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MINE PRESSURE AND ROCK DISPLACEMENT TEMPORAL VARIATION ANALYSIS FOR JIU VALLEY DIRECTIONAL DRIFTS IN THE CONTEXT OF "n" STABILITY CRITERION

ANALIZA CIŚNIEŃ I CHWILOWYCH PRZEMIESZCZEŃ SKAŁ W BADANIACH KIERUNKOWYCH WYROBISK W KOPALNIACH W DOLINIE JIU Z UWZGLĘDNIENIEM KRYTERIUM STABILNOŚCI 'n'

Ensuring mine workings stability over their entire operation period largely depends on the chosen support system and on their interaction with the surrounding rock. Looking at how the main horizontal mine workings are supported in Jiu Valley coal basin, we found that they fall into the category fulfilling a reinforcement role. From the data provided by the documentation of the collieries within this basin, it was found that there were generalized different metal – type supporting systems that with respect to operating and working mode are with constant or malleable strength and increasing – strength (rigid supporting systems). Research conducted on the stability analysis of horizontal mine workings aimed at elucidate the intensiveness and characteristics of mine pressure, the deformation character and contour displacement of rocks, the interplay between geo-mechanical deformation conditions and deformation extension, as good as the influence of these parameters on the supporting system's behavior. This paper presents a methodology for determining the main laws of mine pressure regime distribution, the results of the burden load values and displacement of support, considering the "n" stability criterion as a complex parameter which can express the laws of variation, for the specific location and operating conditions of directional galleries within the floor of coal seam 3 in Jiu Valley.

Keywords: stability – reliability, mine pressure, stability criterion, deformation, interaction, time, dependence

Zapewnienie stabilności wyrobisk w trakcie całego okresu prowadzenia prac górniczych w dużej mierze uwarunkowane jest przez dobór odpowiedniej obudowy i kontroli oddziaływania sąsiadujących warstw skalnych. Obserwując w jaki sposób zabezpieczono i podparto poziome wyrobiska główne w kopalniach zagłębia węglowego w dolinie Jiu, stwierdziliśmy, że obudowy te pełnią rolę wzmocnień. Na podstawie danych dostarczonych przez kopalnie w rejonie zagłębia węglowego, wiadomo, że w większości

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były to różnego typu obudowy metalowe o stałej lub regulowanej wytrzymałości, uwarunkowanej przez dobór metody wybierania, lub obudowy o zwiększonej wytrzymałości (sztywne podpory). Przeprowadzono badania obejmujące analizę stabilności poziomych wyrobisk mające na celu określenie wielkości i charakterystyki ciśnienia, charakteru odkształcenia i przemieszczeń warstw skalnych, a także zależności pomiędzy geo-mechanicznymi warunkami odkształcenia i rozszerzaniem w trakcie odkształcenia i wpływu wyżej wymienionych parametrów na zachowanie podpór. W pracy przedstawiono także metodę określania zasad rozkładu ciśnień w obrębie kopalni, wyniki badań obciążeń wskutek nadkładu oraz przemieszczeń podpór przy wykorzystaniu jako kryterium stabilności złożonego parametru 'n', który określa prawa rządzące zmiennością tych wielkości w zależności od specyfiki miejsca i warunków prowadzenia wydobycia w kierunkowych chodnikach w obrębie pokładu 3 w kopalni węgla w dolinie Jiu.

Słowa kluczowe: stabilność, niezawodność, ciśnienie, kryterium stabilności, odkształcenia, oddziaływania, zależność czasowa

1. Introduction

In the several past decades, an extensive amount of work has been done about the analysis of stresses and displacements around a horizontal drifts considering various rock mass behaviors and failure criteria (Brown et al., 1983; Carranza-Torres, 2004; Hejmanowsky et al., 2009; Lee & Pietruszczak, 2008). As outlined by Kortas (2013), the physical phenomena occurring in the rock mass are described in various size and time scales. The time scale, applicable to rock deposit space or particular workings, is limited by second-long dynamic processes and century-long geological diastrophic processes. In their natural state, the rock massifs as object mining processes, are permanently under the influence of gravitational forces, of tectonic nature forces, under the action of water in its various forms and of time, causing the onset and development of complex stress state known as the **primary or natural stress state**, which as long as the rock mass is impelled and can not be deformed, is contained in a latent form. When the rock massive is disturbed by conducting underground works of any kind, the natural stress state in the surrounding rock is amended, amplified and redistributed, creating a new stress state called **secondary stress state** T_σ. The new stresses that arise can affect at greater or lesser extent the functionality and therefore the stability of underground workings. Two aspects of the stability were emphasized, as follows:

- **natural stability** of the excavation, which can form itself, by the very nature of the rock massif and factors specific to the situation in which mining work is done. It results from the proportion these excavations creates with their execution between the secondary stress state T_σ and the reaction or limit state σ_{lim} of the surrounding rocks, i.e. $T_\sigma < \sigma_{\text{lim}}$. Mining workings executed in such circumstances need not be supported on their entire operational time span;
- **required (imposed) stability** of underground excavations, as a result of the disturbance in the balance created between rock and excavation, the working development being no more favored by natural, technical mining and conditions; this means that $T_\sigma >> \sigma_{\text{lim}}$ and as a result, the stability of the rock massif – mine working can be provided only on based on a counteracting force reaction developed by various methods, such as, for example: consolidation, support – system mounting or a combination of the two, namely by creating an imposed stability (Toderaş, 2006).

In addition to these resources, mining stability analysis is based on a series of criteria for assessing, in concrete mining and technical conditions, to accurate natural and/or imposed stability of mine workings assessment. The involvement of these criteria in theory design creates prerequisites the ultimate objective to find links between the configuration and size of the pressure regime and working conditions of supporting systems (Letu et al., 1981; Popescu et al, 1982). Furthermore, the resort to the stability criteria of rock massif – mine working and supporting system parameters in an imposed stability context of the interaction mechanism may be the basis for choice of alternative of a forecasting model for calculating pressure regime, establish logical links between classes and forms of manifestation of these regimes, state the fundamental principles of a procedure for calculating the development of support systems to address stability and reliability of mine workings throughout their entire life cycle.

2. Directional drifts stability analysis based on „n" criterion

The ability to quantitatively reflect the implications of geo-mechanical characteristics and of certain technical and mining parameters, including the depth of mine working location, can be achieved through the use of various stability criteria. Given the *stability criterion* concept definition, this concept was applied in the analysis of experimental results regarding the pressure regime, obtained by in situ investigations (Toderaş, 1992). In light of these explanations, in a study on the status of surrounding rock deformation around directional drifts, considering rock massif – support system interaction for geo-mining conditions in Petrila Colliery perimeter, Toderaş (1992) analyzed the opportunity of employing the „n" stability criterion to elucidate the issues related to dependence of this criterion on the following parameters: compressive breaking strength σ_{rc}; depth, $n = f(H)$; deformation of mine working's contour, $n = f(u)$; necessary bearing to support; contour deformation of the working; change in pressure and the displacement in time; dependence of pressure and displacement on the value of the stability criterion.

Stability analysis can be substantiated by detailed knowledge of the geo-mechanical characteristics of the rocks and their structure changes occurring over time due to moisture and other agents of deterioration, the depth of mine working's location, the influence of cutting – supporting technology, the impact exerted by other workings and faces etc.

The „n" stability criterion relationship can be expressed as:

$$n = \frac{C_s k_{ld} k_w}{k_{ct} k_1 k_3} \cdot \frac{\sigma_{rc}}{\gamma_a H} = \frac{\sigma_{rc_M}}{k_f k_1 k_3} \cdot \frac{1}{\gamma_a H} \tag{1}$$

where:

C_s — structural weakening coefficient of the rock,

k_{ld} — long-term strength coefficient of the rock,

k_w — coefficient that assesses the influence of humidity on the compressive breaking strength of the rock,

k_{ct} — stress concentration factor, which for underground workings with straight walls is 2.5-3.0,

k_1 — stress concentration factor induced by neighboring mine workings,

k_3 — face-related influence coefficient, with values ranging from 1.0 to 3.5.

