STABILITY ANALYSIS OF THE PRAID SALINE STRENGTH STRUCTURES, IN THE CONDITIONS OF THE ROADHEADERS ROCKS SALT CUTTING

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Abstract

Rock salt deposit mining of the Praid saline is provided by quadrangular long rooms and pillars. Because of the strength structure reduction at the same time with the deep mining of the rock salt deposit, the roadheaders mechanical cutting is proposed. In this paper, in these conditions, the rooms and pillars and ceilings stability is analysed with the aid of certain analytical methods and with the finite element method.

***Key words**: rock salt, room, pillar, ceiling, analytical methods, finite element, safety coefficient*

1. Geological and geo-mechanical characterization

Praid Basin is situated on the eastern frame of the Transylvanian Basin, at the Gurghiu Mountains base and which composes a well defined micro-region, named " Zona Ocnelor de Sare" [6].

Praid rock salt massive belongs to a diapiric anticlinal structure which is developed along a length of about 25km, from Săcădat (north of Sovata) to Corund. In the frame of this anticline, the rock salt rifts to the medio-pliocene curvatures into two diapiric pillars: Sovata and Praid (Fig. 1).

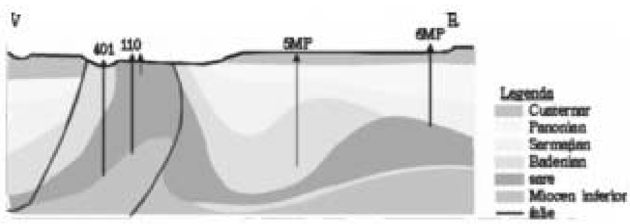

Fig.1. **Geological vertical cross-section on the Praid rock salt massive [1]**

The rock salt from the Praid diapiric pillar cambered the meadows and terraces of the Târnava Mică şi Corund valleys, on a surface of about 1,5km^2, creating a dome morphological shape, with 100m maximum height, suffering a fast degradation process (about 30000 tonnes of rock salt/year) [6].In the horizontal plane, the rock salt body has a quasicircular shape, slightly ellipsoidal, with 1.2 and 1.4km diameters. On the basis of the structural drills, it is appreciated that it has an overburden of 2.6-2.8km, being the most developed and robust diapiric rock salt body from Romania.

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Besides the physical and mechanical characteristics (Table 1), some rheological properties of the rock salt were determined. From the creep tests, the following conclusions result: as the loading rate increases, the deformation speed grows as well; the Praid rock salt shows all three creep characteristic zones, with the loading rate $\Delta \leq 0,3\ \sigma_{rc}$; relative instability zone, Δ = (0,3-0,45) σ_{rc} ; instability zone, $\Delta >$ 0,45 σ_{rc} . From here results that in order to obtain a stability for an unlimited time of the strength elements – pillars and ceilings – these could not be charged at stresses that surpass 30% σ_{rc} , namely $\sigma \cong 8000$ kN/m^2. Dilatant limit of the rock salt is situated in the proximity of the value of $\sigma^* = 55$ kN/m^2, point over beginning the fissuring process, depending on the loading rate. It demonstrates that for the instantaneous loading case, produced mainly on the ceilings, these could not be charged over 55% from the failure loading [6].

Because the roadheader will be used in the new mines zone, at the level +188m (level VI), which is situated at the depth of about *H*=320m measured from the surface, where the mining is made with rooms and long pillars method and will continue in depth, for the stability calculus it will be taken into consideration also the depth of *H*=380m, corresponding to the level +128m.

Because of the fact that the rock salt cutting will be provided without massive fissuring, it will be taken into consideration for the stability calculus, the massive cohesion value, resulted by the drawing of the limit stresses circles of the enveloped curve. Also, the weakening structural coefficient will be taken into consideration, in function of the fissuring distance (Figure 2).

