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MINERAL MINING TECHNOLOGY

Underground Mine Workings Convergence Dependence on Operation Time and Location Depth[1]

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Abstract— The article deals with subsurface location depth as one of the most important technical and mining factors in providing safe stability levels for any underground mine working. With increasing depth, takes place a change of mechanical properties of rocks, their transition into a boundary state, which has a special value and influence in relation to the long-term stability of the mine workings, both vertical and horizontal, in the sense that the mining pressure manifests itself differently and there is the problem of choosing the right support solution; also, it is enhanced the natural and secondary stress state and convergences became strong functions of depth. Based on the results obtained in the laboratory tests and in situ measurements and observations, carried out at several collieries within the Jiu Valley coal basin, in this article is settled the variation law of rocks surrounding mine workings depending on the depth of mining works and time lapse. The article also presents the development of a method for determining critical depth, parameter considered as depth wherefrom the plastic flow of rocks start to occur.

Keywords: Mine working, convergence, critical depth, stability, time, plastic flow, deformation work.

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1. GENERAL INFORMATION AND STATEMENT OF THE PROBLEM

The mine workings located at depths at which specific load resulting from the concentration of stresses that exceed the long-lasting resistance limit, raises serious issues of supporting, and long-term maintenance of these works implies special efforts [1, 9–11]. Such a statement is in fact confirmed by the multitude of processes used, and appearing in the literature, for solving supporting system issue and stability of these workings, as summarized in Table 1 [3–5, 15].

Studies in this respect revealed that on the one hand, these processes do not exhaust all measures which may be taken into account, and on the other hand, it appears that the problem is not solved completely nor worldwide; on the other hand it could not be solved with a single method, but by a comprehensive set of procedures, local deposit conditions having an important role in their implementation [6].

For the time being, in our studies, the influence of location depth on the stability of mine workings outside the area of influence of mining operation, in the seam no. 3 from Jiu Valley coal basin, was addressed as a parameter which can delimit the behavior of vertical deformation in the rocks; there exists a certain depth value, which we called as ***critical depth***, H_{critic}, from which downwards the rocks within the massive behaves non-elastic at distortion [11]. This hypothesis can be motivated through the importance that would have such an action limit of separation of the elastic behavior in respect to the plastic behavior, in reference to the problems of increased pressure and choosing appropriate supporting systems.

Thus, on the basis of observations made at E.M. Petrila colliery and certain tests conducted in the Rock Mechanics laboratory, was established a dependency having the shape given bellow [8, 10]:

$$H = \left(7.52\frac{\gamma_a - A}{\sigma_{rc_M}} - B\right) \pm 0.6, \tag{1}$$

where A and B—statistically obtained coefficients; σ_{rc_M} —compressive breaking strength of rocks in the massif, daN/cm^2.

[1]The article is published in the original.

Table 1. Procedures for ensuring the stability of horizontal mine workings located at different depths

Crt. No.	The procedure of ensuring the stability of horizontal mine workings	Possibility of use and process effectiveness at:	
		Usual depths	High depths
1	Rigid support	Virtually unlimited	Only with supporting measures to strengthen
2	Leaving the safety pillars	Everywhere	Not recommended
3	Provision of technological convergence (delayed mounting of final support system)	In part, depending on the organizational conditions	Generalized in all cases of a rigid support
4	Circular profile	In part, depending on the organizational conditions and technical-economic influence	Everywhere
5	Optimizing of position towards stratification (preference shall be given to perpendicular to the stratification works)	In part, depending on the mining situation	Everywhere for the main mine workings
6	The quality of execution (digging, supporting)	It is not always determined	Everywhere, but improvement measures are required
7	The relative location of workings	The mutual influence of the workings is lesser	Strict measures are necessary to reduce the influence of the neighboring works
8	Rescheduling the preparation workings	Should apply depending on operational technology	Neighboring works (under the influence of other works) are drifted with a gap in time
9	Overmining	As a general rule, it applies	Apply compulsorily, if there is an overlaid coal seam
10	Choosing a favorable location in the lithological sequence	Location is preferred in most resistant rocks, after possibilities	Location is preferred in most resistant rocks, after possibilities
11	Enlarging section of work-cutting	In part, in the case of preparation workings	In the case of works performed with sliding support when they their ultimate convergence is known
12	The introduction of sliding support	In the case of in-seam preparation workings	Everywhere, providing a sliding divider originated with the sense of the rock's movement
13	Drifting with snipped front execution	In the case of in-seam preparation workings	In the preparatory work on the seam
14	Drifting with discharge niches	In some cases for clay rocks	Not recommended
15	Drifting in two stages	In some cases, depending on the conditions	Not recommended
16	Consolidation by injecting rocks	In certain cases of preparation workings	In cracked and layered rocks, as additional measure
17	Combined support (anchors + sliding support, anchors and torcret + sliding support)	In certain cases	In preparation mine workings
18	Plastic-rigid support	Rarely	In difficult geomechanical conditions

Table 2 gives a list of values of such depths from which manifests an intense non-elastic behavior of rocks on the contour of horizontal mine workings from E.M. Petrila, floor of coal seam no. 3.

