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Experimental determination of the boundaries of the influence of a stope working on the earth's surface

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Abstract

The theoretical part of the research methodology is developed according to the scheme of subsidence of points on the earth's surface relative to the projection of the face. The curve of the trajectory of the subsidence of the earth's surface is divided by characteristic points at different stages of subsidence of the earth's surface. Such stages include: the beginning of the displacement of the earth's surface, the active stage of displacement, the end of the active stage and the attenuation of the processes of subsidence of the earth's surface. According to the goal and the design scheme, on the basis of experimental data, we determined the parameters corresponding to the location of a point on the earth's surface where it began to settle. In relation to the scheme under consideration, three well-known dependencies were analyzed to describe the subsidence curve of the earth's surface: the exponential equation, the hyperbolic tangent function, and the logistic curve. Based on them, it was established that the main influencing factor determining the boundary of the dynamic half-mold is the depth of mining operations, and the boundary angles are practically independent of this parameter.

Keywords: Beginning of subsidence, Boundary angles, Boundary, Depth, Dynamic semi-trough, Earth surface, Face, Movement, Point.

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Contents

Contribution of this paper to the literature

This experimental and theoretical studies have made it possible to draw important conclusions for science and industrial activity about the stages of subsidence of the earth's surface. The characteristic points and the curve of dependence of rock subsidence on the degree of development of clearing operations were determined.

1. Introduction

One of the little-studied issues in the development of coal seams is the reliable determination of the boundaries of the influence of stope workings on the earth's surface. This is confirmed by the results [1] of comparing the experimentally determined sizes of the earth's surface displacement troughs with their parameters calculated according to the normative document [2]. For example, in the conditions of the "Stepnaya" mine, the calculated values of the dimensions of the troughs of the earth's surface displacement were significantly less than the experimentally determined parameters. In the conditions of the mine named after P.L. Voikov, on the contrary, the experimental values of the dimensions of the displacement troughs of the earth's surface were several times higher than their calculated values. This situation indicates the relevance of work related to the study of the impact of stopes on the earth's surface.

The results of such work determine the successful solution of engineering problems on the manifestation of rock pressure on the lining of workings, the establishment of possible water and gas inflows from the undermined coal-rock stratum and environmental consequences. The purpose of the work is to establish the factors that determine the boundary of the dynamic semi-trough on the earth's surface in front of the projection of a moving stope.

2. Materials and Methods

The theoretical part of the research methodology was developed taking into account the scheme of subsidence of the earth's surface [3] relative to the projection of the stope Figure 1.

In this scheme, instead of time along the abscissa axis, the distances (*L*) from the projection of the stope line onto the earth's surface to the observation points were plotted. The characteristic points of the curve of subsidence dynamics are: *A*- corresponds to the beginning displacement, *O* - is located in the alignment with a stope and serves as a reference point along the abscissa axis; *B* - the beginning of the active stage; *C* is the maximum settling rate and the inflection point of the curve, *D* is the end of the active stage and the beginning of its decay, *F* is the beginning of the residual effect. The decay stage in the scheme under consideration is limited by the point *F*. Its subsidence (η_o) is approximately 0.97 ÷0.99 of the final ($\eta_к$) at the end of the processes of rock compaction [3].

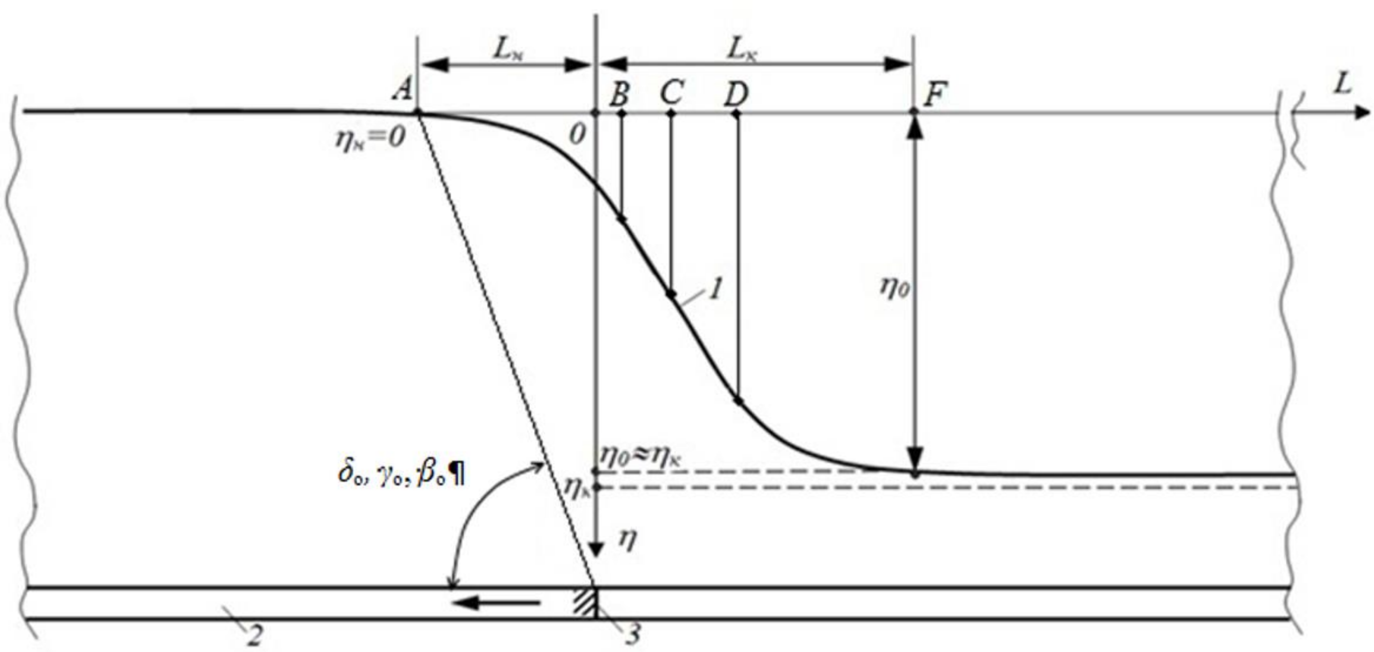

Figure 1. Scheme of subsidence of the earth's surface relative to the projection of the production face.