Table 1. **Average values of the Praid saline geo-mechanical characteristics[6]**

Nr. crt.	Characteristic	U/M	Determination method	Average values			
				Level.+448 100m overburden, 2003	Level.+230 300m overburden, 2005	Level.+188 320m overburden, 2012	Average values, accepted for the calculus
1	Specific weight	kN/m^3	pycnometer	21,4	21,4	20,5	21,4
2	Apparent specific weight	kN/m^3	linear sizes	21	20,2	20,1	21
3	Uniaxial compressive failure strength	kN/m^2	cylinders	22000	26000	21300	22000
4	Tensile failure strength	kN/m^2	Brazilian method	1000-1100	1300	1218	1200
5	Flexural failure strength	kN/m^2	cylinders, prisms	2000	2000-2200	2100	2200
6	Shear failure strength	kN/m^2	cylinders	2200	2600	1900	2000
7	Cohesion	kN/m^2	graphical, analytical	4000	4000	4000	4000
8	Internal friction angle	grade	graphical, analytical	26-30	30	30	30
9	Young modulus of elasticity	kN/m^2	characteristic curve, loading-unloading	3150000	2750000	2950000	3150000
10	Poisson ratio	-	characteristic curve, loading-unloading	0,24	0,24	0,24	0,24
11	Elastic limit stress	kN/m^2	characteristic curve	1000-2000	500	-	2500
12	Dilatant limit	$\% \sigma_{rc}$	dilatant curve	65	55	-	65
13	Failure deformation	%	analytical	5	7	5 - 6	5
14	Longitudinal waves velocity	m/s	experimental, analytical	4000	5000	-	4000
15	Weakening structural coefficient C_S	-	fissuring size	0,6	-	0,66	0,66

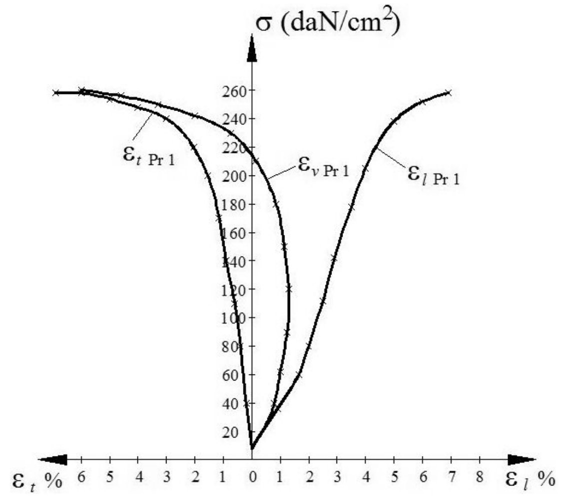

Fig.2. **Dilatant curve of the Praid rock salt, level VI (+188m) [6]**

2. Analytical checking of the mining rooms stability

2.1 Pillars stability checking

In this paper, the pillars stability check will be made, using different calculus analytical methods, validated by the reality.

- ***L.D. Şeviakov' methodology***

In the case of the quadrangular rooms mining method, used at the Praid saline, the safety coefficient is determined with the following relation:

$$n = \frac{L_p \cdot \sigma_{rc}}{\gamma_{st} \cdot H \cdot \left[L_c + L_p \cdot \left(1 + \frac{\gamma_s \cdot h}{\gamma_{st} \cdot H} \right) \right]} \quad (1)$$

where: L_p represents the pillar width (L_p=20m); σ_{rc} - compressive failure strength; γ_{st} - specific weight of the cuverture rock strata (in our case is the roc salt massive, thus: $\gamma_{st} = \gamma_s$); H – depth of the superior part of the pillar by report to the surface; L_c – room width (L_c=20m); h- room height (h=10m).

After the calculus achieved with the aid of the relation (1): for the level +188m (level IV), where H=320m results n=1.6; for the level +128m (level IX), where H=380m results n=1.4.

- ***V.V.Sokolovski-K.V.Ruppeneit' method***

The safety coefficient is calculated with the following relation [2]:

$$n = \frac{\sigma_{\lim}}{\sigma_{ef}} \tag{2}$$

In the conditions of the quadrangular pillars, the limit stress and the effective stress are calculated with the following relations:

$$\sigma_{\lim} = \frac{C_m - C_s}{\alpha} \cdot [2 + F(\alpha, \varphi)] \tag{3}$$

$$\sigma_{ef} = \left(1 + \frac{L_c}{L_p}\right) \cdot \gamma_a \cdot H \tag{4}$$

In the previous relations: L_c=20m; L_p=20m; γ_a apparent specific weight; H- depth of pillar base by report to the surface; C_S - weakening structural coefficient (C_S=0.66 - see Table 1); C_m – apparent cohesion of the massive (graphical- analytical determination from the cycloidal envelope: C_m=6400kN/m^2); $F(\alpha, \varphi)$ - a function value dependent of the α coefficient ($\alpha = 2$ - is the rapport between the weight and the height of the pillar) and the internal friction angle φ. It is established by the graphical way, $F(\alpha, \varphi) = 26$ (for $\varphi = 30^o$ and C=4000kN/m^2 – see Table 1).