In the next stage of the research we proposed that, on the basis of observations and in situ measurements, to establish the variation law of convergence in terms of depth and time, law that we assumed to be of the form:

$$\varepsilon(H,t)=a(H)t+b(H)\,. \tag{2}$$

Table2. Critical depth values in the specific geo-mining conditions from E.M. Petrila colliery

Rock type	Values of parameters		Compressive breaking strength in the massif σ_{rc}, daN/cm^2	Critical depth H_{critic}, m
	A	B		
Sandy clay	1097	0.256	71.3	286
Compact clay	1767	0.361	112	303
Arenaceous clay	3234	0.465	180	348
	4625		240	375
Arenaceous sandstones	6983	0.248	324	421
	9977		396	492
Siliceous sandstone	13720	0.675	473	586
	16578		559	600

Table 3. Laws set out for the rocks in the Jiu Valley, Romania

Studied characteristic	Correlation type set		Colliery
	Rock type	Depth, m	
Uniaxial compressive breaking strength, σ_{rc}	Weak cohesive clays		E. M.Lonea, Jiu Valley
	$\sigma_{rc} = 0.18H + 8.47$	75 m < H < 600 m	
	Poorly cemented sandstone		
	$\sigma_{rc} = 0.44H^2 + 0.44H + 0.22$	$H \le 210$ m	
	$\sigma_{rc} = 0.08H^2 - 1.97H + 19.41$	210 m < H< 360 m	
	$\sigma_{rc} = 1.4H - 18.85$	360 m < H < 430 m	
	$\sigma_{rc} = 6.7H$	430 m < H < 750 m	
	Clays with high cohesion		
	$\sigma_{rc} = 0.48H + 1.98$	25 m < H < 225 m	
	$\sigma_{rc} = 0.1H^2 - 2.12H + 14.87$	225 m < H < 400 m	
	$\sigma_{rc} = 0.1H^2 - 3.27H - 20.63$	400 m < H < 550 m	
	$\sigma_{rc} = 7.2H$	550 m < H < 750 m	

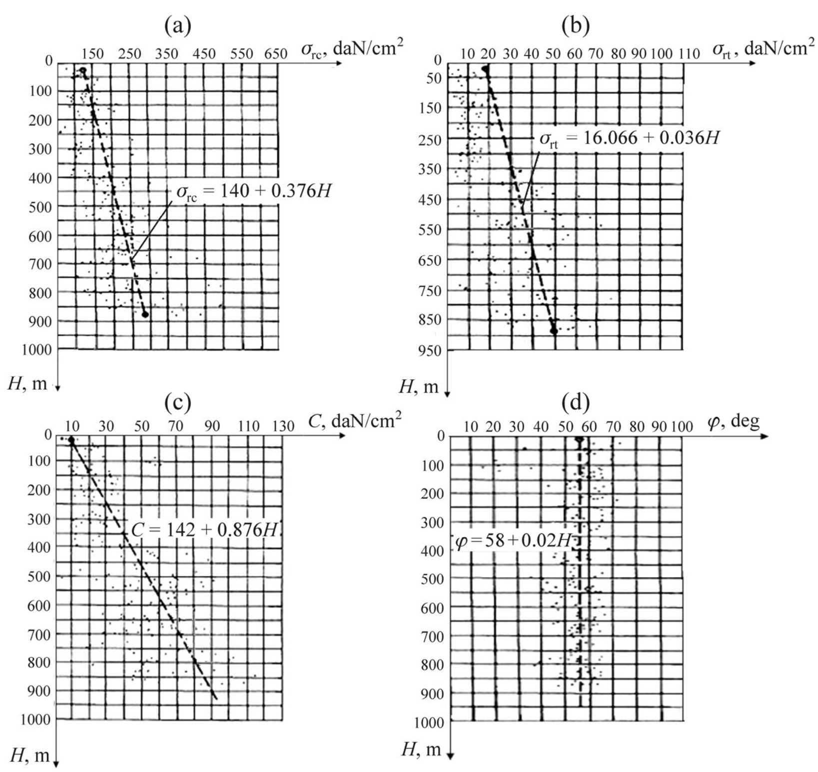

Fig. 1. Laws of strength properties modifications according depth (Jiu Valley coal basin): (a) $\sigma_{rc} = f(H)$; (b) $\sigma_{rt} = f(H)$; (c) c = $f(H)$; (d) φ = $f(H)$.