Note: 1 - curve of the trajectory of the points of subsidence of the earth's surface; 2 - reservoir under development; 3 - the position of the stope relative to the curve of the dynamics of subsidence of the earth's surface at the initial moment of influence on point A ; $\eta_н$, $\eta_к$ - respectively, the initial and final subsidence of the earth's surface; η_0 - depth of the flat bottom of the shear trough to the compaction of the rocks; L_n , L_k - the distance between the projection of the stope and points A and F , respectively, at the beginning and end of the displacement; δ_o , γ_o , β_o - boundary angles (depending on the direction of mining of the extraction column) that determine the position of point A (the beginning of the earth's surface displacement); ⟵ - stope advancing direction.

According to the goal and the design scheme Figure 1, on the basis of experimental data, it is necessary to determine for each specific case the parameters that determine the position of point *A*. These include boundary angles (δ_o - when mining seams along strike, γ_o - along rise, β_o - along dip), as well as $L_Н$ - the distance from the projection of the production face to point *A*.

3. Results and Discussion

The division of the process of displacement of undermined rocks and the earth's surface into separate stages was carried out using the recommended [3-5] functions.

As applied to the scheme under consideration Figure 1, the dynamics of subsidence of the earth's surface is described by an exponential equation [1]:

$$\eta(L)=\eta_K\left(1-\exp^{-\beta_1(L+L_H)^2}\right), \qquad (1)$$

Where η - is the subsidence of the observation point on the earth's surface when its projection is removed at a distance L from the production face, mm;

β_1 - empirical coefficient determined from experimental data.

The first three derivatives of the function (1) are the equations of the settling rate, acceleration and acceleration change. The extrema of the obtained dependencies are used to determine the coordinates of the characteristic points, which are used as the boundaries of the displacement stages [3].

In a similar way, the boundaries of the stages of subsidence of the earth's surface are determined based on the extrema of the first two derivatives of the functions of the hyperbolic tangent [4]:

$$\eta(L)=n_1[1+\tan h(n_2\cdot L+n_3)], \qquad (2)$$

Where n_1, n_2, n_3 - are empirical coefficients determined by the least squares method.

When constructing the curve of the dynamics of subsidence of the earth's surface from the absolute values of the experimental data according to the function of the hyperbolic tangent, it was found that the coefficient n_1 is numerically equal to half of the final subsidence ($n_1=\eta_K/2$).

The distance $L_н$ Figure 1 is determined from the condition $\eta_н=0$. The minimum value of the function (2) asymptotically approaches zero, therefore, to determine the beginning of the impact of cleaning operations on the earth's surface, an assumption was introduced $\eta_H=d_1\cdot\eta_K=0{,}01\,\eta_к$. The parameter $L_н$ for this case is determined from Equation 2:

$$L_н=\frac{\operatorname{arctan}h(2\cdot d_2-1)-n_3}{n_2}=\frac{1.946-n_3}{n_2}. \qquad (3)$$

The derivatives of the hyperbolic tangent function correspond to the dependencies [6]:

$$\eta'(L)=n_1\cdot n_2[1-\tan h^2(n_2\cdot L+n_3)], \qquad (4)$$

$$\eta''(L)=-2n_1\cdot n_2^2\tan h(n_2\cdot L+n_3)\cdot[1-\tan h^2(n_2\cdot L+n_3)]. \qquad (5)$$

Based on the values of the extrema of Equations 4, 5, the coordinates of the characteristic points of the curve of the dynamics of subsidence of the earth's surface are determined.

The logistic curve equation for describing the dynamics of subsidence of the earth's surface has the form [5]:

$$\eta(L)=\frac{a}{1+b\cdot\exp(-c\cdot L)}, \qquad (6)$$

Where a - is an empirical coefficient corresponding to the final subsidence of the earth's surface (η_K);

b, c - empirical coefficients that determine the position of the curve relative to the abscissa axis and the width of the middle section, i.e. the duration of the active stage of subsidence of the earth's surface.

The first derivative of Equation 6 is characterized by the dependence:

$$\eta'(L)=\frac{a\cdot b\cdot c\cdot\exp(-c\cdot L)}{1+b\cdot\exp(-c\cdot L)^2}. \qquad (7)$$

Extreme value of the function $\eta'(L)$ corresponds to the inflection point C of the logistic curve Figure 1 with coordinates ($\frac{\ln b}{c},\frac{a}{2}$).

The second derivative of the original Equation 6:

$$\eta''(L)=\frac{-a\cdot b\cdot c^2\cdot\exp(-c\cdot L)\cdot[1-b\cdot\exp(-c\cdot L)]}{1+b\cdot\exp(-c\cdot L)^3} \qquad (8)$$

Has two extreme values. The values of these coordinates determine the position of the active stage of subsidence of the earth's surface (points B and D).

The parameter $L_н$ for the logistic curve (6) was determined from the conditions $\eta_н=d_1\cdot\eta_к=0{,}01\cdot\eta_к$ and $a=\eta_к$:

$$L_н=-\frac{\ln(\frac{1/d_1-1}{b})}{c}=-\frac{4.595-\ln b}{c}. \qquad (9)$$

Parameter $L_к$ found from the condition $\eta=d_2\cdot\eta_к=(0{,}97\div0{,}99)\eta_к$:

$$L_к=\frac{\ln\cdot\left(\frac{1/d_2-1}{b}\right)}{c}=-\frac{-3.892-\ln b}{c}. \qquad (10)$$

The coordinates of the characteristic points (A, O, B, C, D, F) of the curve of the dynamics of subsidence of the earth's surface, determined according to the initial dependencies (1, 2, 6), are summarized in Table 1.

Table 1. Dependencies for determining the coordinates of the characteristic points of the curve of the dynamics of subsidence of the earth's surface according to the exponential, hyperbolic tangent and logistic equations.

Characteristic points of the curve of the dynamics of subsidence of the earth's surface Figure 1	Exponential equation		Hyperbolic tangent equation		Logistic equation	
	Abscissa L, m	Ordinate η, mm	Abscissa L, m	Ordinate η, mm	Abscissa L, m	Ordinate η, mm
A	$-L_H$	0	$-\frac{2{,}298+n_3}{n_2}$	0	$\frac{4{,}595-\ln b}{-c}$	0
O	0	$\eta_K\left[1-exp\left(-\beta_2 \cdot L_0^2\right)\right]$	0	$n_1\left[1+\tanh n_3\right]$	0	$\frac{\eta_K}{1+b}$
B	$\frac{0{,}5246}{\sqrt{\beta_1}}-L_H$	0.241 η_K	$-\frac{0{,}658+n_3}{n_2}$	0.21 η_K	$\frac{\ln(3{,}73/b)}{-c}$	0.21 η_K
C	$\frac{0{,}7071}{\sqrt{\beta_1}}-L_H$	0.393 η_K	$-\frac{n_2}{n_3}$	0.50 η_K	$\frac{\ln b}{c}$	0.50 η_K
D	$\frac{1{,}2247}{\sqrt{\beta_1}}-L_H$	0.777 η_K	$\frac{0{,}658-n_3}{n_2}$	0.80 η_K	$\frac{\ln(0{,}268/b)}{-c}$	0.79 η_K
F	$\sqrt{\frac{\ln(1-d)}{-\beta_1}}-L$	$(0.97\div0.99)\eta_K$	$\frac{1{,}946-n_3}{n_2}$	$(0.97\div0.99)\eta_K$	$\frac{3{,}892-\ln b}{c}$	$(0.97\div 0.99)\eta_K$

The next stage of the work was to determine for each object of observation the empirical parameters included in the original equations.

