of the continuous system based on the analytical models for evaluating the secondary stress and deformation state of pillars and floors; and numerical methods combined with the results and measurements from the laboratory and in situ tests. A methodology based on the pillar–room–salt massif interaction principle was proposed for the analytically achievable stability exploitation system of rock salt by the dry method as the depth increased. Applying this method, the secondary stress-deformation state in the pillar can be established by taking into account the rheological behaviour of the salt, changing the pillar shape, and the extraction technology. The presented algorithm can be extended in the field of exploitation, where the room and pillar exploitation methods are used.*

Keywords: *salt, pillars, stability, secondary stress-deformation state, interaction, rheological behaviour*

1. General information and statement of the problem

The correct dimensioning of rooms and pillars (safety pillars) presents a particular importance, both from the point of view of exploitation safety and the stability of the entire underground structure, the protection and rational exploitation of the deposit, but especially from the point of view of stability and protection of the day surface when measures are required to prevent the occurrence of surface land movements [1, 2, 3, 4]. Ensuring the stability of underground voids created by the exploitation of salt in a solid way requires the achievement of complex studies in order to understand correctly the geo-mechanical characteristics, the micro- and macroscopic scale behaviour of salt, and rocks where the deposit is located [5, 6, 7, 8, 9]; of particular importance in this regard is the study of the dilatancy phenomenon and especially the involvement of the time factor in order to establish the rheological characteristics and parameters, by means of which the time of keeping the stability of the underground structures can be appreciated during the exploitation period but also after its completion [10, 11, 12, 13, 14]. Given that the exploitation of salt deposits is currently taking place

[*] Corresponding author: Mihaela Toderaș, Prof.Ph.D / Mining Engineering, Surveying and Civil Engineering Department, University of Petrosani, Petrosani, Romania (University of Petrosani, 20 University Street, +40-741501143, toderasmihaela@yahoo.com)

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primarily at depth, with appreciable thicknesses, salt extraction is done in more levels with the coaxial arrangement of the rooms, so that the pillars that are left between them are precisely in prolongation, in order that the lithostatical pressure and the stresses that manifest upon them are transmitted coaxially [14], [15]. In the horizontal plane, pillars (pillars of protection) are left between rooms. In the vertical, it is necessary to leave some floors that have both the role of defining the height and especially the role of increasing safety in exploitation and pillar stability. The thickness of a floor between two rooms is determined according to the way that the exploitation is carried out, namely ascending (a method very rarely used in practice) or descending, which is frequently used. The pillars have the role of taking over the static loads given by the corresponding weight of the deposits themselves and the weight of the overburden rocks, preventing them from collapsing into the voids created by the carrying rooms and preventing the appearance of the displacements that would cause the occurrence of settlements and subsidence of the ground surface. However, because of this, the pillars must be properly sized; establishing the optimal dimensions is a very delicate problem that involves taking into account several factors, such as: the geological and petrographic characterization of salt; the mode of formation; the micro- and macroscopic characterization of salt; the presence of fluid inclusions and pores; the physical -mechanical characteristics of rock salt; deformation behaviour and the phenomenon of dilatancy; the time factor through rheological characteristics that play an important role in assessing the time in which the underground structure is stable etc. [3], [16, 17, 18].

In terms of safety and stability, the safety pillars must satisfy the strength requirements as well as the ones for deformation. Knowing the elastic limit and plastic limit of small deformations of rock salt (the material composing the pillar) and the determinations being based on laboratory tests, checks of the pillars could be performed by measuring the deformations at time intervals or by analytical calculations based on different computing hypotheses existing in the literature. If the measured deformations do not exceed the deformations appropriate to the limit of elasticity or to the limit of small plastic deformations, then the pillars have enough security and stability. Otherwise, there is a potential possibility that at any time the fissures, fractures, or cracks appear and sometimes can trigger a partial or total collapse of the pillars. Regarding the rock salt from Romania, the limits of elasticity and plastic deformation were established at 10 MPa based on laboratory tests [4], [12], [15], with a mean value of 2.5 MPa. If the salt in the pillar is located in the field of plastic deformations, another important factor that we have already mentioned occurs, namely time factor; this one causes the development of deformations even if the external loads acting on the pillar remain constant. In such a situation, the creep phenomenon of rock salt occurs [19, 20, 21, 22, 23]. In fact, this phenomenon has been studied in a laboratory since 1992 by the author. The studies were performed on different kinds of salt, with the results proving that if the samples are loaded beyond the limit of elasticity and through the limit of plastic deformations, an increase in the time of the deformations of the samples takes place [4], [14], [15], [24]. This variation of the deformations is mostly accompanied by the phenomenon of salt dilatancy.

