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ANALYTICAL DETERMINATION OF CO-ORDINATES OF DISTINGUISHED POINTS OF THE EARTH SURFACE DEPRESSION OVER BROKEN WORKINGS

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АНАЛІТИЧНЕ ВИЗНАЧЕННЯ КООРДИНАТ ХАРАКТЕРНИХ ТОЧОК ОСІДАННЯ ЗЕМНОЇ ПОВЕРХНІ НАД ОЧИСНИМ ВИБОЄМ

Purpose. The aim is to define the mathematical equation of coordinates of distinguished points of ground depression depending on the depth of broken workings based upon experimental data.

Methodology. The work consists of theoretical and experimental chapters. In the theoretical chapter, depending on equation in use, principled approaches to defining distinguished points of ground depression are described. In the second chapter the position of distinguished points of ground depression as to the working face are determined based upon the observations; their statistical analysis is provided.

Findings. The usage of exponential, logistic or tangent hyperbolic relation provides almost equal staging of ground depression process by its driving rate. Methods for processing experimental data for mathematical descriptions of these processes have been improved. Hypothesis for the influence of ground depression from the depth of broken workings on basin parameters was confirmed.

Originality. Horizontal coordinate of distinguished points of ground depression depends on depth of broken workings in direct proportion.

Practical value. Relations obtained considerably simplify engineering analysis while elaborating activities for sustainable protection of surface objects

Keywords: *depression, surface, distinguished points, broken workings, depth, directly-proportional relationship, coal seams*

Introduction. For the analytical description of the ground depression under the influence of traversing working face it is expected to use exponential, hyperbolic tangent or logistics dependences [1–3]. According to the mathematical equations and their derivatives of functions, methods for identifying the distinguished points of the curve of dynamics of the ground depression in relation to working face projection were developed [1]. The location of such points determines the stages of the ground depression. Reliable establishment of primary, active and final stages is the current task for mining production. The effectiveness of protection from the destruction of objects on the Earth surface, the success of events on the prevention of mining from flooding, as well as the accuracy of the prediction of the gas emission from the mining array and the establishment of the areas of the increased mining pressure depend on the solution of the current task. However, there are much more possible ways of using the peculiarities of dynamics of the ground depression when effects of mining coal seams occur.

Analysis of the recent research. Any recommendations for identifying the stages of the ground depression process depending on the depth of treatment works have been lacking until now.

Objectives of the article. The aim of the work is to establish the influence of depth of mining operations on coordinates of distinguished points of ground depression in relation to broken workings projection using arithmetic models.

Unsolved aspects of the problem. The theoretical part of the methods for investigations is developed according to the scheme of the ground depression [1] concerning the projection of the broken workings (Fig. 1). In the scheme instead of the time, along the horizontal coordinate the distance (L) from the projection of the line of the broking works to the Earth surface to the points of observation was plotted. The distinguished points of the curve of depression dynamics are: A corresponds to the beginning of the Earth surface shift; O is situated in line with the broking workings and is a point of reference on the horizontal coordinate; B stands for the beginning of the active stage; C is maximum speed of the depression and the point of the bend of the curve; D stands for the ending of the active stage of attenuation; F is the beginning of the residual influence. The attenuation stage in the considered scheme is limited by point F. Its depression (I_O) makes approximately 0.97 + 0.99 of the final (I_k) with finished processes of rock compaction [1]. The division of the shift process of produced rocks and Earth surface of separate stages was made using the recommended [1–3] functions.

Presentation of the main research. Regarding the considered scheme (Fig. 1) the dynamics of the Earth surface depression is described in the exponential equation

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

where η is the depression of the point of observations of the Earth surface with the removal of its projection on distance L from the broken workings; β_1 is the empirical coefficient which is determined by the experimental data.

The first three derivatives of functions (1) are equations of the depression speed, acceleration and variations in acceleration. By the extrema of the obtained dependences the coordinates of the distinguished points are determined that are used as measures of the shift stages [1]. In a similar way the ground depression stages

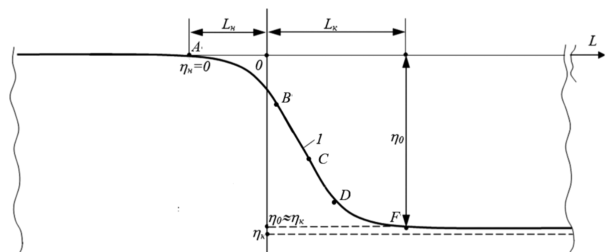

Fig. 1. The scheme of the ground depression according to the projection of the broken workings:

1 – the curve of the trajectory of the ground depression points; 2 – the developed layer; 3 – the location of the broken workings in relation to the curve of dynamics of the ground depression at the starting moment of the influence on point A; I_H, I_k –the starting and final ground depression, accordingly; I_O – the depth of the flat bottom of the mold of shift of the Earth surface till rock compaction; L_H, L_k – the distance between the projection of the broken workings and points A and F according to the beginning and ending of the shift; ⟵ – direction of the broken workings advance

are determined on the basis of extrema of the first two derived functions of the hyperbolic tangent [2].