For the exponential Equation 1 we found the values η_K, β_1, L_H, for the Equation 2 of the hyperbolic tangent - n_1, n_2, n_3 and for the logistic dependence (6) - *a*, *b*, *c*.

The processing of experimental data, in order to determine the empirical coefficients of Equations 1, 2, 3, was carried out by the least squares method. Using their numerical values and dependencies to determine the coordinates of characteristic points Table 1, we found the boundaries of the stages of subsidence of the earth's surface during the cleanup operations at ten sites Table 2.

Table 2. The results of determining the empirical coefficients and correlation relationships (*R*) by the least squares method for the objects of observation.

Mine, reservoir, literary source	Math functions											
	Logistics				Exponential				Hyperbolic tangent			
	$a=\eta_K$	*b*	*c*	*R*	β_1	L_H	η_K	*R*	$n_1=0.5\eta_K$	n_2	n_3	*R*
"Belozerskaya", [3]	810	4.1	0.016	0.998	2.0	105	810	0.999	405	0.008	-0.70	0.997
№22 "Kommunarskaya", K_3, [4]	900	9.3	0.010	0.998	1.0	70	900	0.976	450	0.005	-1.11	0.998
"Gramoteinskaya", Sychevsky- III, [7]	2375	13.0	0.028	0.999	5.0	Thirty	2420	0.987	1180	0.015	-1.28	0.995
Appalachian basin mine, [8]	980	26.0	0.040	0.995	6.5	20	1010	0.991	490	0.019	-1.65	0.994
"Anniversary", C_6', [9]	915	12.5	0.050	0.997	1.5	20	910	0.974	458	0.026	-1.27	0.996
Them. A.F. Zasyadko, t_3, [10]	400	7.0	0.006	0.997	3.0	70	400	0.974	200	0.003	-1.20	0.996
Staszic, 352, [10]	480	4.1	0.020	0.999	5.0	60	980	0.984	490	0.010	-0.70	0.999
Ruhr basin mine, Grimberg 2/3, [10]	1420	5.8	0.010	0.998	5.5	200	1420	0.979	710	0.005	-0.87	0.998
Them. CM. Kirov, PO "Leninskugol", Boldyrevsky, [11]	1300	7.1	0.070	0.996	3.3	21	1310	0.997	638	0.041	-0.98	0.994
"Steppe", [12]	832	5.8	0.064	0.996	3.1	20	835	0.994	416	0.029	-0.95	0.995

It should be noted that in most cases the values η_K, determined using the considered functions, were practically equal to each other. Differences, as a rule, did not exceed 1.0% and only in one case (the mine of the Appalachian basin), the maximum difference was 3.1%. This indicates the possibility of using any of the considered functions to determine the ordinates of characteristic points.

A similar conclusion was reached about the possibility of using the analyzed functions to determine the abscissas of the characteristic points of subsidence of the earth's surface. Using the empirical coefficients of the equations Table 2 for all mines, we calculated the abscissa (L_A) of the characteristic point *A* Table 3.

On the basis of experimental data [7, 13] it was established that the parameters of the trough of displacement of the earth's surface by 80% or more can be determined by the depth of work. To test and confirm this assumption, on the basis of the data Table 3, we determined the dependences of the average values of the abscissas of the characteristic point *A* on the depth of the treatment. The results of these calculations show that the characteristic point abscissas are directly proportional to the mining depth Figure 2. In absolute value, the correlation coefficient (r) for different coal basins was equal to 0.89.

Table 3. The results of determining the coordinates of the characteristic point *A* of subsidence of the earth's surface along the abscissa and boundary angles (δ_o, γ_o, β_o).

Mine, reservoir, literary source	Depth of cleaning operation, *H, m*	The thickness of the developed reservoir, *m, m*	*H/m*	Seam dip angle, α, degrees	The distance between the projection of the production face and point *A*, L_A, *m*	Boundary angles, δ_o, γ_o, β_o, degrees
"Belozerskaya", [3]	420	1.30	323	12	169	68
No. 22 "Kommunarskaya", K_3, [4]	652	1.47	444	20	178	75
"Gramoteinskaya", Sychevsky- III, [7]	220	4.50	49	Four	57	75
Appalachian Basin Mine, [8]	220	1.65	133	-	28	83
"Anniversary", S_6, [9]	150	1.00	150	3	34	77
Them. A.F. Zasyadko, m_3, [10]	1195	2.10	569	10	292	76
"Stashitz", 352, [10]	480	2.10	229	-	126	75
Ruhr mine, Grimberg , 2/3, [10]	920	2.20	418	-	253	75
Them. CM. Kirov, PO "Leninskugol", Boldyrevsky, [11]	205	1.70	121	6	Thirty	82
"Steppe", [12]	106	0.91	116	Four	37	71