Because at the Praid saline, above the level +188m (level IV) were mined 5 levels, of which 3 levels with I_c=12m and h_p=8m and 2 levels, with I_c=10m and h_p=10m, and above the level +128m (level IX) will be mined three other levels, with I_c=10m and h_p=10m, then, from the effective stress value σ_{ef}, it is necessary to extract the loading generated by the mined levels, in according with the following relation:

$$\Delta P = n_i \cdot (I_c + h_p) \cdot \gamma_a \cdot (1 - \eta) \tag{5}$$

where: n_i represents the mined level number; I_C and h_p – rooms height, respectively ceilings thickness; γ_a - apparent specific weight; η - rock salt recovery ratio.

Therefore, for the level +188m (level VI), ΔP_{VI} = 1050kN/m^2, and for level +128 m (oriz.IX), ΔP_{IX} = ΔP_{VI} = 1680kN/m^2. In these conditions, the real stress will be:

$$\sigma_{real} = \sigma_{ef} - \Delta P \tag{6}$$

From the relation (4), for the calculus of σ_{ef}, results that: for H=320m, σ_{ef} =13440kN/m^2 and σ_{real} = 12390kN/m^2; for H=380m, σ_{ef} = 15960kN/m^2 and σ_{real} =14280kN/m^2.

Taking into account the previous established relations, it is obtained the following value for $\sigma_{\lim}$ = 59140kN/m^2. Finally, the safety (stability) coefficients of the pillars, at the two mining levels taken into considerations are: for H = 320m, n = 4, and for H = 380m, n = 4.1. Considering the safety coefficients value, it could be see that, in the two analyzed situations, the pillars will be stable for a period of more than 20 years.

- ***Stamatiu' methodology***

Safety (stability) coefficient is determined with the relation [11]:

$$n = \sqrt{\frac{\sigma_{rc}^2 \cdot (d_1 - 2 \cdot h \cdot ctg\psi)}{\gamma_a^2 \cdot h \cdot H^2}} \tag{7}$$

where: σ_{rc} represents the compressive failure strength; d – pillar width; h – pillar height; γ_a - apparent specific weight; $\psi = 45^o + \frac{\varphi}{2}$; φ - internal friction angle.

Using the relation (7), for the Praid saline conditions, it is obtained: for H=320m, results n=3.0; for H=380m, results n=2.5.

Taking into account the calculus results obtained by previous analytical methods, it could be *concluded* that, generally, regardless of the applied checking method, the pillars are stable.

2.2 Stability check of the sublevel ceilings

- ***Stability check of the sublevel ceilings considered as embedded plates***

To check if the ceiling thickness h_p satisfies the stability condition, it is established the safety coefficient n [2]:

$$n = \frac{B \cdot a \cdot h^2 \cdot \sigma_{rt}}{L_c^2 \cdot (\gamma_a \cdot h + q_s)} \tag{8}$$

where: h is the pillar height; L_c – room span; γ_a - apparent specific density; σ_{rt} - tensile failure strength; B – coefficient depending on the plate shape (for the quadrangular shape, B=2.21); a- coefficient resulting from the characteristic curves (for rock salt, a = 1.3); q_s – supplementary loading generated by the roadheader weight [7], trucks and others equipments, stocked rock salt, etc.

As a result of the calculations with the aid of relation (8) arises a safety coefficient $n \cong 4$, value that express a ceilings stability for a period of more then 70 years.