For the rock salt from Romania, the data based on laboratory tests demonstrated the dilatant character of the salt's behaviour under load. The same dilatant character of salt was also mentioned by Penkova in his studies, which concluded that, during the fast triaxial tests on rock salt, the transversal deformations may exceed the axial deformations, so the salt is characterized by a pronounced phenomenon of dilatancy. The same dilatancy phenomenon of rock salt was described by Stavrogin (1967) and presented by Todorescu in [25]. Stavrogin shows that, for prismatic specimens of 15×15×30 cm and a load equal to $0.7\sigma_{rc}$ (where σ_{rc} is the uniaxial compressive breaking strength), the volume of specimens increased by 17 % over a period of 800×24 hours. Studies have shown that for rock salt from Romania, the maximum depth up to which it can be exploited in a solid way by the rooms and pillars method is 1,000 m; beyond this depth, the risks and technical and safety difficulties occur, so it is recommended that the exploitation should be carried out by dissolution, with the creation of caverns from which the brine is then extracted at the surface.

2. Interaction principle in the assessment of pillars' secondary stress – deformation state

Because the rooms and pillars method forms a unique spatial system of dry exploitation of salt, from the point of view of stability and reliability, it is obvious that an effective correlation between the geometrical parameters of its system and the surrounding massif is required. Generally, for each given situation (level, salt mine), the dimensioning of the most requested element in the system is looked at, and depending on its geometric elements, the other parameters of the system are established [1], [3], [19, 20, 21], [24, 25, 26]. Currently, the analytical way to assess the stability and reliability of the exploitation system of salt by means of a dry method is limited to the use of calculation methods based on the "limit equilibrium theory". These methods, precisely because of the principle on which they are based, present a number of disadvantages, among

Revista Minelor – Mining Revue
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which we recall: leading to an enlargement of the pillars and floors of a salt mine's first horizon; limiting the depth of exploitation by excessively increasing the size of pillars to the detriment of the rooms, resulting in a significant reduction in the salt extraction coefficient; failing to account for salt behaviour variations in correlation with the increase of exploitation depth and stresses in pillars; all computing relationships do not take into account the implications of the loading time, namely the rheological behaviour of salt (the long existence of salt and the changes that occur in the strength characteristics during the salt exploitation period) etc. In relation to the formulated underlines, it is believed that pillar dimensioning is a susceptible problem that requires corrections, improvements, and even the development of new and more efficient methods to facilitate the safe expansion of exploitation salt in depth. By virtue of the role of the pillars as elements of the rock salt exploitation method, they can be assimilated as a natural support system. As the pillars have a role as elements of the salt exploitation method, they can be assimilated as a natural support system. However, such a support system must be studied in the context of two conditions: 1) the amount of useful mineral substance (rock salt) stored in the pillar is minimum (obtaining a maximum coefficient of extraction); and 2) to assume and accomplish the role of ensuring the overall stability of a room, level, and implicitly of a salt mine. We believe that such an objective can be achieved on the basis of the principle of the interaction mechanism, that is, the communion of rock deformations around an underground excavation and the mounted support system. The evaluation of such a compound effect can be done by superimposing the rock deformation curve and the support system curve (Figure 1).

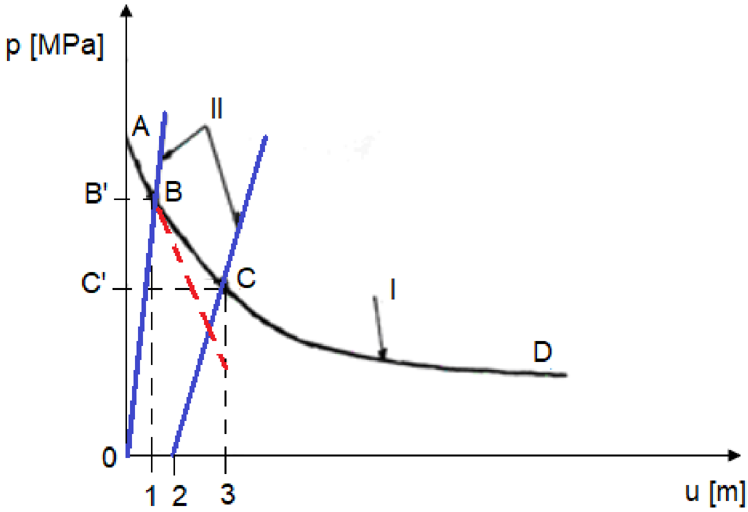

Figure 1. Principle of the interaction mechanism: I – relaxation curve; II – supports reaction curves (p – load on the support; u – displacement; AB – domain of elastic behaviour; BD – domain of inelastic behaviour; $\bar{0}1$ - elastic displacement; $\bar{0}2$ - rock displacement until the support is setting; $\bar{2}3$ - common displacement of rock and support; B – equilibrium point of the system in the elastic domain; C – the equilibrium point of the system in the inelastic domain; B' and C' - pressure values on the support (natural and artificial respectively).