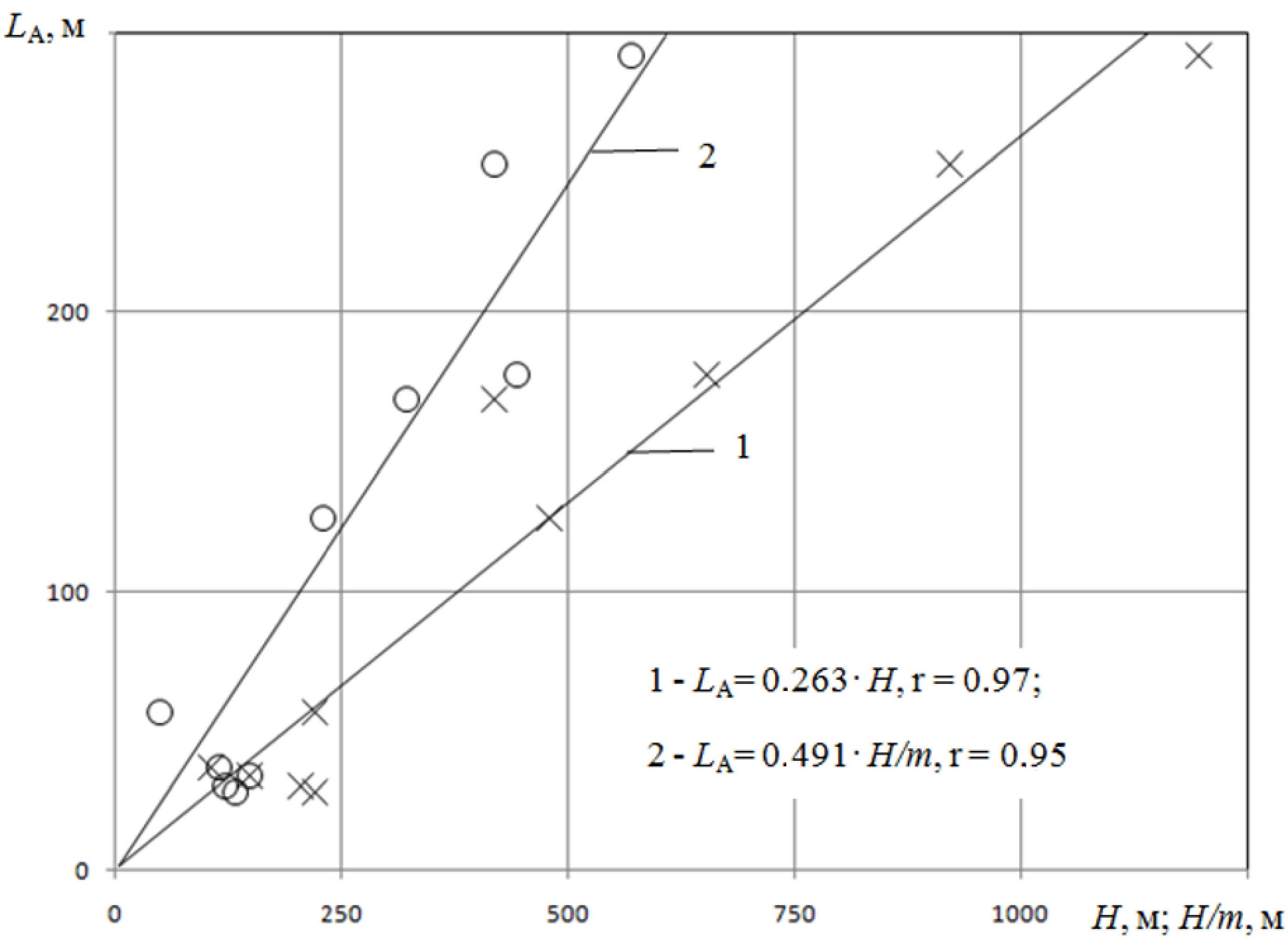

Figure 2. Dependence of the abscissa L_A of the characteristic point *A* on the depth of the cleaning operations *H* and the parameter *H/m*.
Note: 1, 2 - Averaging direct links L_A respectively with *H* and *H m*; ×, ○ - Experimental data; r - Correlation coefficient.

A fairly close correlation (r = 0.95) was established between the abscissas L_A and the relative parameter *H/m* Figure 2. This indicates that the parameter *H/m*, along with the depth, can determine the boundary of the dynamic trough in front of the projection of the stope.

Connection of boundary angles (δ_o, γ_o, β_o) with *H* and *H/m* has not been established Figure 3. Correlation coefficients were respectively - 0.13 and - 0.25. Boundary angles (δ_o, γ_o, β_o) were in the range of 68-83°, with an average value of 76°.

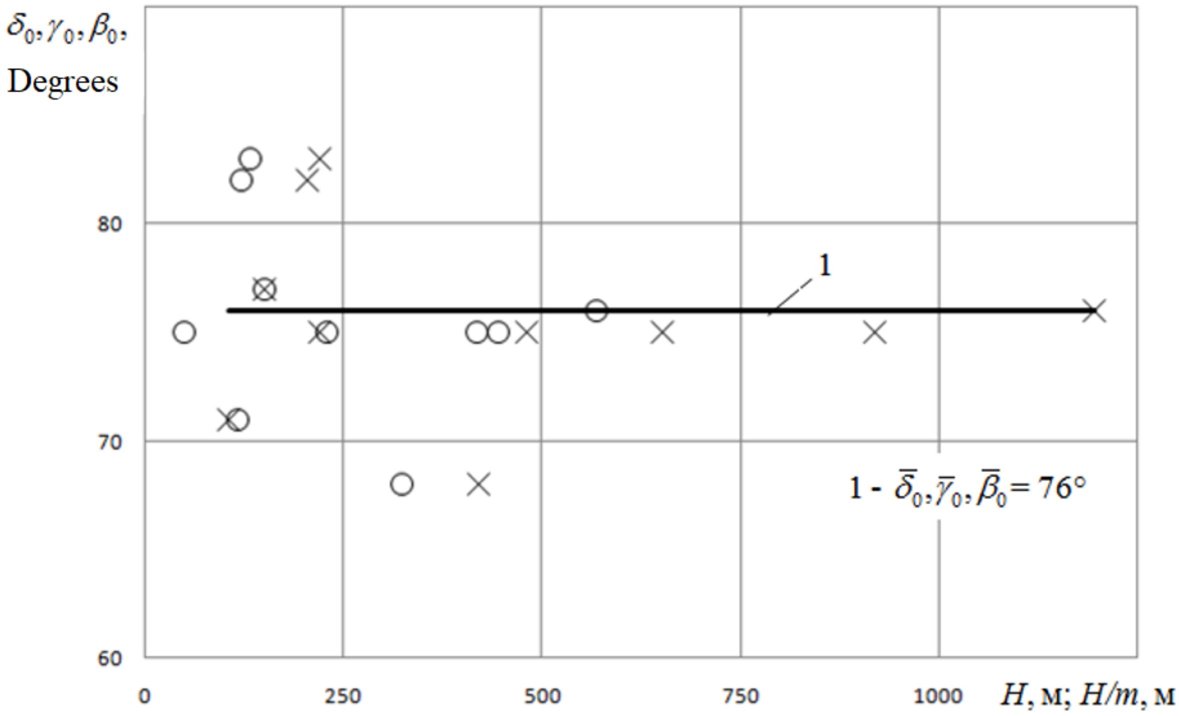

Figure 3. Dependence of the boundary angles (δ_0, γ_0, β_0) on the depth of treatment operations H and the parameter H/m .
Note: 1 - Straight line corresponding to the average values of the angles (76°); ×, ○ - Experimental values, respectively, of the lependence on H and H/m.