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

where n_1, n_2, n_3 are experimental coefficients determined by the least square method.

While constructing the curve dynamics of the Earth surface depression in magnitude of the experimental data according to the function of hyperbolic tangent it is established that coefficient n_1 numerically is equal to one half of the final depression ($n_1 = n_k/2$). The distance L_n (Fig. 1) is determined according to $\eta_H = 0$. The lowest value of the function (2) is reaching to zero asymptotically that is why define the beginning of the impact of broken workings on the Earth surface the assumption $\eta_H = d_1 \cdot \eta_k = 0.01\eta_k$ is introduced.

The parameter L in this case is determined from equation (2)

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

The derivatives of functions of the hyperbolic tangent correspond to functional connections [4]

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

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

On the basis of the value of extrema of equations (4, 5) the coordinates of the distinguished points of the curve of dynamics of the Earth surface depression are determined. The equation of the logistic curve for description of the dynamics of the Earth surface depression looks like this

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

where a is the empiric coefficient corresponding to the final Earth surface depression (η_k); b, c are empirical coefficients determining the state of the curve concerning the horizontal coordinates and width of the average site, i. e the duration of the active stage of the Earth surface depression.

The first derivative of the equation (6) is characterized by functional connection

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

Point C of the bend of the logistic curve (Fig. 1) with coordinates $\left(\frac{lnb}{c},\frac{a}{2}\right)$ corresponds to extreme value of the function $\eta'(L)$.

The second derivative from the original equation (6)

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

has two extreme values. The values of these coordinates determine the state of the active stage of the Earth surface depression (points *B* and *D*).

The parameter L_H for logistic curve (6) is established from statement $\eta_H = d_1 \cdot \eta_k = 0.01 \cdot \eta_k$ and $a = \eta_k$

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

Parameter L_k is found from statement $\eta = d_2 \cdot \eta_k = (0.97 \div 0.99)\eta_k$

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

Coordinates of distinguished points (*A, O, B, C, D, F*) of the curve dynamics of the Earth surface depression, defined in accordance with the original functional connections (1, 2, 6), are summarized in Table 1.

The next project completion stage involved determining each object of the observation of empiric parameters included into original equations.

For the exponential equation (1) values of η_k, β_1, L_H were found, for the equation (2) of the hyperbolic tangent those of n_1, n_2, n_3 were defined and for logistic dependency (6) – *a*, *b*, *c*.

The detailed methods for processing the experimental data are given by the example of "Stepnaya" mine. The data [5] on depression of land-marks 25, 30, 35, 40 and 45 was used for the analysis; in the process of the removal of the broken workings, the land-marks got from the split oven into the area of the full underworking (Fig. 2). Then, the results of these investigations were summarized, taking the moment of the broken workings traversing the line going through the point (land-mark) of the observation as the origin of coordinates (Fig. 3).

Processing of the experimental data aimed at establishing the empirical coefficients of the equations (1, 2,

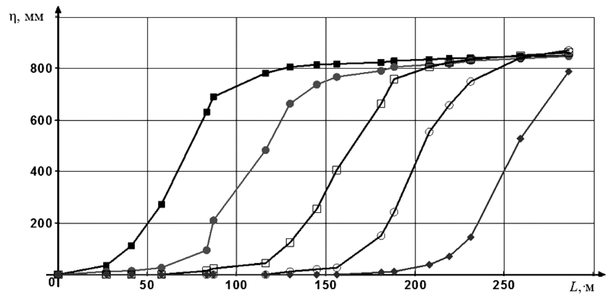

Fig. 2. Land-mark depression (η) on the Earth surface in the removal (L) of the broken workings from the split oven at "Stepnaya" mine [5]:

■, ●, □, ○, ♦ – experimental data of the depression of land-marks 25, 30, 35, 40 и 45, correspondingly

Table 1

Dependencies for determining the coordinates of the distinguished points of the curve dynamics of the Earth surface depression according to exponential, hyperbolic tangent and logistic equations.