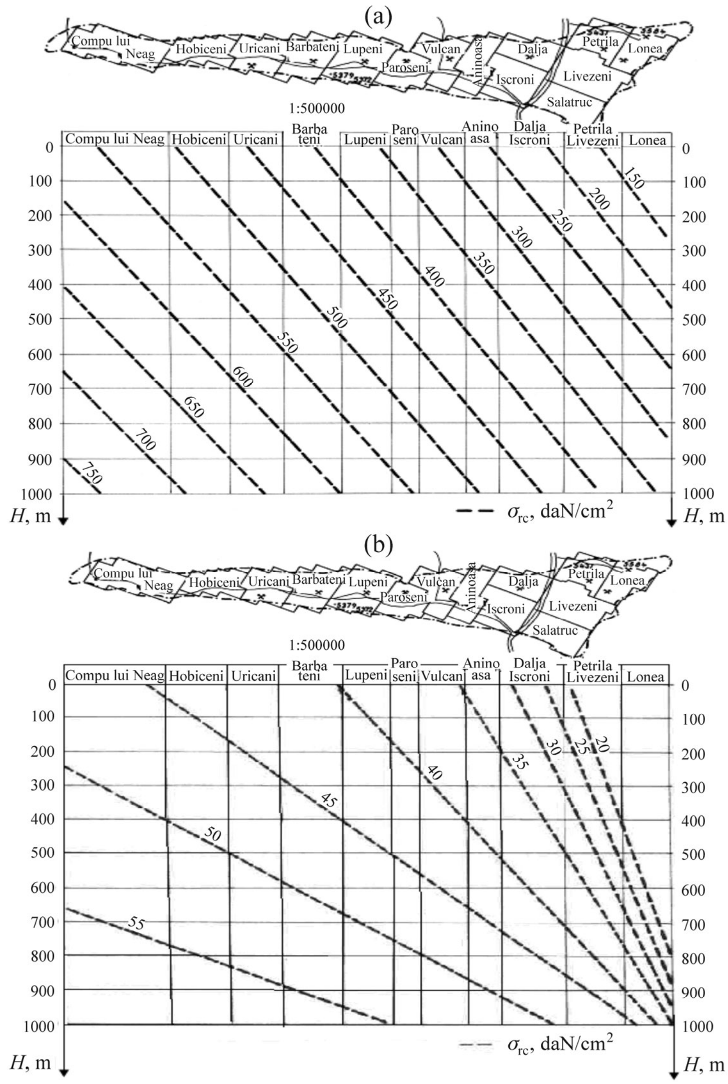

Fig. 2. Rock strength modification patterns according depth in Jiu Valley coal basin: (a) compressive breaking strength; (b) tensile breaking strength.

2. VARIATION OF DEFORMATION CHARACTERISTICS OF ROCKS IN RELATION TO DEPTH

Researches aimed at analysis of the variation pattern of convergence of rocks on the outline of underground mine workings, for the conditions of the Jiu Valley coal basin [12–14], have reveal a number of laws amending the geomechanical characteristics based on depth, outlined in Table 3 and depicted in Fig. 1, while for the entire basin, the variance of compressive breaking strength and uniaxial tensile strength are shown in Figs. 2a and 2b.

It follows, therefore, an increase in the resistance of the rocks, but not in proportion to the depth. Properties as porosity and moisture content are reduced with increasing depth. Poisson's coefficient value is modified by deep, as illustrated in Fig. 3; even the literature [8, 14] provides a $\mu = f(H)$ way of approaching the problem:

$$\mu = 0.25\left\{\left(\frac{\sigma_e^*}{\gamma_a H} - 1\right) + \left[\left(\frac{\sigma_e^*}{\gamma_a H} - 1\right)^2 + 8\left(\frac{\sigma_e}{\gamma_a H} - 1\right)\right]^{0.5}\right\}. \tag{3}$$

where σ_e^* represents the elastic stress for the case of triaxial compression.

Depending on the depth, it amplifies the natural state of stress in the massif, the secondary stress state surrounding the mine workings, increases the intensity of the rock's side pressure in the excavation's floor; also, mine pressures increases and as a result, it amplifies its manifestations, i.e. convergences amplitude, becoming themselves functions of depth H.

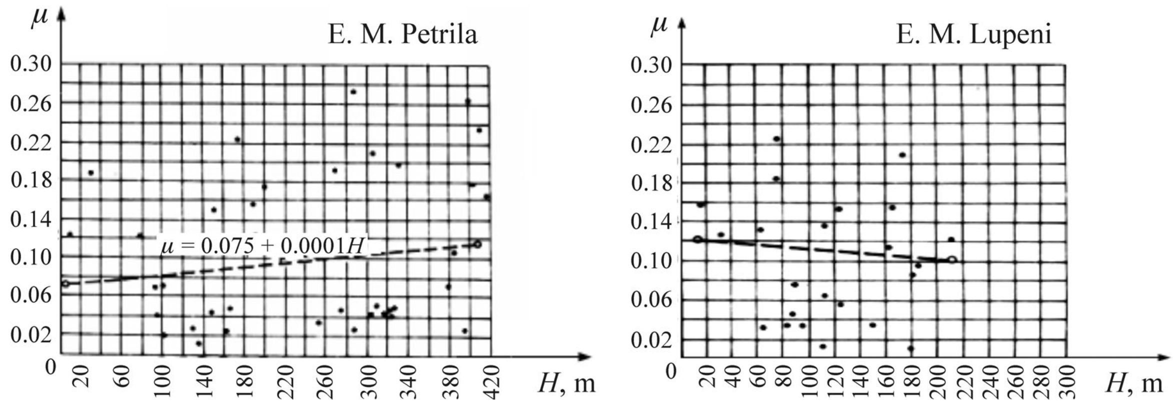

Fig. 3. Poisson's coefficient μ modification pattern with depth (E.M. Petrila and E.M. Lupeni collieries).