Mining of coal seams has, first of all, an impact on the displacement of host rocks. As a result, the rock pressure on the lining of the development workings changes, and displacement troughs form on the earth's surface. In one case, the lining of the workings is deformed and the conditions for their maintenance in the zone of influence of the mining operations become much more complicated. In the second, it is necessary to take measures to protect objects on the earth's surface. Based on the similar course of the processes of subsidence of the earth's surface and the displacement of rocks under the influence of a moving stope on the contour of sectional workings, an assumption was made about a possible connection between the phenomena under consideration. The establishment of general patterns or differences between the subsidence of the earth's surface and the conditions for maintaining section workings can contribute to the successful solution of many engineering problems. These tasks include the development of rational measures for the protection of objects on the earth's surface and the maintenance of sectional workings in the zone of influence of clearing operations. Research in this direction is very relevant.

A characteristic feature that combines the subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings is the same type of experimental dependences of the dynamics of the processes under consideration. The common features of these processes include a gradual increase in the subsidence of the undermined rock mass on the contour of the section workings. The intensity of subsidence of the earth's surface and the displacement of rocks increases as the stope approaches. After the passage of the lava, the subsequent attenuation of the processes occurs. The dynamics of subsidence of the earth's surface and the displacement of roof rocks and soil of a sectional mine under the influence of a stope can be described by a diagram Figure 4. In this scheme, the abscissa shows the distances ($L_З$) from the projection of the stope line onto the earth's surface to the observation points, as well as the distances from the stope ($L_П$ and L_K) to the points of observation of the displacement of soil and roof rocks on the working contour.

Characteristic points that determine the dynamics of ongoing processes are: $A_П$, A_K, $A_З$ - correspond to the beginning of the shift of soil rocks and the roof of workings and the earth's surface; $O_П$, O_K, $O_З$ - are located in the alignment with the stope and serve as the origin of the coordinate axes; $B_П$, B_K, $B_З$ - the beginning of the active stage of displacement of soil rocks and the roof of workings and subsidence of the earth's surface; $C_П$, C_K, $C_З$ - correspond to the maximum rate of rock displacement and subsidence of the earth's surface and are the inflection points of the curves; $D_П$, D_K, $D_З$ - end of active stages and beginning of attenuation stages; $F_П$, F_K, $F_З$ - the beginning of the residual impact of the stope on the processes under consideration.

The decay stages in the scheme are limited by the points $F_П$, F_K and $F_З$. The subsidence of the earth's surface at a point $F_З$ is approximately 0.97 ÷ 0.99 of the final (η^K) at the end of the rock compaction processes. The end of the processes at the points $F_П$ and F_K can be established experimentally by comparing their shift with a change in the working contour outside the influence of the stope. According to, when workings are located outside the zone of mining operations, the difference between the roof-soil convergence does not exceed 10%, and the decrease in the design sections of workings is 0.8%. When calculating the coordinates of the points $F_П$ and F_K, taking into account the above ratios, we used the recommendations.

The purpose of the work is to establish, on the basis of experimental data, the characteristic stages of subsidence of the earth's surface and the displacement of soil rocks and the roof of a sectional mine under the influence of a moving stope.

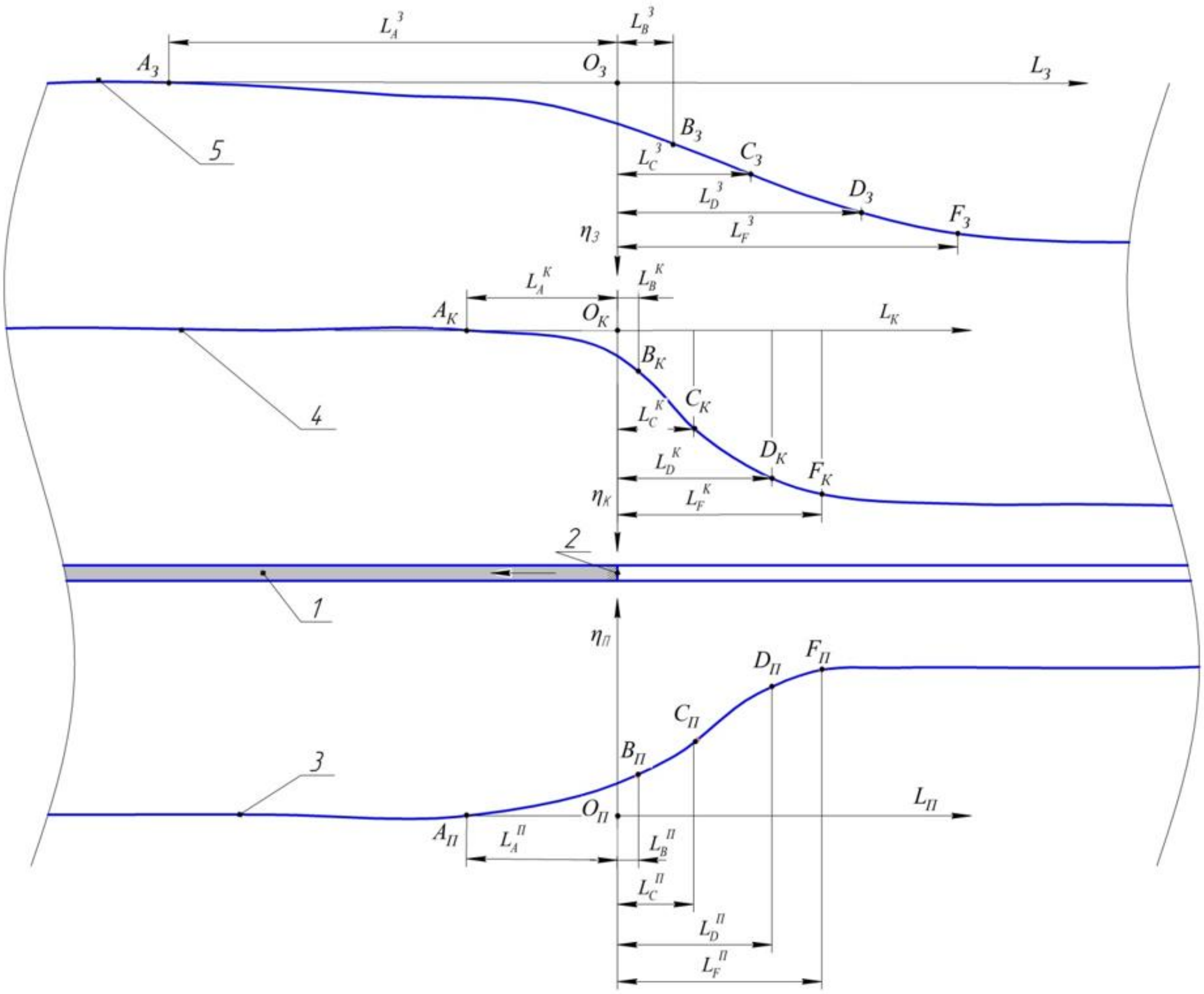

Figure 4. The scheme of subsidence of undermined rocks and the earth's surface and soil relative to the face.