- ***Shear loading check***

Checking the ceiling thickness at the shear loading is made in function of the safety coefficient established with the relation [2]:

$$n = \frac{\tau_{\lim}}{(\tau_{\max})_M} \tag{9}$$

In the previous relation, the limit shear strength of the ceiling is calculated thus:

$$\tau_{\lim} = C \cdot \frac{1}{K_i} \cdot \frac{\cos\varphi}{1-\sin\varphi} + \frac{\sin\varphi \cdot \cos\varphi}{1-\sin\varphi} \cdot \gamma_a \cdot h_p \tag{10}$$

and the maximum stress value of the most dangerous point is expressed with the relation:

$$(\tau_{\max})_M = \frac{3}{2} \cdot \frac{\zeta \cdot q \cdot a}{h_p} \tag{11}$$

where: C is the rock salt cohesion of the ceiling; φ - internal frictional angle of the ceiling rock salt; γ_a - apparent specific weight; h_p – ceiling thickness; K_i – reduction coefficient of the parameters because of the clay parting ($K_i = \sigma_{rc} / \sigma_{rc,neom} = 1.06$); σ_{rc} - rock salt compressive strength; $\sigma_{rc,neom}$ - rock salt compressive strength including the clay parting [2]:

$$\sigma_{rc,neom} = \frac{\sigma_{rc}}{1 + \left(\frac{\sigma_{rc}}{\sigma_{rc,\arg}} - 1 \right) \cdot \frac{h_{i,\arg}}{h_p}} \tag{12}$$

$\sigma_{rc,\arg}$ represents the clay parting compressive strength ($\sigma_{rc,\arg}$= 3100 kN/m^2); $h_{i,arg}$ – thickness of the clay parting ($h_{i,\arg} = 0.1$ m); a – distance between the abutment axis (a=40m); ξ - coefficient depending on the ”room– pillar” system width (after *Timoşenko-Kruegel*, it has the value $\xi = 0.4$); q – specific loading on the ceiling ($q = \gamma_a \cdot h_p + q_s$, where q_s is the supplementary loading generated by the equipments, etc.).

As a result of calculations results the value of the stresses $\tau_{\lim}$ =6718kN/m^2 and $(\tau_{\max})_M$ =984kN/m^2, corresponding to a safety coefficient n = 6.8.

- ***Checking with the Ennour' methodology***

This methodology is applied in the thick plate theory, namely when the rapport between the plate thickness and its span is more than 1/5. In these cases the effect of the shearer forces, neglected in the thin plates, becomes preponderant. Therefore, in the case of Praid saline, this rapport is $\frac{h_p}{L_c} = \frac{10}{20} > \frac{1}{5}$, and the ceiling is checked by the thick plates theory, in according with idea that stability exists when the following condition is accomplished $\tau_{xy\max} < \tau_{xy}$; where, the maximum shear stress is [3], [4]:

$$\tau_{xy\max} = \frac{3}{4} \cdot \frac{\sigma_v \cdot L_c}{h_p} \tag{13}$$

and the effective shear stress has the form:

$$\tau_{xy} = \frac{H_f}{h_p} \cdot tg\varphi + C \tag{14}$$

where: L_c is the room span (L_c=20m); h_p – ceiling span (h_p=10m); φ - internal friction angle; C- cohesion; γ_a - apparent specific weight.

Vertical stress (the specific loading on the ceiling) has the value $\sigma_v = 410$ kN/m^2 and it is expressed by the relation:

$$\sigma_v = \gamma_a \cdot h_p + q_s \tag{15}$$

In the relation (14), confinement horizontal stress is $H_f = \sigma_h \cdot h_p$, where the horizontal stress is expressed thus:

$$\sigma_h = k_o \cdot \frac{\mu}{1-\mu} \cdot \gamma_a \cdot H \tag{16}$$

In the relation (16) we have: coefficient of stresses concentration $k_o = (h_p + I_c)/h_p = 2$; I_c - room height; μ - Poisson ratio; H –mining depth (380m, for the level +128m- level IX).

As results of calculations $\tau_{xy\max}$= 615kN/m^2 < τ_{xy} = 6910kN/m^2, which leads to the conclusion that the imposed condition is accomplished and the ceiling stability is ensured.

- ***Checking with the Coates' methodology***

According to this methodology, the ceiling stability is ensured if the following conditions are accomplished:

$$\tau_{\max} \leq \sigma_{rf} \text{ and } \sigma_{t\max} \leq \sigma_{rt} \quad (17)$$

where: σ_{rf} is the shear failure strength of the rock salt; σ_{rt} - tensile failure strength of the rock salt; $\tau_{\max} = \tau_{xy\max}$ = 615 kN/m^2 is determined with the Ennour' methodology [3], [4].