The point of intersection of the two characteristic curves simultaneously expresses the magnitude of the loads and support deformation that characterize the stability state of the rock-support system. Such a principle, which has been used successfully in the design of underground artificial supports (wood, metal, concrete, etc.) [4], [14], [24], [27], [28], can also be applied in the case of natural supports and also for the situation of salt exploitation by rooms and pillars. The possibility of its application is also facilitated by the advantages that numerical analysis methods provide today. As a result, the method that we proposed consists of establishing: 1) the relaxation curve of salt, namely the deformation behaviour of salt on the contour of excavation (room–floor) following the load that acts on the exploitation system; and 2) the relaxation curve developed by the pillar, with the role of natural support as a result of the loads acting on the pillar. The analytical and graphical intersection of the equations of the two curves leads us to the equilibrium condition of the exploitation system. The proposed method was applied to Praid Salt Mine (Romania), where, in fact, both observations and in situ measurements of the secondary stress and deformation state in square-shaped pillars, as well as experimental research in the laboratory by modelling [14], [15], [24], were realized. It was considered that the part of salt to be left in the pillar (Figure 2) is subjected to a stress state even before the pillar is contoured, namely the natural stress state, which is well defined by its normal components σ_z, σ_y, and σ_x, which, in the context of elastic deformation behaviour, are determined by the known relationships:

$$\sigma_z = \gamma_a H$$
$$\sigma_x = \sigma_y = \frac{\mu}{1-\mu}\sigma_z = \xi_o \sigma_z \quad (1)$$

where: γ_a - the apparent specific weight of salt; μ - Poisson's coefficient; ξ_0 – the active pressure coefficient given by Poisson's coefficient:

$$\xi_o = \frac{\mu}{1-\mu} \quad (2)$$

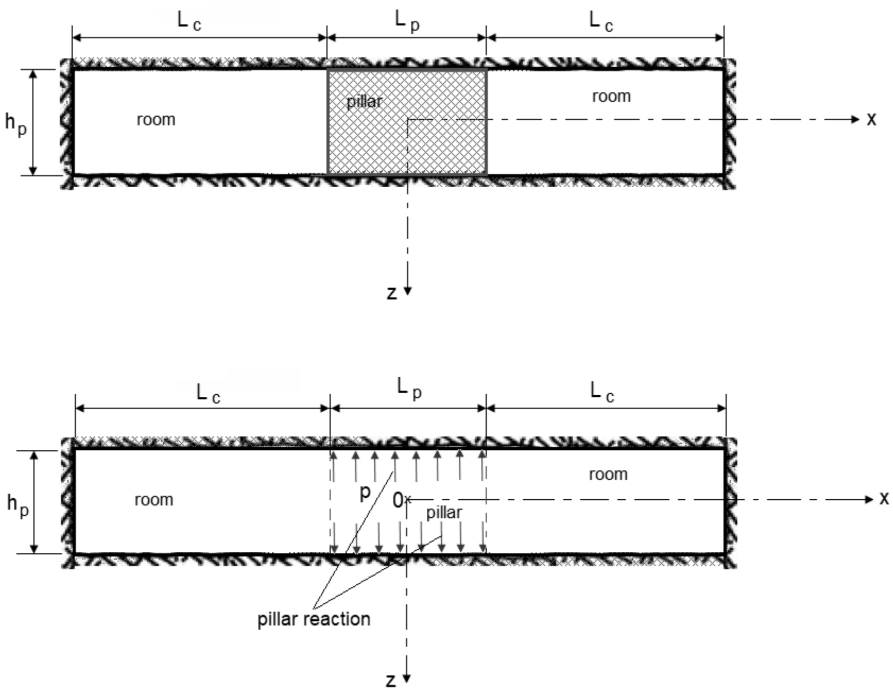

Figure 2. Cross-section through the small-rooms and square pillars exploitation system
(L_c – the width of the room; L_p – the width of the pillar; h_p – the height of the pillar)

Once the beginning of pillar contouring occurs, stress concentrations occur [27] and lead to the occurrence of the secondary stress state materialised in the salt part of the pillar through the normal components: σ_z^S ; σ_y^S and σ_x^S . Such a secondary stress state, through its components, undergoes changes with the beginning of the pillar contour in the sense that the lateral stresses σ_x^S and σ_y^S decrease and tend to zero; at the same time, the vertical respectively axial components increase, precisely because of the support function that the pillar begins to develop. These two sources of change in the equilibrium of the exploitation system (the natural state and the secondary stress state) act simultaneously in the way we have shown.

The principle of interaction was used to evaluate the stability of the proposed room-pillar system, respecting the following conditions: the coordinate system is the one shown in figure 2; the pillar has a role of support; the axis of the pillar is parallel to one of the main normal components of the natural stress state, namely at σ_z; the axial load of the pillar generates a uniform distribution of the axial stress (a fact confirmed by the in situ measurements [4], [14], [24]); the maximum load gives the main axial component of the secondary stress state σ_z^S . Once the pillar is realised, the normal components of the secondary stress state in the z, y, and x directions change according to the relations:

$$\Delta\sigma_z^S = \sigma_z - \sigma_z^S \quad (3)$$

$$\Delta\sigma_y^S = \sigma_y - \sigma_y^S \quad (4)$$

$$\Delta\sigma_x^S = \sigma_x - \sigma_x^S \quad (5)$$

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At the end of the achievement of the pillar, the secondary stress state becomes:

$$\sigma_z^S \neq 0 \quad and \quad \sigma_y^S = \sigma_x^S = 0 \tag{6}$$

In the context of plane deformation conditions, according to [27], it can be written that:

$$\Delta\sigma_z^S = \mu\left[\Delta\sigma_x^S + \Delta\sigma_y^S\right] \tag{7}$$