In this regard, we are further highlighting such dependency of convergence on time and location depth of the mine working, $\varepsilon = f\,(t$ and $H)$. In terms of mining pressure manifestation, the notion of high depth, or *deep mine*, is a very relative notion, because it was found that the burden exerted on the support-system depends not only on the location depth, but also several geomechanical, technical, mining and organizational factors.

The concept of the „deep mine, however, is also relative in numerical value. One should specify that the name is correct, for example, in the Jiu Valley basin, where hard coal is mined out, in the case of mine workings drifted in rocks with $\sigma_{\rm rc} < 40$ MPa at depths higher than 600 m, but also for lignite mines with production activity located at 80 m from the surface; it no longer finds meaning in the case of mines where mine workings are developed at depths greater than 1000 m, but in very hard rocks, having $\sigma_{\rm rc} > 180$–200 MPa.

Working experience acquired in the Jiu Valley collieries at higher depths, the results of investigations regarding the status of mine workings, observations and measurements carried out in time, as well as theoretical research, allowed altogether the highlighting of several distinctiveness of birth and manifestation patterns of mine pressure at depths greater than 500–600 m (until 1100 m, at E.M. Petrila colliery).

The distribution of secondary stress state on the contour and around the main mine workings is determined by the value of the ξ_0 coefficient or σ_x / σ_z ratio. With the increase of the coefficient $\xi_0 >$ 0.33, the tangential tensile stress values are growing, and the rocks surrounding the mine workings begin to experience strong rheological properties, which actually induces a number of features of mine pressure manifestations. They determine both the size and character of the loads on the support system and its required malleability. As a result of rocks rheological properties manifestation, the massif's secondary stress state around mine workings, at large depths (in the previously specified sense), differs considerably from the one taken in the calculations for the rock—like rocks located at small depths. At considerable depths, in rocks with $\sigma_{\rm rc} \le 40$ MPa, with time tension relaxation occurs, the stress state is balanced, which is why with increasing depth ξ tends toward unity. At small depths, ξ_0 is small, in the roof and floor tensile stresses are occurring and consequently rock is destroyed, it breaks, at the roof of the mine working is formed the canopy, or arch, of dislocated rocks whose height is bordered by a stable, i.e. outline of such a form of the work on which dangerous traction stresses are cancelled.

In the case of high depths and low resistance rocks (($\sigma_{\rm rc} \le 40$ MPa), where we dispose of theoretical and experimental basis to admit that $\xi_0 \rightarrow 1$, outline the working are occurring just compression stresses , which often proves sufficient for destroying rocks or leading to their inelastic - plastic deformation. As a result, around mine workings a region of bedrock forms that has gone into the field of inelastic deformation. In such case, it occurs and intensifies the rock shifting towards the mine working and multilateral support-system compression, which is why the stability of such mine workings is complicated.

Along with the peculiarities of mine pressure manifestations, at greater depths is also found a stirring up of some forms of them, namely:

- considerably grow of rock recession limits from the mine working's floor, observing such phenomena even in the case of sandstones and limestone rock types;
- values of these recessions from the floor reaches a few tens of centimeters, often surpassing the size of the movements at the roof; these findings can be explained, in the case of plane – floor mine workings, by producing massif's discharge the direction of their floor;
- rock movements are comprising the entire outline of the mine working and spread into the interior of the massif, forming the inelastic deformation area;
- the shape of such zones is a *lemniscate*, depending on the determinative anisotropy of rocks, the strength of surrounding rocks, on mine working's size, depth; and can reach dimensions ranging from 2 to 9 m;
- in the case of high depth values, rock movements towards the mine working and, therefore, towards the support system, the load occurs throughout the mine working's contour;
- such a pressure distribution on the mine working's contour leads to support destruction not only at the floor and roof, but also in the side walls;
- displacement size can range from a few tens of centimeters (in argillaceous and sandy schist to a few centimeters in sandstones and limestone; in the latter case, the movements usually are occurring without breaking the rocks, which can ensure a longer conservation of the mine working.

3. CRITICAL LOCATION DEPTH OF MINE WORKINGS

The influence of mine depth on the stability of the working is addressed in literature [2, 7, 8, 11, 13] as a parameter that can delineate on the massif's vertical the deformation behavior of rocks, in the sense that there is a certain critical value, H_{critic}, starting from which the rocks within the massif do have an inelastic-plastic deformation behavior or dynamic phenomena are occurring.

The idea of approaching stability and reliability of mine workings in the context of critical depth involvement is motivated by the importance given to such a depth limit of separation between the elastic behavior area and the plastic behavior area, with reference to the issues of increased pressure and choice of appropriate supports for providing the stability of excavations executed below this depth. For example, research conducted in this regard in Krivoi Rog [15] has emphasized the dependence of rocks inelastic-plastic deformation increase around the mine workings on their location depth, in the form of the relationship:

$$H_{critic} = \left(7.34\frac{\gamma_a}{\sigma_{rc}} - 0.248\right) \pm 0.1, \tag{4}$$

where H_{critic} represents the average depth beginning from which the development of inelastic deformations is initiated in Krivoi Rog massif area. In Table 4 we present some of the analytical relations provided by the literature to assess the critical depth.