The situation met in the mine workings located in the floor of seam 3 from Petrila Colliery can be described through the data synthesized in Tables 1 and 2.

TABLE 1

Horizontal mine workings situation in the floor of seam 3 from Petrila Colliery

Rock type	Depth [m]	Value of „n" index	Characterization
Sandy clay	695	0.138	Mine working is highly unstable, rock deformation occurs in the form of plastic flow all around the working. Displacements become unlimited, support must work under simultaneous deformation regime with the surrounding rock and have a lift p_i = (300-600) kN/m^2 to restore the original balance of the massif.
	745	0.1286	
	795	0.12054	
Compact clay	695	0.2098	
	745	0.1957	
	795	0.1834	
Arenaceous clay	695	0.390	The working is unstable, tending to greater instability. Non-elastic deformations occur throughout the mine working contour. 450 mm or even larger. Displacements are comprised in $100 < u \le 450$ mm or even larger. Support must work under simultaneous deformation with rocks and have a lift of p_i = (60-200) kN/m^2 to restore the original balance of the massif.
	745	0.364	
	795	0.341	
Argillaceous sandstone	695	0.664	
	745	0.619	
	795	0.580	
Siliceous sandstone	695	0.92	The working is of average stability, displacements being u = 50-100 mm. Support is working in given load regime. It is recommended, however, a constant resistance malleable support, p_i = (10-60) kN/m^2
	745	0.858	
	795	0.80	

TABLE 2

Contour displacements of horizontal mine workings, seam 3 floor

Rock type	Depth [m]	Displacement values outside the seam, *u* [mm]		Displacement values considering seam's influence, *u* [mm]		Characterization
		Roof	Walls	Roof	Walls	
Sandy clay	695	251.9	568.8	392.7	707.6	Rock contour is unstable to very unstable especially in the side walls of the working, fully passing to „very unstable" category in the influence area of seam 3 mining operation.
	745	276.48	622.08	417.28	762.88	
	795	313.34	705.00	454.14	569.3	
Compact clay	695	213.50	428.50	354.34	569.30	
	745	215.04	483.80	355.84	624.60	
	795	230.50	516.40	371.20	659.20	
Arenaceous clay	695	184.32	414.72	325.12	555.52	
	745	211.968	476.90	352.77	617.70	
	795	218.11	490.75	358.91	631.55	
Argillaceous sandstone	695	43.00	96.77	31.00	144.77	Outside the influence area of seam 3 mining the workings are stable; otherwise, they move in the average stability domain.
	745	52.20	117.5	100.20	165.50	
	795	55.30	124.42	109.30	172.40	
Siliceous sandstone	695	18.44	41.47	66.44	89.49	
	745	30.72	69.12	78.72	11.12	
	795	33.80	76.03	81.80	12.03	

Analyzing the stability of mine workings according to “n” dependency criterion and the contour deformation “u” through relationship:

$$n = \frac{1,35}{\ln\left(\frac{u}{0,1a}+1\right)} \tag{2}$$

and considering Figure 1 for the geo-mechanical and mining conditions in Jiu Valley, it appears that supporting systems of these workings are working under heavy loads when $n < 0.35$, while the contour deformation of simple profile mine workings is included in the 100 mm-410 mm range or 200 mm-600 mm for double profiles (Toderaş, 1999).