When we combine the relationships (3), (6), and (7), we get:

$$\Delta\sigma_z^S = \mu\left[\sigma_x - \Delta\sigma_y^S\right] \tag{8}$$

The axial load of a pillar is a consequence of its axial deformation. For a zero deformation of the pillar (namely, before any deformation occurs, at t = 0), in the conditions of a linear, homogeneous, and isotropic elastic medium, it follows that:

$$\varepsilon_z^S = \varepsilon_z \tag{9}$$

where: ε_z and ε_z^S are the normal components of deformation in the z direction due to the natural stress state (namely, the state of stress existing before the pillar execution) and the secondary stress state after the achievement of the pillar but before any deformation occurs:

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \mu\left(\sigma_x + \sigma_y\right)\right] \tag{10}$$

$$\varepsilon_z^S = \frac{1}{E}\left[\sigma_z^S - \left(\sigma_x^S + \sigma_y^S\right)\right] \tag{11}$$

According to the expressions (10), (11) and the relations (3) – (8), the condition (9) becomes:

$$\sigma_z^S = \sigma_z - \Delta\sigma_z^S \tag{12}$$

Considering the fact that:

$$\Delta\sigma_z^S = \frac{\mu}{1-\mu}\sigma_x \tag{13}$$

Finally, the expression of the preloading normal component of the secondary stress state after the axial direction of the pillar results in being:

$$\sigma_z^S = \sigma_z - \frac{\mu}{1-\mu}\sigma_x \tag{14}$$

which, as will be shown below, is a constant term in the equation of the characteristic reaction curve developed by the pillar as a natural support.

In order to establish the salt relaxation curve, the cross-section was considered for a pillar located between the two rooms, as presented in Figure 2. Geometrically, the situation taken into study was characterised as: small rooms and square pillars exploitation system, with the width of the rooms L_c = 16 m, the width of the pillar L_p = 14 m, and the height of the pillar h_p = 8 m. However, it was considered, as we have in fact mentioned, that the conditions of plane deformation and the salt from the pillar and around the pillar are characterised by the following values of the geo-mechanical properties involved in the computations: the apparent specific weight of the salt $\gamma_a = 2.1 \times 104$ N/m^3; the elasticity modulus E = 950 MPa; and the coefficient of Poisson's μ = 0.26. To obtain the relaxation curves for different depths (from 100 m to 1,000 m), it was necessary to determine the secondary stress state and the secondary displacement state that affect the pillars until failure. These were obtained by an analytical method using the finite element method [4], [15], and the values obtained for a depth equal to 100 m at Praid Salt Mine (Romania) have been verified by the obtained data from the measurements [4], [15], [28]. The ranges of variation of the axial component of the secondary stress state and the corresponding displacements obtained for different depth ranges are shown in Table 1.

Table 1. Values of axial load and displacements

Depth range H, m	**Value of axial component of secondary stress state that acts on the pillar, MPa**	**Displacements v, cm**
0 - 200	1.64	0.945
	0.795	0.713
	0.375	0.489
200 - 400	8.4	4.25
	6.16	2.62
	3.54	1.28
400 - 600	12.6	26.82
	11.5	1.8456
	9.45	0.7325
600 - 800	16.8	9.0012
	14.9	1.897
	13.65	1.275
800 - 1000	21.00	16.25
	19.4	3.0016
	17.85	1.655

Noting σ_{zp}^S ; σ_{yp}^S and σ_{xp}^S the main normal components of the secondary stress state after the pillar begins to be loaded, then:

$$\Delta\sigma_{zp}^S = \sigma_z^S - \sigma_{zp}^S \tag{15}$$

$$\Delta\sigma_{yp}^S = \sigma_y^S - \sigma_{yp}^S \tag{16}$$

$$\Delta\sigma_{xp}^S = \sigma_x^S - \sigma_{xp}^S \tag{17}$$

where: $\Delta\sigma_{zp}^S$; $\Delta\sigma_{yp}^S$ and $\Delta\sigma_{xp}^S$ are the increases of the main components of the stress state resulting from the axial load of the pillar.

While maintaining the same boundary conditions as in equations (6) and (17), the shortening *v* of the pillar at its half height (at h/2) due only to the axial stress is:

$$v = \frac{\Delta\varepsilon_{zp}^S\, h}{2} \tag{18}$$

where: $\Delta\varepsilon_{zp}^S$ is the change of the axial deformation in the pillar due to the action of the axial load and which, based on the boundary conditions, has the value:

$$\Delta\varepsilon_{zp}^S = \frac{1-\mu^2}{E}\Delta\sigma_{zp}^S \tag{19}$$

where E is the elasticity modulus of salt from pillar.