The maximum tensile stress is calculated with the relation:

$$\sigma_{t\max} = \frac{1}{2} \cdot \frac{\sigma_v \cdot L_c^2}{h_p^2} = 820\text{kN/m}^2 \quad (18)$$

where the value of $\sigma_v = 410$ kN/m^2 is calculated with the Ennour' methodology [3], [4], and L_c is the room span and h_p is the ceiling thickness.

Taking into consideration the obtained results provided by analytical methods, regardless of the applied checking method, it could be concluded that sublevels ceilings are stable for thickness of 10m.

3. Finite element analysis of the stress-strain state of the support structure (pillars and ceilings) from Praid saline, level +188m

CESAR-LCPC code was used in this work to achieve the finite element models in the plane strain and the Mohr- Coulomb elasto – plastically without hardening behaviour hypothesis [5],[8],[9],[10], following a vertical cross-section NE-SW by rock salt body, perpendicular to the quadrangular long rooms of Praid saline.

Considering the mined space sizes, for a better accuracy of the computations, the model with the sizes X=1600m/Y=799m was achieved. Also, it was established the interest area around the underground excavations so as to involve the model surface where the variation of the stresses and strains is maximum [8],[9],[10]. The model meshing, respectively of every region, was provided by finite elements with triangular surface with quadratic interpolation (the total number of nodes is 3894 and the number of triangular surface elements is 19416) [5].

The initial loading conditions of the model were considered as geostatic, corresponding of the variable thickness of the overburden between about 192m and 267m of depth. The vertical geostatic stresses, corresponding to the average depth of the level +188m are 62563kN/m^2 and for the horizontal ones, the value is 20020kN/m^2 [6].

In Table 2 it is synthetically presented the variation area of the main computational parameters, resulted from the finite element modelling, in different cross-section by the rock salt body, in conformity with the maps and geological and mining documentation of the Praid saline.

Table 2. **Variation area of the main computational parameters of the model [6]**

Parameter [U/M]	**Variation area**	**Parameter [U/M]**	**Variation area**
Horizontal displacement u, [mm]	+17,5 ÷ -16,5	***Maximum principal stresses*** σ_1, [kN/m^2]	+2370 ÷ -8990
Vertical displacement v, [mm]	+99,7 ÷ -75,4	***Minimum principal stresses*** σ_2, [kN/m^2]	+600 ÷ -40200
Total displacement d_{uv}, [mm]	+99,6 ÷ 0	***Maximum shear stresses*** $\tau_{f\max}$, [kN/m^2]	+15600 ÷ 0
Horizontal stresses σ_{xx}, [kN/m^2]	0 ÷ -21600	***Tensile stresses*** σ_t, [kN/m^2]	+2370 ÷ 0
Vertical stresses σ_{yy}, [kN/m^2]	-1300 ÷ -28000	***Compressive stresses*** σ_c, [kN/m^2]	0 ÷ 40200
Tangential stresses σ_{xy}, [kN/m^2]	+15200 ÷ -15200		

In view to assess the rooms, pillars and ceilings stability related to the level +188m, it was analysed, in particular, the room no.6604, of this level (the third room toward the level centre, at the eastern limit of the model), considering it to be the most critical situation (Fig. 3).