For example, such a critical depth H_{critic} also can be addressed in the following manner: at a certain depth, H, into an undisturbed massif, acts a natural state of tension σ_1, σ_2, σ_3 and $\sigma_2 = \sigma_3$; plastic flow is supposed to occurs when:

$$S = \frac{1}{2}(\sigma_1 + 2\sigma_3). \tag{5}$$

Table 4. Analytical relations for critical depth assessment

Author	Relationship for critical depth calculation, H_{critic}, m	Significance
H. Labasse V.D. Slesarev E.T. Proeavkin A.P. Maximov	$H_{critic} = \frac{\sigma_{rc}}{\gamma_a}$	σ_{rc} is the uniaxial breaking strength to compression of rocks γ_a is the volumetric weight of the rock
P.M.Ţimbarevici K.V. Ruppeneit	$H_{critic} = \frac{2\sigma_{rc}}{2\xi_0\gamma_a}$	$\xi_0 = \frac{\mu}{1-\mu}$ —the knockback lateral pushing due to Poisson's coefficient
F.A. Belaenko	$H_{critic} = \frac{\sigma_e}{\xi_1\gamma_a}$	$\xi_1 = \frac{1-2\mu}{1-\mu}$
I. Bealer	$H_{critic} = \frac{\sigma_{rc}}{k\,\gamma_a}$	k is a coefficient characterizing bedrock; for an average strength of rocks k = 1, 3–2
R. Cvapil	$H_{critic} = \frac{\sigma_{rc}}{k_1\,\gamma_a}$	k_1 coefficient that depends on the type of the rock; for σ_{rc} = 200 daN/cm^2, k_1 = 3 for σ_{rc} = 400 daN/m^2, k = 1,25
***	$H_{critic} = \frac{\sigma_{pl}}{\gamma_a\sqrt{3}}$ —galleries $H_{critic} = \frac{(1-\mu)\,\sigma_{pl}}{\mu\,\gamma_a\sqrt{3}}$ —mine shafts	σ_{pl} is the rock's stress at the plasticity. _Remark:_ for mine shafts, plastic behavior begins at greater depth than in the case of galleries.

Based on deformation mechanic work hypothesis [6, 9, 12], where deviators are:

$$S_1 = \sigma_1 - S = \frac{2}{3}(\sigma_1 - \sigma_3),$$
$$S_2 = \sigma_2 - S = \frac{1}{3}(\sigma_1 - \sigma_3), \tag{6}$$
$$S_3 = \sigma_3 - S = \frac{1}{3}(\sigma_1 - \sigma_3).$$

The deformation work induced by the stress state is:

$$\frac{1+\mu}{E} J_3 = \frac{1}{3}(\sigma_1 - \sigma_3)^2 \frac{1+\mu}{E} \tag{7}$$

and the plastic flow condition is given by the relation:

$$J_3 - \frac{\sigma_{pl}}{3} = 0, \tag{8}$$

namely:

$$\sigma_1 - \sigma_3 = \sigma_{pl}. \tag{9}$$

Under a determined depth value, the plastic flow phenomenon takes place:

$$\sigma_1 = \gamma_a H, \quad \sigma_2 = \sigma_3 = \xi_0\,\gamma_a\,H \tag{10}$$

and, accordingly, the phenomenon begins at:

$$H_0 = \frac{1-\mu}{1-2\mu} \cdot \frac{pl}{\gamma_a}. \tag{11}$$

At H_0 depth value, rocks will be subject to a main stress state, due to their own weight:

$$\sigma_3 = \sigma_2 = \sigma_1 - \sigma_{pl}\,. \tag{12}$$

The ratio of main stresses will be:

1) for the case when we stand above H_0:

$$n = \frac{\sigma_3}{\sigma_1} = \frac{\mu}{1-\mu} \quad \Rightarrow \quad n = \xi_0\,; \tag{13}$$

2) for the case when we stand bellow H_0:

$$n = \frac{\sigma_3}{\sigma_1} = 1 - \frac{\sigma_{pl}}{\gamma_a\, H}\,. \tag{14}$$

If the value of σ_{pl} is low and H is large, then the value of n tends to 1. In the context of the above-mentioned, the critical depth value can be also highlighted for the axial symmetrical stress state. Thus, when deformation work on the mine working's contour is:

$$J_3 > \frac{\sigma_{pl}^2}{3}, \tag{15}$$

then, the horizontal mine working should not be supported; it lies in the field of elastic deformation, and theoretically it is necessary only a support having the role to protect against potential breakaways, and falls of rock. In the case of vertical mine workings:

$$S = \frac{\sigma_r - \sigma_\theta}{2} = \sigma_3 \tag{16}$$

and flow condition on the surface ($r = a$) is:

$$\sigma_3^2 - \frac{1}{3}\sigma_{pl}^2 = 0, \qquad \sigma_3 = \xi_0\,\gamma_a\, H. \tag{17}$$