Based on the relationships (18) and (19), the following expression was obtained:

$$\Delta\sigma_{zp}^S = \frac{2\,E\,v}{h\left(1-\mu^2\right)} \tag{20}$$

Substituting the equations (14) and (20) in (15), the axial component of the stress state in the pillar was obtained:

$$\sigma_{zp}^p = \sigma_z - \frac{\mu}{1-\mu}\sigma_x - \frac{2\,E\,v}{h\left(1-\mu^2\right)} \tag{21.a}$$

or:

$$\sigma_{zp}^S = \left(1-\xi^2\right)\sigma_z - \frac{2\,E\,v}{h\left(1-\mu^2\right)} \tag{21.b}$$

Actually, this equation represents the reaction curve developed by the pillar, considered to have the role of natural support.

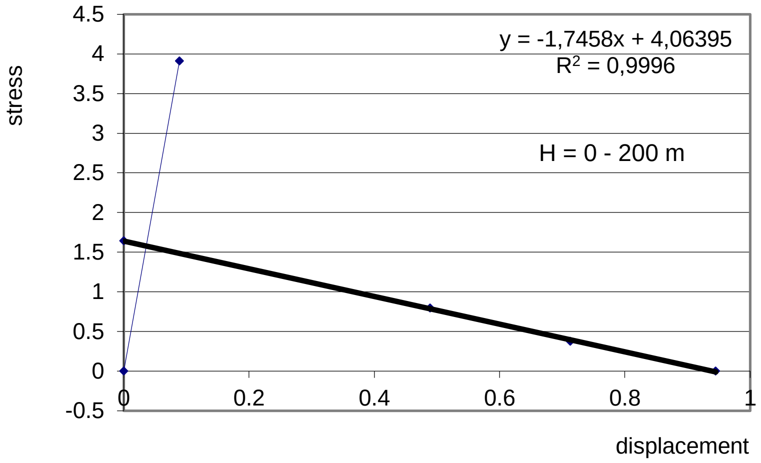
3. Results and discussions

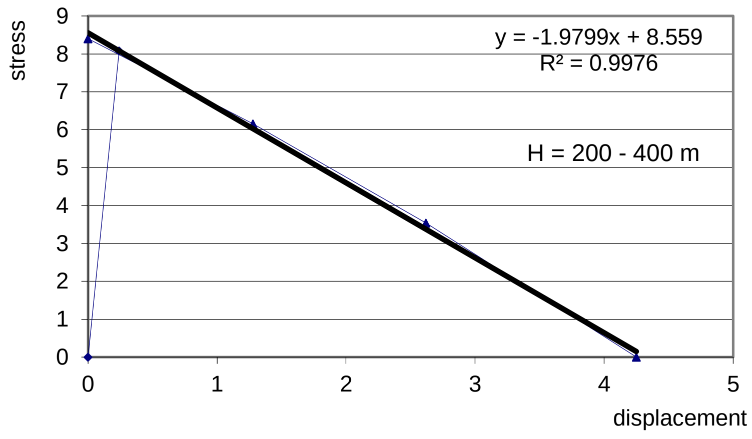
Table 2 shows the reaction equations developed by pillars at various depths in the case of Praid salt mine. In Figure 3, the intersection of these curves is shown graphically.

The intersection of the two types of curves (salt relaxation and reaction developed by the pillar) led me to obtain the axial stress value in the pillar and offered the possibility to assess its stability and exploitation system stability too. The stability of the pillar is conditioned by the value of the deformation obvious on the abscissa and the value of the load to which it is exposed, a value that is represented on the ordinate [4], [14], [15], [18]. From the analysis of the obtained data, it is found that, with the increase in depth, the stability conditions of the exploitation system change; these changes are made by the coordinates of the intersection points of the pairs of curves.

Table 2. Salt relaxation and pillar reaction equations

Depth range, H, m	Equations of salt relaxation curves	Equations of pillar reaction curves
0 - 200	σ = -1.7458 v + 4.06395	$\sigma_{zp}^{S} = 43.932v - 4 \times 10^{-16}$
200 - 400	σ = -1.9799 v + 8.559	$\sigma_{zp}^{S} = 30.778v + 10^{-15}$
400 - 600	σ = -1.8666 v + 12.773	$\sigma_{zp}^{S} = 30.166v$
600 - 800	σ = -1.8928 v + 17.098	$\sigma_{zp}^{S} = 26.098v$
800 - 1000	σ = -1.3136 v + 21.428	$\sigma_{zp}^{S} = 38.11v$