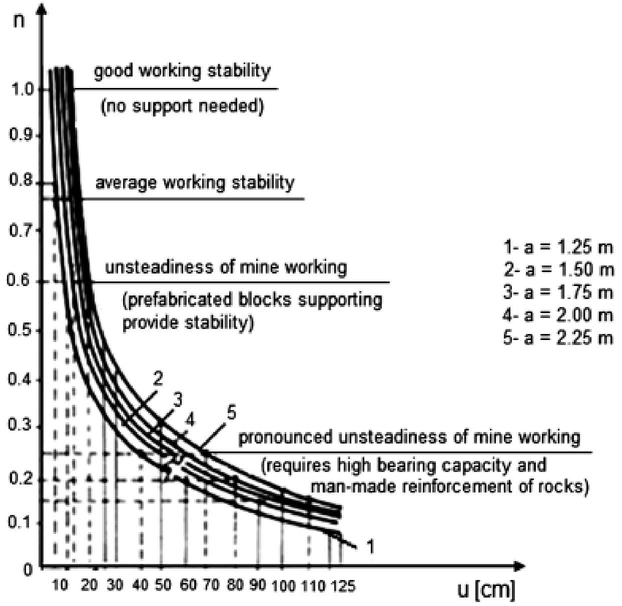

Fig. 1. The „n” stability criterion dependency on rock displacement on the mine working’s contour „u”

3. Stress – strain regime emergence in directional drifts located in seam 3 floor at Petrila Colliery

During 3 years measurements were carried out on the deformation of the support in galleries from levels +50, –50, –100 and –150, and the results (Toderaş, 1992) allowed mathematical statistics processing and setting: the dependence on specific minimum bearing capacity required to metal arched support according to the values of the stability coefficient; dependence of the support movement according to the coefficient of stability; the pressure dependence of the support with respect to time and the rock displacement versus time dependence for calculated stability coefficients.

A) Dependence on specific minimum bearing capacity required to metal arched support according to the values of the stability coefficient

For each of the stations tracking displacements it was determined the specific bearing capacity of the real support installed (P_r) by multiplying the specific bearing capacity of an arch to the number of arches, N, installed in 1meter of mine working (3 arches/meter) i.e.:

$$P_r = N \cdot P_{sc} \tag{3}$$

The specific bearing values obtained were inlaid in the coordinate system: stability coefficient n on the x-axis and bearing capacity on the y-coordinate line (Toderaş, 1992; Todorescu, 1993). Based on experimental data were approximated for each P_r interval, the points which interlinked yielded a curve that determines the minimum bearing capacity required to ensure a reliability level of about 0.95.

B) Experimental dependence of support displacement on stability coefficient values

Such a dependence was obtained by statistical processing of data values recorded at mine levels +50, –50, –100 and –150, resulting in the following regression equation:

$$U = 0{,}0414 - \frac{0{,}043}{n} + \frac{0{,}019}{n^2} \tag{4}$$

C) Pressure dependence on the support versus time span

The same results obtained from measurements (Toderaş, 1992; Toderaş, 1999) led to the establishment of pressure relationship that we consider to approximate the experimentally obtained curves of pressure values; in the resulting correlation, parameters a and b were determined according to stability coefficient „n". Such a correlation is a curve of the form:

$$p = \frac{1}{a} \ln \frac{t+b}{b} \tag{5}$$

where: a and b are dimensionless factors determined by the method of least squares, or by replacing in Eq. (5), the values of the pressure p, for $t = 200 \times 24$ hours, respectively, $t = 1000 \times 24$ hours and whose expressions are having the shapes given bellow

Level –50:

$$\begin{aligned} a &= 0{,}664 n^2 - 0{,}1785 n + 0{,}0839 \\ b &= 0{,}000824 n^2 + 4{,}948 n - 0{,}000839 \end{aligned} \tag{6}$$

Level –100:

$$\begin{aligned} a &= 0{,}00426 n^2 + 0{,}517 n + 0{,}000443 \\ b &= -0{,}00768 n^2 + 4{,}952 n - 0{,}0017 \end{aligned} \tag{7}$$

Level –150:

$$\begin{aligned} a &= 0{,}00161 n^2 + 0{,}521 n - 0{,}000806 \\ b &= -0{,}00644 n^2 + 4{,}942 n + 0{,}00304 \end{aligned} \tag{8}$$

Through pressure calculations according to relation (5) there were obtained corresponding time tracking values; Table 3 synthesizes the results for the directional gallery located at –150 level.