In conclusion, the H_{critic} value is given by Eq. (18):

$$H_{\text{critic}} = \xi_0 \frac{\sigma_{pl}}{3\,\gamma_a}\,. \tag{18}$$

For horizontal mine workings it shows that, if value of $n \le 1$, H_{critic} can be assessed as follows:

Considering normal stresses:

$$\sigma_3 = \sigma_2 = \sigma_1\,, \tag{19}$$

then total stress will be:

$$S = \sigma_1 \tag{20}$$

and deviators:

$$S_r = \frac{a^2}{r^2}\sigma_1, \qquad S_\theta = \frac{a^2}{r^2}\sigma_1. \tag{21}$$

The flow condition for $r = a$ is:

$$\sigma_1 = \frac{1}{3}\sigma_{pl} = \gamma_a\, H \tag{22}$$

and, consequently:

$$H_{\text{critic}} = \frac{1}{\sqrt{3}} \cdot \frac{\sigma_{pl}}{\gamma_a}\,. \tag{23}$$

Considering the depth of H_{critic} for which on the horizontal mine workings acts a stress equal to the unit and the value of σ_3:

$$\sigma_3 = \xi_0\,\gamma_a\, H\,,$$

then H_{critic} is given by Eq. (24):

$$H_{\text{critic}} = \frac{1-\mu}{\mu} > 1\,, \tag{24}$$

and, comparing with critical depth for shafts, it is found that in the case of vertical mine workings, plastic flow begins at a greater depth than in the case of horizontal mine workings.

4. ASSESSMENT OF ROCK CONVERGENCE VARIATION WITH TIME ON THE CONTOUR OF MINE WORKINGS LOCATED AT DIFFERENT DEPTHS

Based on *in situ* research regarding pressure regime on mine workings drifted in coal deposits [8–12] it was determined the dependence between convergence, mine working's operating time t and their location depth H, as highlighted in Fig. 4 [10; 14].

Setting convergence, as a function of the depth H and the operation time t, $\varepsilon = f(H, t)$, can be done by several methods. Further, are illustrated two of these methods:

(a) Using the convergence measurements according to H and t given in Table 5 and Fig. 5, for H = constant, is the general shape of such a function is given in Eq. (25) bellow:

$$(H, t) = a(H)t + b(H)\,, \tag{25}$$

where H remains constant.

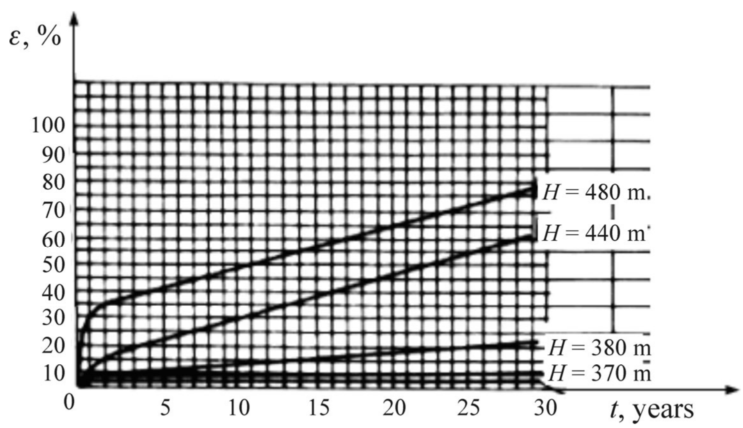

Fig. 4. Convergence dependence on operation time t and depth location of mine working H.

Table 5. Convergence dependence on operation time t and depth of mine working H

Depth H, m \ Time t, years	0.5	1.0	2.0	3.0
300	0.2	0.2	0.2	0.2
370	0.4	0.4	0.4	0.4
380	0.6	0.8	1.2	1.6
440	1.5	2.5	4.0	5.5
480	3.6	4.3	5.8	7.2

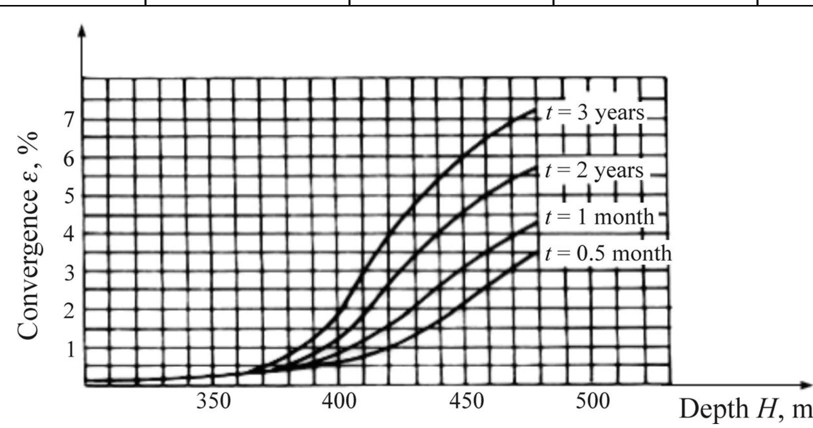

Fig. 5. Rock convergence variation versus time and location depth.