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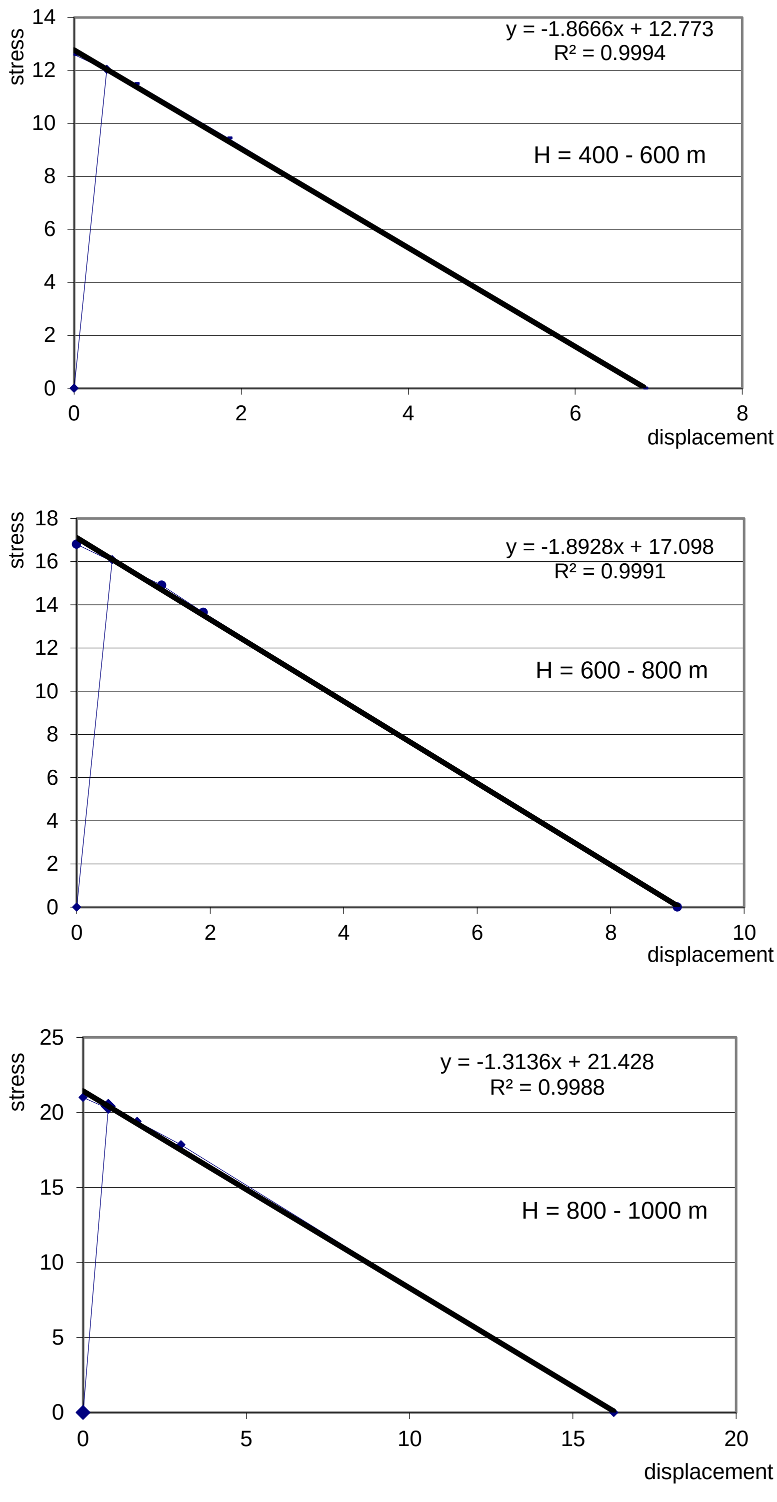

Figure 3. Intersection of relaxation curve and reaction curve of pillar: for H from 200 m to 400 m ÷ 800 m to 1000 m

Analysing the degree of stress on the pillar, it was found that the stress threshold of 0.3 is exceeded at a depth of 600 m. As a result, it was considered necessary to analyse the interval of 600-1000 m in the context of the increase in the height of the pillar to highlight whether in this area the pillars with dimensions of L_p = 14 m and h_p = 8 m, respectively, and h_p = 10 m and L_c = 16 m are stable or not. As a result, for the depth intervals specified in Table 2, the situation where the height of the pillars increased from 8 m to 10 m was also analysed.

The question of heterogeneity that confers a difference in pillar load can be approached in the manner of the presented method. Interesting conclusions lead us to the graphical analysis, which means that in the case of rock salt, as in the case of rock with pronounced plastic behaviour, the characteristic curve of salt deformation approaches the shape and value of a line. To a known extent, the interaction has opened and continues to maintain consciousness and clear the assessment possibility of directing the factors that determine the interaction phenomenon. The correlation of the same equations presented in Table 2 shows that the degree of pillar load, corresponding to the load threshold of 0.3 admitted by the rheological research [4], [15], [29], is exceeded starting with the depth of 600 m. For exploitation in depths below 600 m, we consider that changes to the dimensions of the exploitation system are necessary, namely: in the range of 600 m to 800 m, the dimensions of the pillars should be L_p = 14.5 m and h_p = 8 m, and in the range of 800 m to 1,000 m depth, the dimensions should be L_p = 15 m, L_c = 15 m, and h_p = 8 m.

The use of this method based on the principle of interaction can be performed by means of an algorithm that can be expanded not only for any situation (Figure 4) encountered in the Romanian salt mines but also for the ore exploitation situations where the exploitation method with rooms and pillars is applied. The findings and their implications should be discussed in the broadest possible context. Future research directions may also be highlighted.