Note: 1 – reservoir under development; 2 - stope; 3,4,5 - curves characterizing, respectively, the displacement of the soil and the roof of the sectional working and the subsidence of the earth's surface; $L_П$, L_K, L_3 - abscissa axes, respectively, for the soil and the roof of the working and the earth's surface; $\eta_П$, η_K, η_3 - y-axis for the soil and the roof of the working and the earth's surface, respectively; $A_П$, $B_П$, $C_П$, $D_П$, $F_П$ - characteristic points of the soil displacement curve; A_K, B_K, C_K, D_K, F_K - characteristic points of the roof displacement curve; A_3, B_3, C_3, D_3, F_3 - characteristic points of subsidence of the earth's surface.

The method of work included several stages:

- Development of a general scheme for the subsidence of the earth's surface and the displacement of soil rocks and the roof of a sectional mine Figure 4;
- Analysis of the available experimental data on subsidence of the earth's surface and displacement of rocks on the contour of sectional workings;
- Selection of mathematical dependencies that most accurately describe the processes under consideration and reflect their physical essence;
- Study of empirical equations obtained on the basis of the accepted mathematical dependence using derivatives to establish the characteristic points of subsidence of the earth's surface and the displacement of rocks on the contour of a sectional working;
- Determination of the distances from the characteristic points of subsidence of the earth's surface to the projection of the production face (L_A^3, L_B^3, L_C^3, L_D^3, L_F^3) and the removal of characteristic points of displacement of soil and roof rocks from the production face ($L_A^П$, $L_B^П$, $L_C^П$, $L_D^П$, $L_F^П$ and L_A^K, L_B^K, L_C^K, L_D^K, L_F^K);
- Comparison of the established parameters and conclusions about the general or distinctive patterns of the processes under consideration.

For the practical implementation of the scheme Figure 4, as the initial function describing the processes under consideration, based on the results of work, we took the logistic curve of the form:

$$\eta(L) = \frac{a}{1 + b \cdot \exp(-c \cdot L)}, \tag{11}$$

Where η is the subsidence of the observation point on the earth's surface or the displacement of rocks on the contour of the working; a is an empirical coefficient corresponding to the final value of subsidence (η^K); b, c are empirical coefficients that determine the characteristic stages of the processes; L - distances characterizing the position of points relative to the production face along the abscissa axis.

Empirical coefficients of Equation 11 a, b, c, which correspond to the parameters of subsidence of the earth's surface in the conditions of the Stepnaya mine, were determined according to empirical dependencies. It was found that the coefficients *a*, *b* And *c* depend on the thickness of the developed seam (t), the depth of work (H), the speed of advancing the stope ($\upsilon_{оч}$) and the length of the lava ($L_л$):

$$a = \frac{1}{(-2{,}64 \cdot 10^{-4} \cdot m + 1{,}54 \cdot 10^{-3})}, \quad (12)$$

$$b = \frac{1}{(-0{,}14 \cdot \upsilon_{оч} / H + 0{,}19)}, \quad (13)$$

$$c = 0{,}205 + 0{,}0148 \cdot \ln\left(\frac{1}{m \cdot L_л \cdot H}\right). \quad (14)$$

Correlation relationships (R) for empirical dependences (12,13,14) were respectively 0.881, 0.884 and 0.986. This indicates the possibility of a fairly accurate determination of the coefficients of dependence (11) according to Equations 12,13,14. For their calculation, we used the parameters characterizing the operating conditions of the 157th and 161st longwalls of the Stepnaya mine (t = 1.04m, H = 395m, $\upsilon_{оч}$ =122m/month, $L_л$ = 300m). For the specified conditions, the values of the coefficients *a*, *b* and *c* characterizing the subsidence of the earth's surface, respectively, amounted to 809, 6.81 and 0.032.

The empirical coefficients of Equation 11 for the analytical description of the displacement of roof and soil rocks on the contour of the 159th and 163rd drifts were determined from the results of processing the experimental data using the least squares method Figure 5. The established dependencies practically functionally describe the dynamics of rock displacement on the contour of sectional workings (R = 0.964÷0.986). This indicates the possibility of their application in engineering calculations. Thus, on the basis of the analysis of the available experimental data, the empirical coefficients of the logistic dependence (1) were determined, characterizing both the subsidence of the earth's surface and the displacement of roof rocks and soil of sectional workings. The use of one initial dependence allows you to establish the degree of closeness or difference between the parameters of subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings.