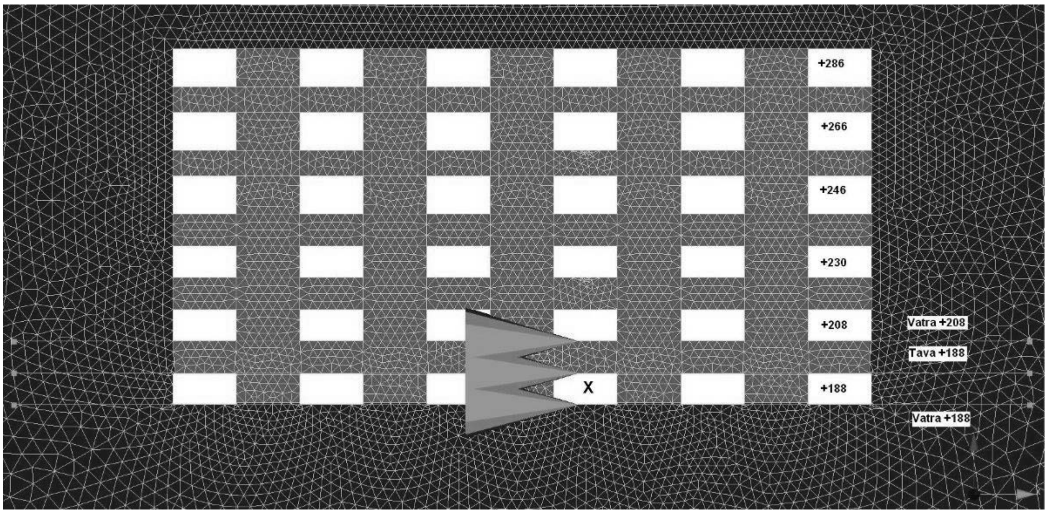

Fig.3. **Cross-sections on the floor of the level +208m, ceiling and floor of the level +188m (X- Room 6604) [6]**

The *horizontal displacements* in the ceiling between level +208m and +188m are maximum $\pm 8-9$ mm and in the pillars, maximum $\pm 5-6$ mm (Figure 4).

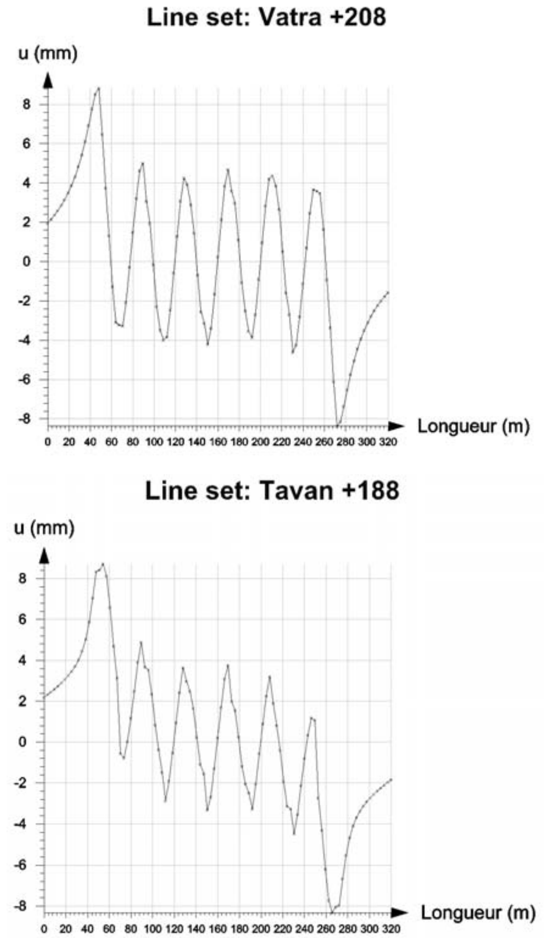

Fig.4. **Horizontal displacements *u*, in mm**
a) Cross-section by the floor of level +208m;
b) Cross-section by the ceiling of level +188m

As regards to the *vertical displacements*, these are all positive. Which means that, because of the fact that rock salt body is mined on the 6 levels, at a relatively important depth, it was produced a lifting of the rooms and the support structures at the last two levels (+208m and +188m). At the ceiling between the levels +208m and +188m, exists a vertical ascendant displacement (see Figure 5) of about 20-60mm, and at the floor rooms of +188m, of about 50-100mm (they mean a relative vertical convergence of the rooms of about 20-40mm).

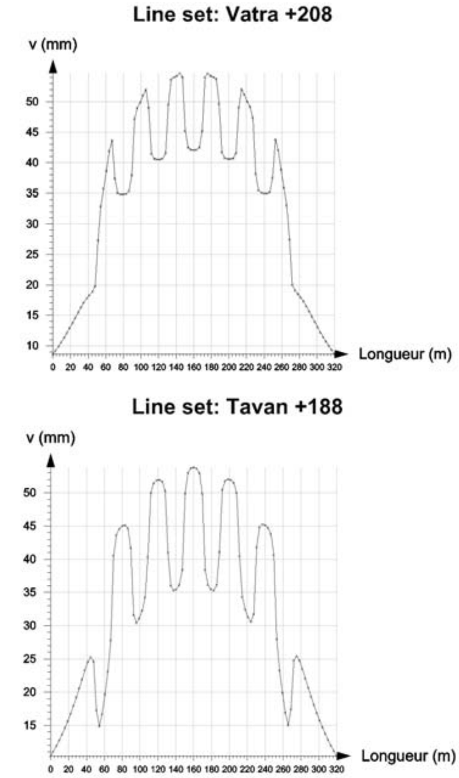

Fig.5. **Vertical displacement *v*, in mm**
a) Cross-section by the floor of level +208m;
b) Cross-section by the ceiling of level +188m

From the stresses analysis (Figures 6, 7 and 8), it is obvious the stress concentration at the limits between ceilings and pillars.