The exploitation technology that is applied has an influence on the stability and, therefore, implicitly, on the secondary stress-deformation state of the elements of the chamber-pillar exploitation system. The technology used is the classic one: using the explosives' dislocation energy, which affects the bearing capacity of the pillars and floors by inducing, following the blasting of an artificial microcrack zone in these elements, the amplification of pre-existing natural microcracks at a depth of about 0.5 m at the pillars and 0.9 m at the floors. With the current exploitation technology, it is possible to go to a depth of 600 m, in which case the load on the pillars σ_{ef} would be about 30 MPa, the load degree Δ = 0.31, and the extraction coefficient C_e = 26 %. However, by changing the shape of the pillars (the special type shape with a rounded contact between the pillar and the floor) and applying a cutting technology with a drilling machine with a point attack or some saws with a long arm of about 4.5 m and cutting possibilities in the vertical plane, namely, a non-destructive technology that allows the creation of vaulted chambers or with rounded corners, over 800 m. For exploitation depths between 200 and 600 m, the variation of the effective loads (of the components of the secondary stress state) that return as a load confirms what was stated previously that the pillars will maintain their stability.

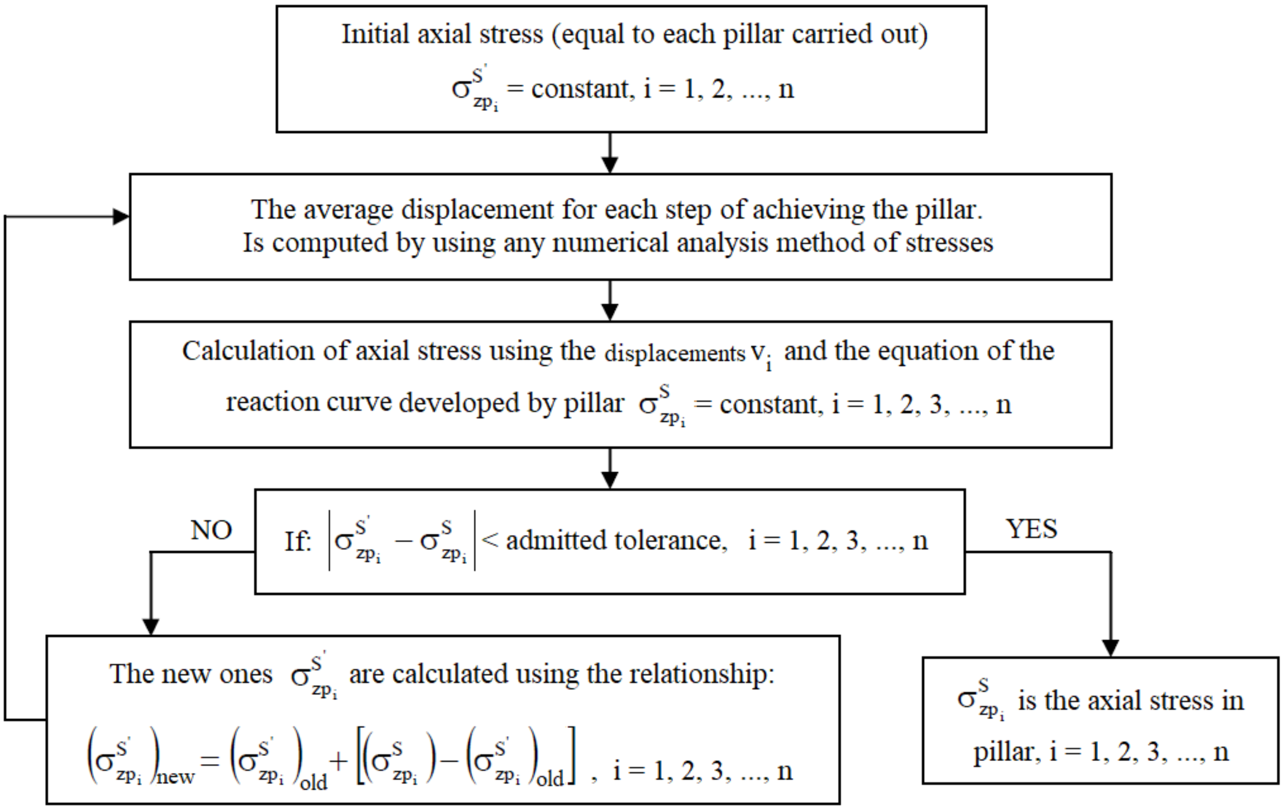

Figure 4. The proposed computing algorithm

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Along with the increase in the exploitation depth, the degree of stress on the room-pillar exploitation system also increases, and at the same time, the deformation process intensifies. The average strain rate increases, the breaking strain value decreases, and the stability time decreases. A modification of the extraction technology is also required in order to improve even more significantly the stability conditions of the chamber-pillar system below the depth of 600 m and above 800 m.