TABLE 3

Pressure variation with time for the directional drift level –150, Petrila Colliery

Rock type / Time [days]	Sandy clay	Compact clay	Arenaceous clay	Argillaceous sandstone	Siliceous sandstone
0	0	0	0	0	0
18	106.27	65.59	31.53	16.68	11.3
38	118.23	73.53	35.76	19.15	13.08
48	121.99	76.01	37.08	19.92	13.63
60	125.59	78.38	38.35	20.66	14.17
81	130.43	81.57	40.06	21.66	14.89
100	133.83	83.82	41.25	22.36	15.39
116	136.22	85.39	42.09	22.85	15.75
130	138.06	8.,6	42.74	23.23	16.02
144	139.71	87.69	43.32	23.57	16.27
160	141.41	88.81	43.92	23.92	16.52
176	142.94	88.83	44.46	24.24	16.75

Solving equations (6), (7) and (8) according to „n" stability criterion values allowed to obtain the *a* and *b* coefficients values as given in Table 4.

TABLE 4

Values of *a* and *b* coefficients according to „n" stability criterion

„n" stabilitaty criterion	**Coefficient values obtained**	
	a	***b***
0.138	0.072	0.682
0.2098	0.1153	1.038
0.390	0.204	1.929
0.664	0.348	3.285
0.920	0.482	4.551

In the cases considered, Eq. (5) assessing the load exerted on metal supports of directional drifts located in the floor of seam 3 at Petrila Colliery, will have the shapes given bellow (see Figure 2):

Level –50:

$$p = \frac{\ln \dfrac{t + 0{,}000824\,n^2 + 4{,}948\,n - 0{,}000839}{0{,}000824\,n^2 + 4{,}948\,n - 0{,}000839}}{0{,}664\,n^2 - 0{,}1785\,n - 0{,}0839} \tag{9}$$

Level –100:

$$p=\frac{\ln\dfrac{t-0,00768\,n^2+4,952\,n-0,0017}{-0,00768\,n^2+4,952\,n-0,0017}}{0,00426\,n^2+0,517\,n+0,000443} \tag{10}$$