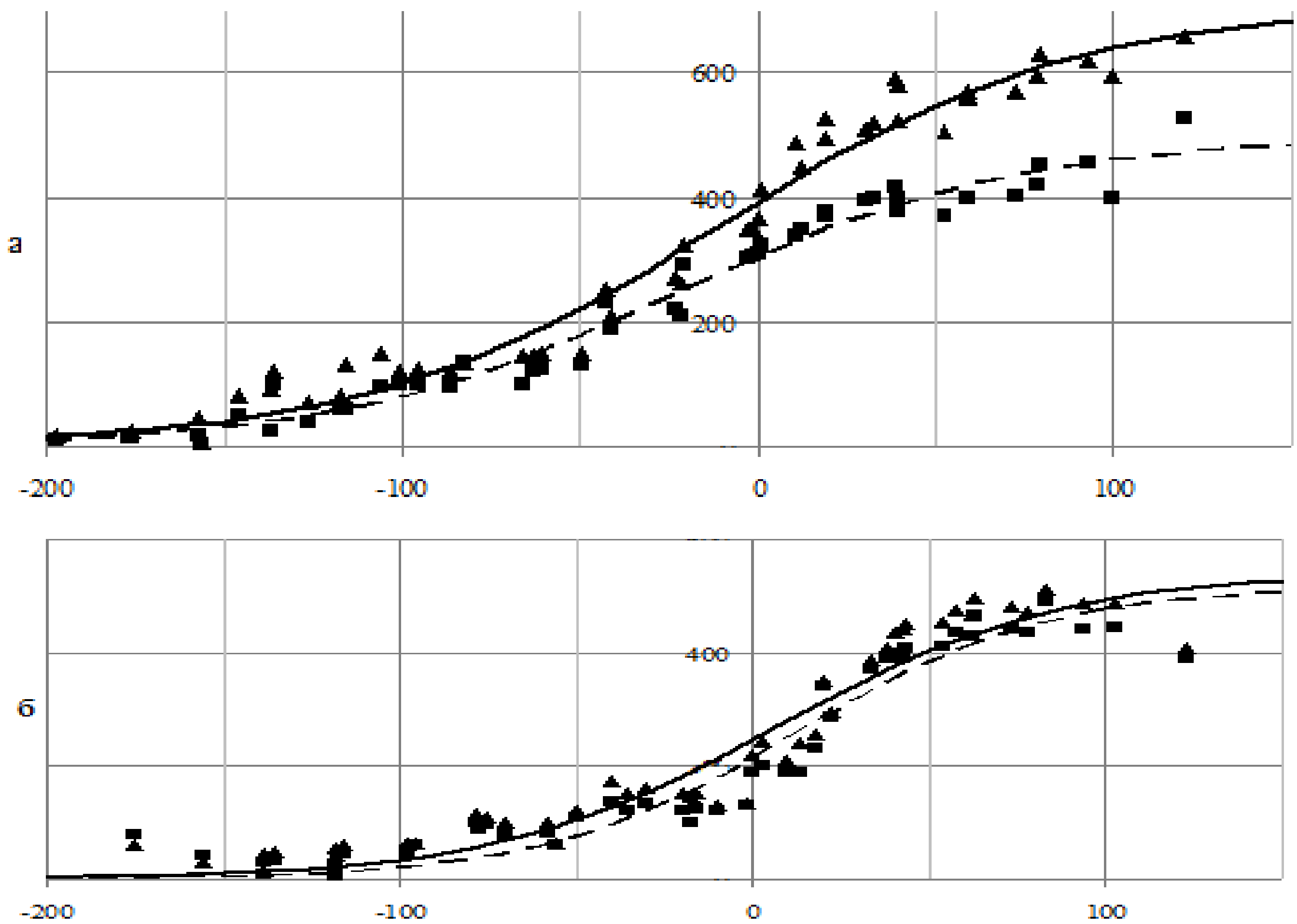

Figure 5. Dependence of rock displacement (η) on the contour of the 159th (a) and 163rd (b) drifts on the distance to the stope (L) during the development of the 157th 161st lava by the Stepnaya mine.

Note: 1,2 - averaging curves for the displacement of rocks, respectively, of the roof and soil; ▲, ■ - experimental data; R is the correlation ratio.

To establish the stages of the processes of subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings (determining the coordinates of characteristic points), methodological approaches were used to study functions using their derivatives. The results of the study of the logistic curve and the general equations for determining the coordinates of the characteristic points are shown in Table 4. Substituting the values of the empirical coefficients (*a*, *b* , *c*) into these equations, we determined the coordinates of the characteristic points of subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings during the development of the 157th and the 161st lava by the Stepnaya mine. Based on the numerical values of the coordinates of the characteristic points Table 4 and the location of the curves relative to the stope Figure 6, a comparative analysis was made of the processes of subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings.

Table 4. The results of determining the coordinates of the characteristic points of subsidence of the earth's surface and the displacement of rocks on the contour of the excavation 159th and 163rd drifts of the Stepnaya mine.

Characteristic points of the logistic curve	Equations for determining the coordinates of the characteristic points of the logistic curve		Values of empirical coefficients (a, b, c) of logistic dependence and coordinates of characteristic points (L, η)									
			Earth surface		159[th] Drift				163[rd] Drift			
					Roof		The soil		Roof		The soil	
	Abscissa, L, m	Ordinate, η, mm	a=809, b =6.81, c =0.032		a=712, b =0.812, c =0.020		a=497, b =0.631, c =0.021		a=542, b =1.203, c =0.025		a=517, b =1.427, c =0.028	
			L, m	η, mm	L, m	η, mm	L, m	η, mm	L, m	η, mm	L, m	η, mm
A	$\frac{4{,}595-\ln b}{-c}$	0	-84	0	-240	0	-241	0	-176	0	-151	0
O	0	$\frac{\eta_K}{1+b}$	0	104	0	393	0	305	0	246	0	213
B	$\frac{\ln(3{,}73/b)}{-c}$	$0.21\cdot\eta_K$	19	170	-76	150	-85	104	-45	114	-34	109
C	$\frac{\ln b}{c}$	$0.50\cdot\eta_K$	60	405	-10	356	-22	249	7	271	13	259
D	$\frac{\ln(0{,}286/b)}{-c}$	$0.79\cdot\eta_K$	101	639	17	562	20	393	60	428	60	408
F	$\frac{3{,}892-\ln b}{c}$	$0.99\cdot\eta_K$	182	801	184	705	163	492	163	537	152	512