Analysing the *shear stresses* (Figure 6), it is observed that these surpass with at least 5-6 times the shear strength value of the rock salt (which is about 1200kN/m^2) in the corners and in the rooms walls, where could arise the shears phenomena of the rock salt (respectively, detachment of salt from the walls, more pointed toward the rooms corners). We mention that, although the ceilings have stability relatively well, because of the shear failures, which are the most common degradation phenomena of rock salt support structure.

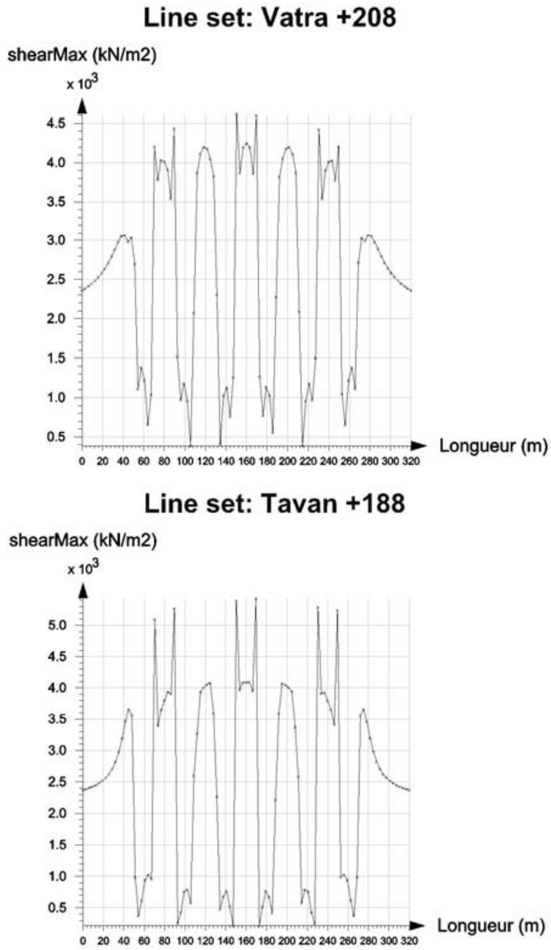

Fig.6. **Maximum shear stresses $\tau_{f\,\max}$, in kN/m^2**

a) Cross-section by the floor of level +208m;
b) Cross-section by the ceiling of level +188m

Tensile stresses (Figure 7) are, obviously, surpassed with 100% in the room's floor at the level +188m, where arise the most emphasized swelling phenomena. But, in the room's floors at the level +208m, these phenomena are less intensive.

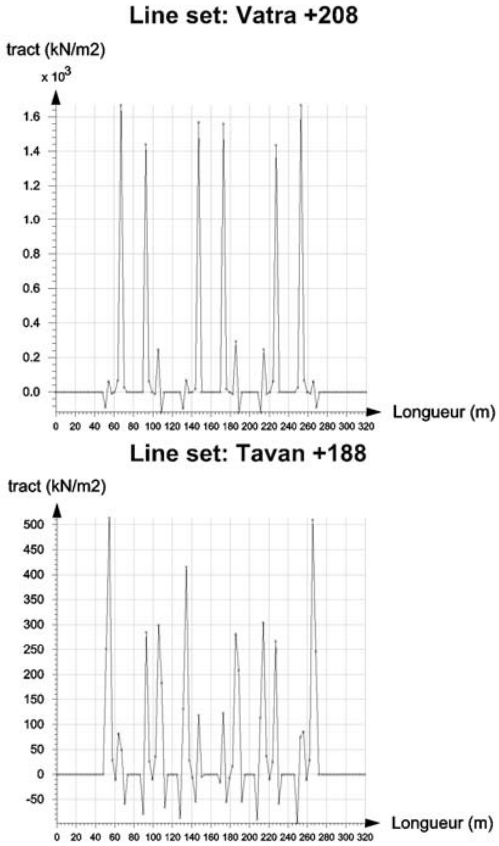

Fig.7. **Tensile stresses σ_t, in kN/m^2**

a) Cross-section by the floor of level +208m;
b) Cross-section by the ceiling of level +188m