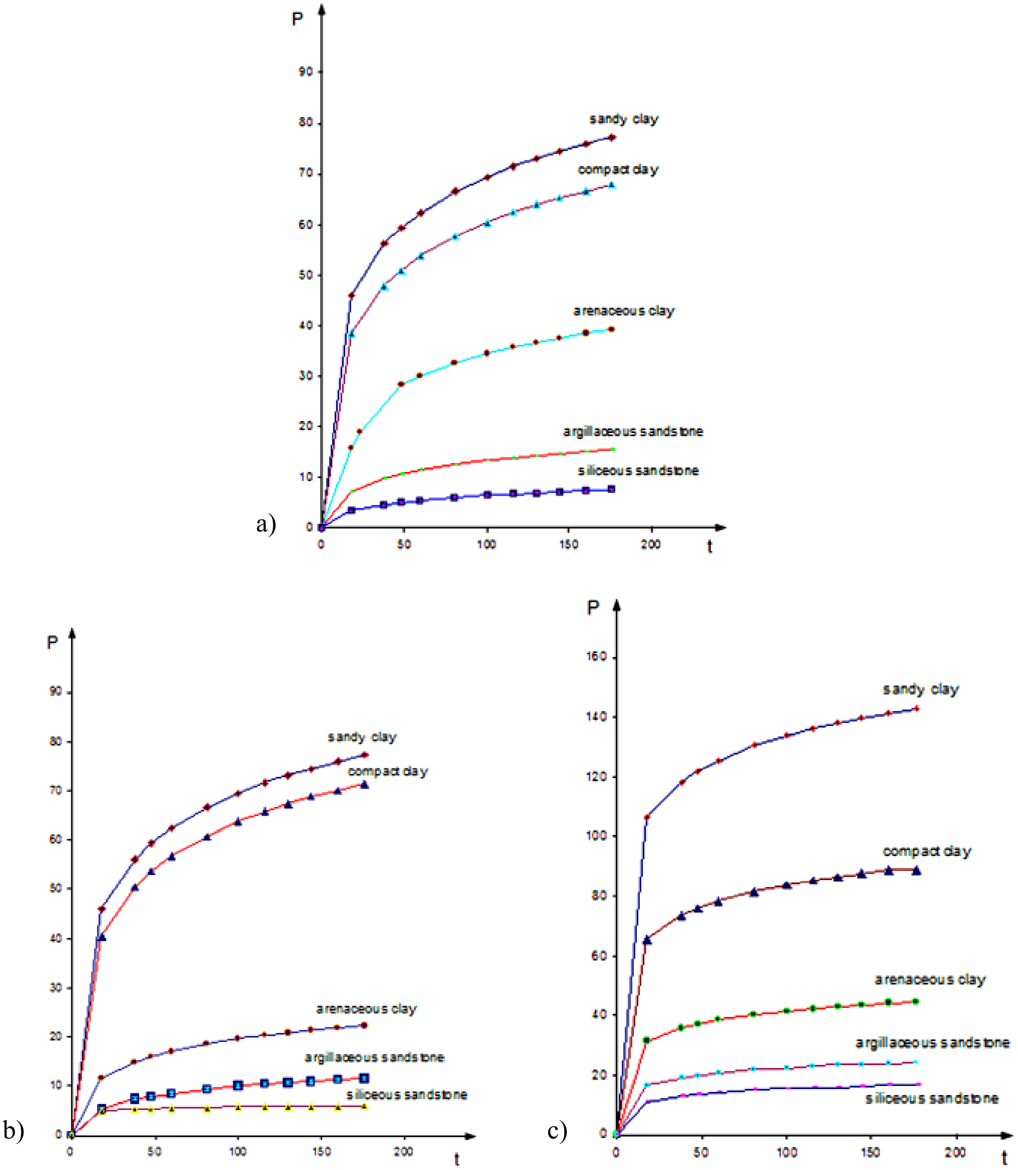

Fig. 2. Graphs of pressure variation in time in directional drifts located in seam 3 Petrila Colliery – Jiu Valley basin: a) Level –50; b) Level –100 c) Level –150

Level –150:

$$p = \frac{\ln \dfrac{t - 0,00644n^2 + 4,942n + 0,00304}{-0,00644n^2 + 4,942n + 0,00304}}{0,00161n^2 + 0,521n - 0,000806} \tag{11}$$

Similarly, by processing the results of measurements based on the values support displacement according the „n" stability coefficient, we have reached a corresponding relationship, as it follows:

$$u_t = 28,571 \frac{t + 0,174n^{-2} - 0,436n^{-1} + 0,28}{0,174n^{-2} - 0,436n^{-1} + 0,28} e^{3,94n} \tag{12}$$

on which were built the graphs relating the rock contour movements of the mine working, to the duration of observations and the stability coefficient „n" (see Figures 3 and 4).

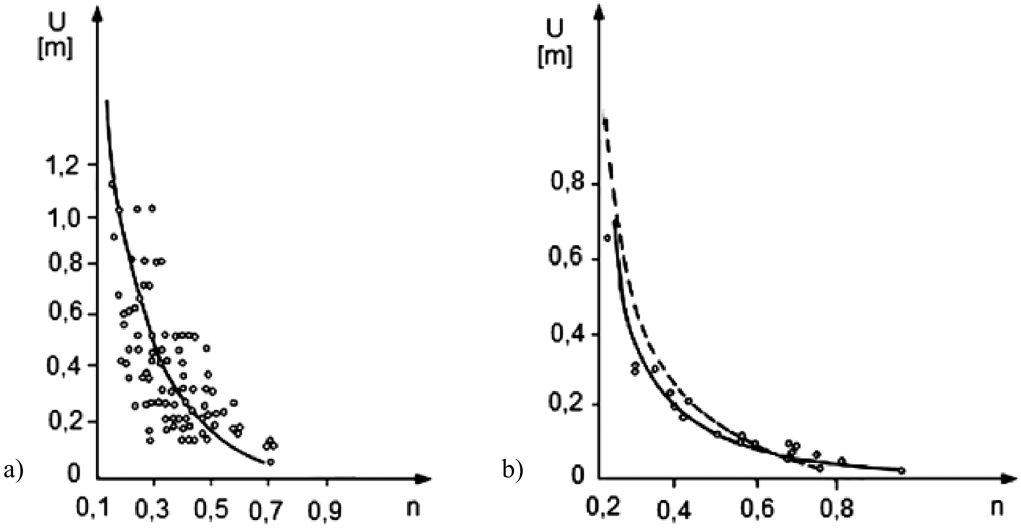

Fig. 3. Graph of rock displacement variation on working's contour versus „u" the "n" stability criterion