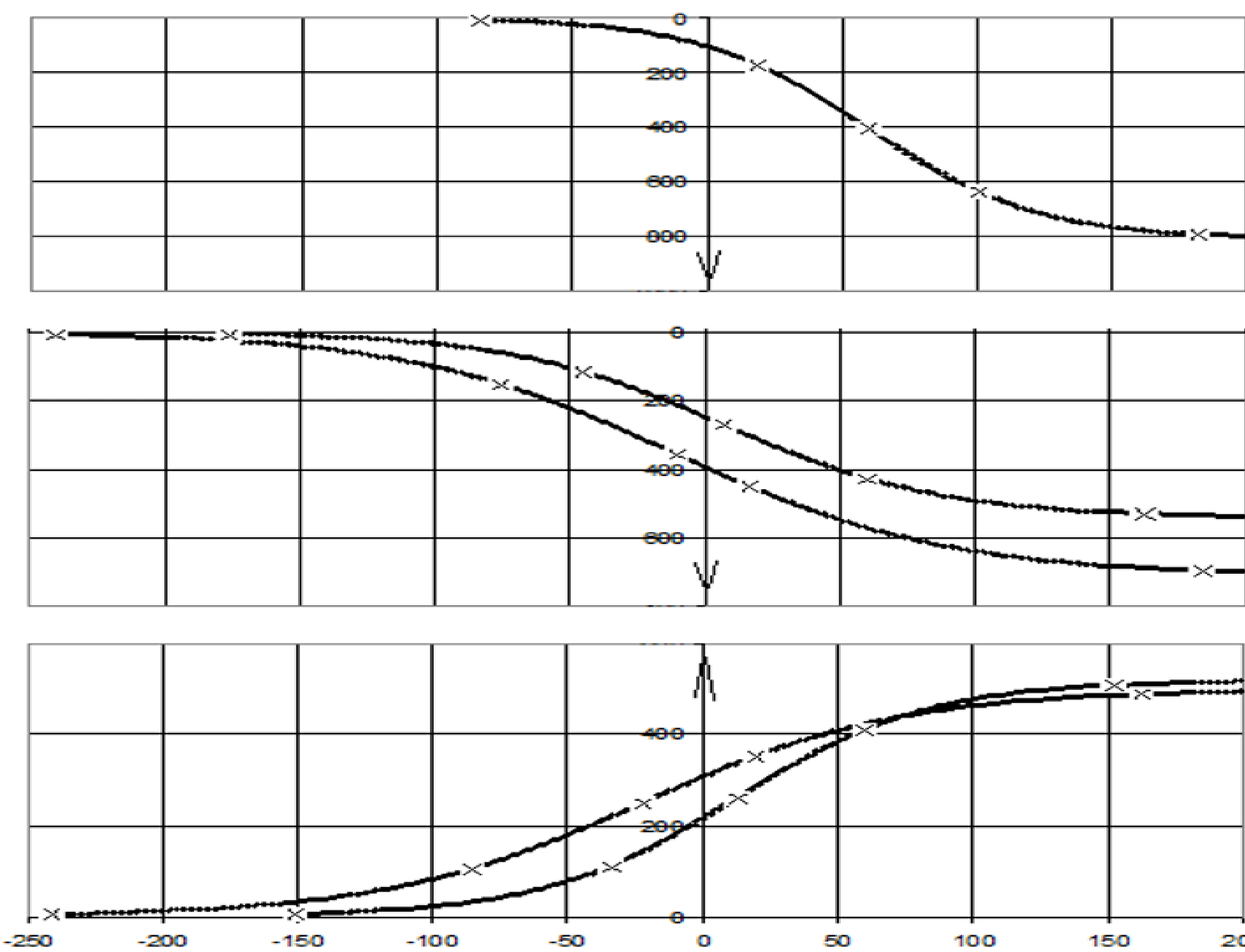

Figure 6. Dependences of the subsidence of points on the earth's surface and the displacement of rocks on the contour of development workings (η) on their position relative to the stope (L) in the conditions of the Stepnaya mine.

Note: 1 - curve of subsidence of the earth's surface; 2,4 – roof and soil displacement curves on the contour of the 159th drift; 3.5 - roof and soil displacement curves on the contour of the 163rd drift; A_{Π}, B_{Π}, C_{Π}, D_{Π}, F_{Π} - characteristic points of displacement of soil rocks; A_K, B_K, C_K, D_K, F_K - characteristic points of displacement of roof rocks; A_3, B_3, C_3, D_3, F_3 - characteristic points of subsidence of the earth's surface.

Coefficient a characterizes the end of processes. Its maximum value corresponded to the subsidence of the earth's surface (809 mm), which is somewhat less than the recoverable thickness of the developed seam (t = 1.04 m). The displacement of the roof on the contour of the 159th and 163rd drifts, respectively, reached 705 and 537 mm. The final displacement of the soil in these workings was 492 and 512 mm. The displacement of soil rocks, in terms of the nature of manifestation and the absolute values of the parameters, differs little from the displacement of roof rocks. This is obviously due to the low strength properties of the host rocks. Under the conditions of strong enclosing rocks, the differences in the displacement of the roof and soil of sectional workings should be expected to be more significant. Coefficients b and c define the coordinates of the characteristic points along the x-axis. The sizes of individual stages characterizing the intensity of the processes depend on their ratio. The coefficient $b = 6.81$ for the earth's surface was 5–10 times higher than its value (0.631–1.422) for the circuit of section workings, and the value $c = 0.032$ was comparable with similar coefficients for workings ($c = 0.020$–0.028).

Different values of the empirical coefficients caused the unequal location of the characteristic points of the shear trough on the day surface and the rocks on the contour of the sectional workings relative to the stope. The beginning of the shift of the roof and soil rocks occurred at a distance of -151 ÷ -241 m (Figure 6, Table 4), which is much more than the distance from the projection of a point on the earth's surface A_3 to the stope alignment (L_A = -84 m).

The beginning of subsidence of the earth's surface corresponds to the beginning of active stages of rock displacement (points $B_П$ and B_K) on the contour of workings. In all cases, the active stage of rock movement began ahead of the stope. This indicates that the location of the point A_3 on the earth's surface determines the beginning of the active manifestation of high rock pressure in front of the stope (the zone of HRP). The obtained results indicate the participation of the entire rock mass from the developed reservoir to the earth's surface in the formation of the HRP zones. They are confirmed by directly proportional experimental dependences of rock displacements in workings on the depth of mining. The maximum intensity of rock displacement on the contour of workings was observed Figure 6 in the immediate vicinity of the stope at points $C_П$ and C_K. The active stage of subsidence of the earth's surface occurred (points A_3, B_3, C_3) after the stope passed over the goaf.

Approximately the same distances (152÷184 m) from the stope (points $F_П$, F_K, F_3) corresponded to the end of the processes of subsidence of the earth's surface and the displacement of rocks in the contour of workings.

The above experimental and theoretical studies made it possible to draw the following important conclusions for science and production activities:

- The beginning of subsidence of the earth's surface corresponds to the beginning of the stage of intensive displacement of the roof and soil rocks ahead of the stope;
- The active stage of displacement of rocks in the contour of development workings begins in front of the stope, and ends after its passage;
- The active stage of subsidence of the earth's surface occurs above the worked-out space behind the stope;
- The processes of subsidence of the earth's surface and the displacement of rocks on the contour of sectional workings stop at approximately the same distance after the passage of the stope.

4. Conclusions

The conducted research allowed to establish the following:

- The main influencing factor that determines the boundary (L_A) of the dynamic half-trough on the earth's surface in front of the projection of the moving stope is the depth of mining (H). This dependence is directly proportional $L_A = 0.263 \cdot H$;
- Boundary angles (δ_o, γ_o, β_o) practically do not depend on the depth of treatment operations. Their values were in the range of 68÷83°, with an average value of 76°.

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