In the calculations of salt massif stability, its essential features must be evaluated, namely the rheological properties, its nonlinear character of behaviour σ - ε and the dilatancy phenomenon under the action of shear stress. In the case where the state equation (namely, the behaviour equation) doesn't describe the three stages of creep, then to be able to resolve the stability problem, first the stress–deformation state must be established, and then the long-term strength condition is imposed. As a long-term strength condition, the criterion that satisfactorily characterises the strength of salt under an instantaneous load can be used. In the condition of the salt's strength, the long-term strength value will be introduced instead of the instantaneous characteristics (t = 0).

The magnitude of the rheological deformations of rock salt raises the question of the predominant role of the rheological characteristics of this material in the study of the stability of underground structures. In the vicinity of underground excavations and in saliferous geological formations (domes, strata), the field of stress develops very slowly over time, which allows it to approach the state of evolution through creep. To assess the stability of underground structures made of salt massif, first understand salt behaviour at both the micro- and macro-structural scales; microscopic analyses allow the identification of neo-formation minerals. For a better understanding of the rheological behaviour of salt and for a complete analysis of the stability of an underground structure achieved in salt in its exploitation by solid way, the following scheme was proposed (figure 5); this scheme shows the main stages of study that must be respected or taken into account in such an analysis.

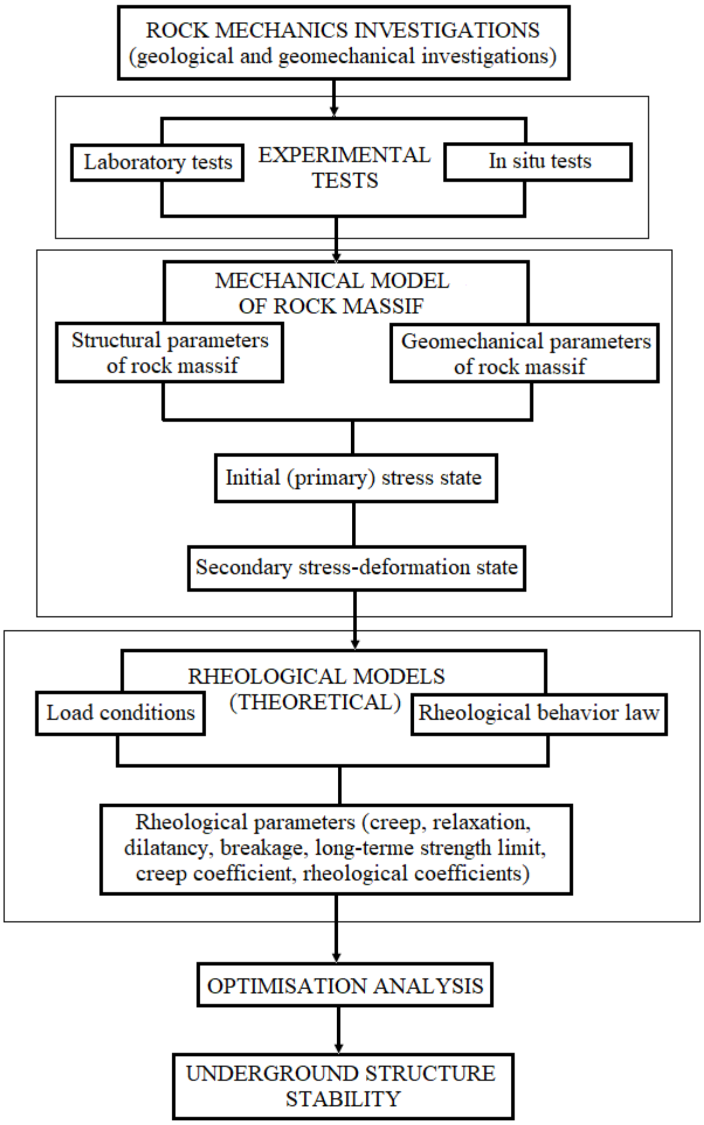

Figure 5. Stages of stability analysis of an underground structure

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4. Conclusions

The proposed methodology offers the possibility of an analysis of the unfavourable non-uniformity of the pillar geometry (not the same dimensions), the unfavourable implications of their non-coaxiality, and the pillar asymmetry over the main axis of the mining field. At the same time, it offers the possibility of assessing the stress state in pillars, meaning that, if in the design, a symmetry is not maintained in relation to the centre axis of the mine, then the central pillars may act on an identical stress state that differs from the one on the marginal pillars - a problem that can be solved by expanding this method.

This method, based on the principle of interaction, through the algorithm proposed for any situation in the salt mines in Romania, can be extended and used in the case of the exploitation of ore deposits when using the method of exploitation with rooms and pillars.

Acknowledgements

This work was developed from a theoretical and experimental study of the rocks and mine workings at Praid Salt Mine, Romania. All the observations and experimental research in the laboratory were realised by M.T. I would like to express my gratitude to the University of Petrosani, which provided the necessary equipment to perform in situ measurements and all laboratory tests in prior experimental research leading to the results synthesised in this article.

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