Expressing the experimental results in the form of dependencies $p = p(n)$ and $u = u(n)$, a correlation relationship can be observed between the two parameters considered:

$$\begin{aligned} p &= -0,091 + 0,112n^{-1} - 0,068n^{-2} \\ u &= -0,0016 - 0,0195n^{-1} + 0,043n^{-2} \end{aligned} \tag{13}$$

From the above, it follows that the index „n" can be considered as a complex parameter through which we can express most of the main laws of pressure regime manifestation and assess the mining loads on support and it's displacement.

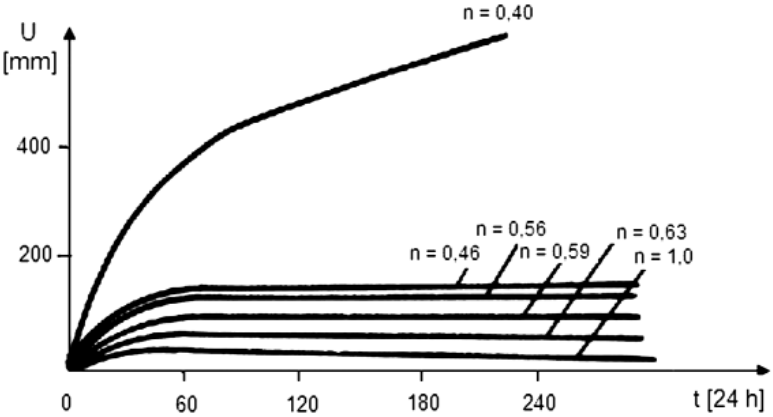

Fig. 4. Diagrammatic representation of the rock contour displacement „u"dependence on observation time span "t" and the „n" criterion of stability

Analyzing further the implications of such a stability criterion it was found that for values of $n < 0.2$ and $n > 1$ practically the displacements do not depends on the value of cross-sectional area of the mine working, or the angle of rock stratifications. For the range $0.2 < n < 1$, the displacement increase is proportional to the increase in the cross – sectional area of the mine working. With increasing angle of rock stratifications, $\alpha = 0°\text{-}90°$, it proportionally decreases the rock and support displacement, approximately with 30% for cross-cut galleries and only (10-15) % for directional drifts.

4. Conclusions

Objective primary information on the laws that can characterize in geomechanic terms the rock massif describe in a qualitative and quantitative way the deformation of the rock massif and elucidates the pressure regime manifestation in all its forms. They are needed for creating improvement opportunities of the existing techniques and development of new methods aimed to find means to ensure the mine workings stability according to the present level of scientific and technical development. To achieve such a goal complex research was carried out, combining laboratory and *in situ* field tests with thorough analytical research. The concept of stability is cumulative, aimed firstly at knowledge of the real geo-mechanical characteristics of the rock, a natural state of tension, the secondary stress-strain state, i.e. the pressure of the rock massif, and secondly trying an explanation of geotectonic processes and groundwater presence in the very context of production activities related to the construction of underground excavations. Currently, there is an intensive development of analytical research on the evaluation of the mine workings stability. However, they allow yet only approximate evaluations, guidance and therefore it requires in almost all cases, laboratory test for experimental verification (modeling) and *in situ* observations – measurements. Laboratory and in situ research techniques alone, allow to obtain only the cumulative effect of all determinants, without being able to separate the effects of each. This is why in our case study regarding Petrila Colliery from the Romanian Jiu Valley coal basin we applied this combined approach. Based on the same analysis, diversification can be achieved in several main groups of the manifestation character of the pressure regime from the Jiu Valley, with direct reference to Petrila Colliery, namely:

a) for $n \geq 0,7$, the load on the support for a period of (30-60) days increases to an average of 30 kPa, following a reduction thereof by about (20 to 25) %, followed by a further but slow increase (1.2 kPa/year), tending to a constant value in $t \geq (2.5\text{-}3)$ years. As a result, the load on the support, for $t > (10\text{-}15)$ will be (40-50) kPa and basically depends on the malleability of the support system. This mode of manifestation of the pressure corresponds to the formation of a natural dome of equilibrium at the mine working's roof, as confirmed by both displacement measurements and direct observations during excavation and support setting stages;

b) for $0,2 < n < 0,7$ the burden increases more intensively on the support, although in this case both the pressure and displacement curves gradually flattens. The value of load on the support depends essentially on the malleability of the support system. In such circumstances, around the mine working the non-elastic deformation area (pseudoplastic deformation behavior) is formed, whose size can change quite broad limits;

c) for $n \leq 0,2$, rock around mine working will manifest as a viscous – plastic massif. The loads on the support are quickly increasing and rock movements, when backward push is not enough, are having a viscous flow character. The load on limited supporting malleability after (6-10) months of operation does not really depends on the characteristics of support, reaching; the load burden reaches (0.8 to 2.2) MPa at a depth of 800 m.

Conclusively, in the context of stability concept are included three main categories of problems: (i) issues related to determining the deformation and fracture behavior of rocks in which mine workings are located, due to the complex actions occurring around them; (ii) problems involving the phenomenon of rock massive elements interaction with each other, and with the elements of the mine structures based on the geo-mechanical conditions and characteristics of the support; (iii) problems related to the influence of mining operations on the workings, particularly the undermining phenomenon, and respectively overmining.

References

Brown E.T., Bray J.W., Ladanyi B., Hoek E., 1983. *Ground response curves for rock tunnels*. ASCE J. Geotech. Eng., 109, 15-39.

Carranza-Torres C., 2004. *Elasto-plastic solution of tunnel problem using the generalized form of the Hoek-Brown failure criterion*. Int. J. Rock Mech. Min. Sci., 41(3), 480-1.

Hejmanowski R., Kwinta A., 2009. *Determining the Coefficient of Horizontal Displacements with the Use of Orthogonal Polynomials*. Arch. Min. Sci., Vol. 54, No 3, p. 441-454.

Kortas G., 2013. *Long- and short-term processes indicated by the displacement of the chamber roofs in the monumental Wieliczka salt mine*. Arch. Min. Sci., Vol. 58, No 1, p. 119-123

Lee Y.K., Pietruszczak S., 2008. *A new numerical procedure for elasto- plastic analysis of a circular opening excavated in a strain- softening rock mass*. Tunnelling and Underground Space Technology.

Lețu N., Semen C., 1981. *Influence of rock physical and mechanical characteristics caracteristicilor on the stability of horizontal mine workings and selection of most fitted support for Jiu Valley conditions (in Romanian)*. Mines. Oil and Gasses.Vol. 32, No 10, 78-86.

Popescu Al., Todorescu A., 1982. *Rock Mechanics in Mining (in Romanian)*. Technical Publishing House, Bucharest.

Toderaş M., 1992. *Critical analysis of horizontal drifts stability in Jiu Valley and assessment of main factors influencing their stability (in Romanian)*. Ph.D. Research Report, December, University of Petroşani, Romania.

Toderaş M., 1999. *Research regarding the rheological behaviour characterization of rocks within Jiu Valley basin and implications on main horizontal mine working provision (in Romanian)*. Ph.D. Thesis, University of Petroşani, Romania.

Toderaş M., 2006. *The evaluation of the pressure's manifestation way from the surrounding main horizontal mining workings from Valea Jiului area, according to the knowledge of the reological behavior of the surrounding rocks*. Journal of Mines, Metals and Fuels, 54(12): 300-304.

Todorescu A., 1993. *Research regarding the stability of main opening horizontal mine workings at Petrila Colliery through pressure regime knowledge and dolutions for stability provision (in Romanian)*. Research Grant No 24/1993, National Hardcoal Company.

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