Table 6. The interpretation and analysis of experimental data in Figs. 4 and 5, approximation of functions ε_1 (H) and ε_2 (H)

H	ε_1 (H)	ε_2 (H)
300	0	0.2
370	0	0.4
380	0.4	0.4
440	1.6	0.8
480	1.5	2.8

For the determination of $a(H)$ and $b(H)$, for different values of H, we used the least-squares method or Newton's interpolation method, obtaining:

$$(H,t)=\left(-199.17\,H^2+180.49\,H-39.4\right)t+\left(361.67\,H^2-285.24\,H+56.54\right). \qquad (26)$$

(b) Another method that can analyze and interpret experimental data consists in the creation of Table 6.

Based on the data from Fig. 5, the relationship (27) is written:

$$\varepsilon\,(H,t)=\varepsilon_1(H)\cdot t+\varepsilon_2(H)\,, \qquad (27)$$

which can be approximated by a relationship of the form ($at + b$), obtaining, for different values of H, the following equations:

$$\begin{aligned}\varepsilon\,(300\,,t)&=0\cdot t+0.2,\\ \varepsilon\,(370\,,t)&=0\cdot t+0.4,\\ \varepsilon\,(380\,,t)&=0.4\cdot t+0.4,\\ \varepsilon\,(440\,,t)&=1.6\cdot t+0.8,\\ \varepsilon\,(480\,,t)&=1.5\cdot t+2.8.\end{aligned} \qquad (28)$$

Based on Eqs. (28), the functions $\varepsilon_1(H)$ and $\varepsilon_2(H)$ are approximated in Table 6, thus obtaining:

$$\varepsilon_1(H)=a\cdot e^{-b\,(H-c)^2}\,. \qquad (29)$$

Employing the chosen points method, i.e. solving the system of equations given by Eqs. (28), with the shape given bellow:

$$\begin{aligned}a\cdot e^{-b\,(380-c)^2}&=0.4,\\ a\cdot e^{-b\,(440-c)^2}&=1.6,\\ a\cdot e^{-b\,(480-c)^2}&=1.5,\end{aligned} \qquad (30)$$

it was obtained that a = 1.69; $b = 2.56\cdot 10^{-4}$; c = 445 and consequently, for the depth interval $H\in$ [380, 480] m, $\varepsilon_1(H)$ is:

$$\varepsilon_1(H)=1.69\;e^{-2.56\left(\frac{H-455}{100}\right)^2}\,, \qquad (31)$$

while for the depth interval $H\in$ [300, 370] m, as an identical null function.

Furthermore:

$$\varepsilon_1(H)=\begin{cases}1.69\;e^{-2.56\left(0.01H-4.55\right)^2} & \text{pentru}\quad H\geq 375\text{ m}\\ 0 & \text{pentru}\quad H<375\text{ m}\end{cases}. \qquad (32)$$

This expression may put in the form of a homogeneous, continuous and summable relationship, using the expression:

$$S(H)=\frac{1}{2}+\frac{1}{x}\cdot\arctan\left[100\,(H-375)\right], \qquad (33)$$

which for H < 375 m is 0, while for H > 375 m is 1, and subsequently:

$$\varepsilon_1(H)=S(H)\cdot 1.69\;e^{-2.56\,(0.01\cdot H-4.455)^2}\,. \qquad (34)$$

Similarly, it was approximated the function $\varepsilon_2(H)$, resulting:

$$\varepsilon_2(H)=0.0036\,e^{3.65\,(0.01\cdot H-3)}+0.29 \qquad (35)$$

or, otherwise:

$$\varepsilon_2(H) = \frac{1}{\sqrt{3.56 - 0.15 \cdot (0.01 \cdot H)^2}} - 0.43\,. \tag{36}$$

Using Eqs. (32) and (35) the convergence function was expressed as it comes:

$$\varepsilon(H,t) = \left\{ \left[\frac{1}{2} + \frac{1}{x} \arctan[100(H - 375)] \right] \cdot 1.69 \cdot \exp\left(-2.56 \frac{(H-455)^2}{4} \right) + 0.0036 \cdot \exp\left(3.65 \frac{H - 300}{100} \right) + 0.29 \right\} \tag{37}$$

or, based on Eq. (36), this is rewritten in the following expression:

$$\varepsilon(H,t) = \left\{ \left[\frac{1}{2} + \frac{1}{\pi} \arctan[100(H - 375)] \right] \cdot 1.69 \cdot \exp\left(-2.56 \frac{(H-455)^2}{4} \right) + \frac{1}{\sqrt{3.56 - 0.15 \left(\frac{H}{100} \right)^2}} \right\}. \tag{38}$$

The results obtained with such relationships are rendered in Table 7, finding (see Fig. 5) that it can be very accurately forecasted the convergence of the mine workings drifted in weak rocks, depending on time and depth location, in the range $H = 300$–500 m.

Based on the above results and discussion, the parameter *depth* must be taken into account in assessing the stability-reliability, i.e. in designing efficient mining excavations. Such a possibility of forecasting, in the absence of evaluation metrics in situ, is given by depth value calculated according to the relationship $H_c = k \cdot H$, where H is the projected depth of mine working or portions of it, m; k is a coefficient which assesses the state of stress of the rock massif, in comparison with the stress created by the weight of the entire thickness of rock to the surface. In the gravitational context k = 0.8–1, and in the case of a state of complete tectonic stress, so amplified tectonic origin stress state, in the rock massif areas subject to tectonic movements or existing tectonic disturbance, k is equal to 1.5–3.46.