According to expectation, the *compressive stresses* are more important in the pillars, with a significant concentration toward the room's walls, of about 8000-12000kN/m^2, up to the limit of rock salt compressive strength, in the contact area with the ceiling (Figure 8).

Because the previous analysis was exhaustively achieved, a synthetic analysis could be provided with the aid of the failure criteria. In this case, we appealed to the Mohr-Coulomb criterion, where the principal stresses, beside the characteristic curve of the rock salt (where is involved the strength parameters of the rock salt massive), have a significant role in the support structure behaviour assessment. Such as, there were computed the safety coefficients in certain significant points along the room 6604 contour (the most loaded room). From the safety coefficients analysis was concluded that the ceiling of the room is characterized by the safety coefficients with the values of about 5-6, and in the floor room by the values of 2.5-3.5, that convinced us to appreciate their stability as very good. In return, only at the rooms walls (external surface of the pillars), the safety coefficients are at the stability limit ($\cong 1$).

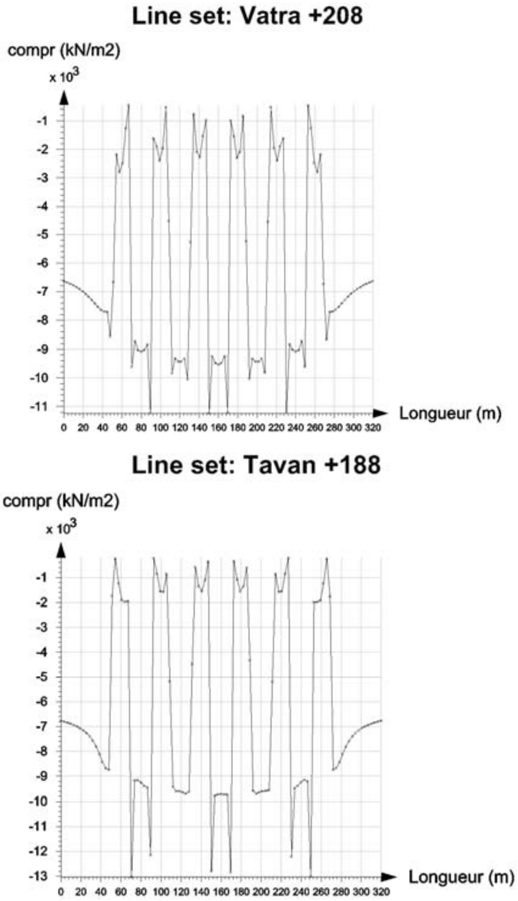

Fig.8. **Compressive stresses σ_c, in kN/m^2**

a) Cross-section by the floor of level +208m;
b) Cross-section by the ceiling of level +188m

4. Conclusions

From the previous analysis, we can detach, immediately, the following significant conclusions [6]:

a) At the level +188m, this is planned before long to start the mining, it can be appreciated that the ceiling and the floor rooms will have a very good stability, but the phenomena may occur of rock salt detachment from the walls rooms (especially because of the shear loadings) - more poignantly to the limit between the pillars and the ceilings;

b) Taking into account the limit stability of the support structure at the level +188m, the roadheaders use in the mining technological process of the rock salt cutting, in comparison with rock salt blasting, gives to the support structures the conditions of stability increase; furthermore, the rooms mining into a two slices, with 5m of thickness, ensure, at least during the first slice mining, the supplementary conditions for increasing the stability;

c) As regards the deepness mining, under the level +188m, of the Praid rock salt body, we believe that it is necessary a deepened study for to reconsider the rooms and pillars sizes. We appreciate that, the continued mining, under the level +188m, preserving current sizes of the support structures; will lead, implicitly, to reducing with 20-30% the safety coefficient, at the least at the external surfaces of the pillars – worsening thus the stability conditions of the support structures.

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