Calculating the value of H_c reflects the influence of natural stress state in the rock massif on the pressure intensity in mine workings; for most areas uncomplicated by tectonic activity, the vertical component, estimated by the relationship $\sigma_v = \sigma_z = \gamma_a H$ or relations of the shape $\sigma_z = \frac{a + bH}{c + H} \cdot H$ is the active one, and the normal horizontal components are equal to $\sigma_0 = \xi_0 \sigma_v$ (where ξ_0 is the lateral pushing coefficient and depends on the degree of plasticity of the rock).

In the case of areas subjected to erosion or tectonic disturbances, under the slopes of the mountains (as is the case in the Jiu Valley mines), under water basins, etc., manifests a very particular stress state, because the horizontal components can manifest themselves as active ones and will far exceed the value of the vertical component, σ_v.

Table 7. Variation with time and depth of convergence of mine workings drifted in low strength rocks

$\varepsilon(H, t)$, t / H, m	Based on Eq. (37)				Based on Eq. (38)			
	0.5	1	2	3	0.5	1	2	3
300	0.29	0.29	0.29	0.29	0.24	0.24	0.24	0.24
370	0.34	0.34	0.34	0.34	0.38	0.38	0.38	0.38
380	0.56	0.76	1.16	1.56	0.61	0.81	1.21	1.61
440	1.48	2.27	3.86	5.45	1.69	2.39	3.98	5.57
480	3.52	4.24	5.68	7.12	3.39	4.11	5.55	6.99

REFERENCES

1. Aitaliev, S.M., Erjanov, J.S., Erofeev, L.M., Integrated Study of Unstable Roc Pressure in Permanent Tunnels, *Problemy mekhaniki gornykh porod* (Problems in Rock Mechanics), Alma-Ata: Nauka, 1996.
2. Aitaliev, S.M., Isakson, V.Iu., and Zakamaldin. A.I., Rock in the Vicinity of a Working with an Asymmetric Cross Section, *J. Min. Sci.*, 1979, vol. 15, no. 3, pp. 213–217.
3. Aitaliev, S.M. and Kaionov, M.A., A Method to Estimate Stress State of Rocks around a Non-Circular Cross-Section Tunnel, *Analiticheskie i chislennye issledovanyia gornykh porod* (Analytical and Numerical Investigation of Rocks), Novosibirsk, 1981.
4. Gurău, A., Microtectonica (in Romanian) Tehnică Publishing House Bucharest, 1982.
5. Oparin, V.N., Yakovitskaya, G.N., Vostretsov, A.G., Seryakov, V.M., and Krivetsky, A.V., Mechanical-Electromagnetic Transformations in Rocks on Failure, *J. Min. Sci.*, 2013, vol. 49, no. 3, pp. 343–356.
6. Oparin, V.N., Vostretsov, Krivetsky, A.V.,Bizyaev, A.A., and Yakovitskaya, G.E., Integrated Measurement and Recording of Loads, Displacements and Electromagnetic Emission in Rocks under Uniaxial Compression, *J. Min. Sci.*, 2011, vol. 47, no. 5, pp. 547–557.
7. Popescu, Al.and Todorescu, A, Rock Mechanics in Mining (in Romanian), Tehnică Publishing House Bucharest, 1982.
8. Toderaş, M., Depth Increase Influence on Design of Opening and Mining Methods Parameters, *Mining Scientific Symposium Proc*., Deva, Romania, 1988.
9. Toderas, M., The Study of the Deformation Regime of Rocks around the Directional Galleries from the Seam no. 3 Bottom E.M. Petrila through in the Context of Interaction in the Rock Mass–Support System and Choosing the Type of Supports Appropriate to the Geo-Mining Conditions from Petrila's Perimeter, Graduation Project, 1990.
10. Toderas, M., Critical Analysis of Horizontal Mine Working's Stability in Jiu Valley and Assessment of Main Factors Determining Their Stability (in Romanian), *Ph.D. Report*, University of Petroşani, Romania, December 1992.
11. Toderas, M., Rock and Soil Mechanics and Underground Constructions (in Romanian), Universitas Publishing House, Petroşani, Romania, 2014.
12. Toderaş, M. and Moraru, R.I., Mine Pressure and Rock Displacement Temporal Variation Analysis for Jiu Valley Directional Drifts in the Context of "*n*" Stability Xriterion, *Arch. Min. Sci.*, 2014, vol. 59, pp. 347–358.
13. Todorescu, A., Properties of Rocks (in Romanian), Technical Publishing House Bucharest, 1984.
14. Todorescu, A., Rock Rheology with Applications in Mining (in Romanian), Technical Publishing House Bucharest, 1986.
15. Bologo, V.V. (Ed.), *Spravocinik inzhenera-shakhtostroitelyia* (Engineer–Mine Builder's Manual), vol. 1, Moscow: Nedra, 1983.