The distinguished points of the curve dynamics of the Earth surface depression	Exponential equation		Equation of the hyperbolic tangent		Logistic equations	
	The horizontal coordinate *L*, m	The vertical coordinate *I*, mm	The horizontal coordinate *L*, m	The vertical coordinate *I*, mm	The horizontal coordinate *L*, m	The vertical coordinate *I*, 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	$n_1[1 + \tan h n_3]$	0	$\frac{\eta_k}{1+b}$
B	$\frac{0.5246}{\sqrt{\beta_1}} - L_H$	$0.241\eta_k$	$-\frac{0.658 + n_3}{n_2}$	$0.21\eta_k$	$\frac{\ln(3.73/b)}{-c}$	$0.21\eta_k$
C	$\frac{0.7071}{\sqrt{\beta_1}} - L_H$	$0.393\eta_k$	$-\frac{n_2}{n_3}$	$0.50\eta_k$	$\frac{\ln b}{c}$	$0.50\eta_k$
D	$\frac{1.2247}{\sqrt{\beta_1}} - L_H$	$0.777\eta_k$	$\frac{0.658 - n_3}{n_2}$	$0.80\eta_k$	$\frac{\ln(0.268/b)}{-c}$	$0.79\eta_k$
F	$\sqrt{\frac{\ln(1-d)}{-\beta_1}} - L_H$	$(0.97 \div 0.99)\eta_k$	$\frac{1.946 - n_3}{n_2}$	$(0.97 \div 0.99)\eta_k$	$\frac{3.892 - \ln b}{c}$	$(0.97 \div 0.99)\eta_k$

6) was done by the least square method. Using their numerical values and functional connections for establishing the coordinates of the distinguished points (Table 1), the measures of the stages of the Earth surface depression were found while conducting treatment works by "Stepnaya" mine (Fig. 3, Table 2). Using the same techniques, the experimental data [1, 2, 6–10] was processed and empiric coefficients for their objects were established (Table 3). It is worth saying that in the majority of cases the values of η_k, which were defined

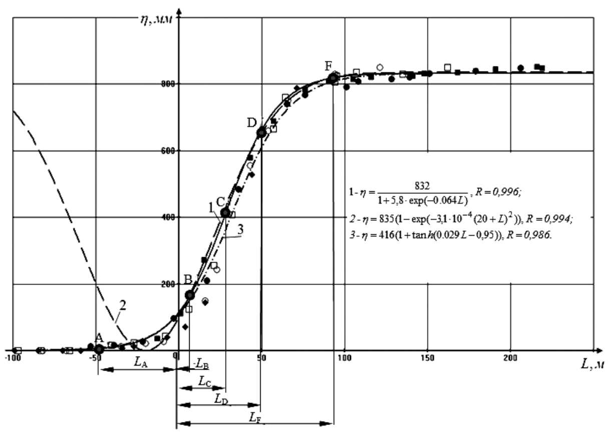

Fig. 3. Depression (η) of the points of the Earth surface while conducting treatment works by "Stepnaya" mine concerning the location of the broken workings projection (L) according to data [5]:

1, 2, 3 are approximating curves corresponding to logistic, exponential dependencies and function of hyperbolic tangent; A, B, C, D, F are distinguished points of the curve dynamics of the Earth surface depression according to logistic equation; L is distance from the point (land-mark) of observation to the projection of the broken workings line; R is correlation ratio; ■, ●, □, ○, ♦ are experimental data of land-marks 25, 30, 35, 40 и 45, correspondingly

with help of functions considered, were practically equal to each other. As a rule, differences did not exceed 1.0 % and only once (the mine of Appalachian basin) the maximum difference was 3.1 %. This gives evidence of possibility of using any functions considered to determine the ordinates of the distinguished points.

A similar conclusion was reached regarding a possibility to use the analyzed functions to determine the horizontal coordinates of the distinguished points of the Earth surface depression. Using empiric coefficients of the equations (Table 3) horizontal coordinates of the distinguished points L_A, L_B, L_C, L_D and L_F were calculated for all the mines. Determined by different equations, these parameters were different from each other by maximum of 20 %. For further calculations their average values of $\overline{L_A}$, $\overline{L_B}$, $\overline{L_C}$, $\overline{L_D}$ and $\overline{L_F}$ were used. On the basis of the experimental data [6, 11] it was established that parameters of the mold of the Earth surface depression can be defined by the depth of works 80 % and more. In order to check and prove this suggestion, dependences of the average values of the horizontals of distinguished points on the depth of the broking workings were determined of the basis of data (Table 4). The result of such calculations shows that horizontals of the distinguished points feature directly proportional dependence on the depth of mine workings (Table 5).

According to the absolute value, the coefficients of correlation (r) for different coal basins were in the range of 0.50–0.89. For mines of the Donetsk basin more close relation between these parameters ($r = 0.96 \div 0.99$) was noted. The results prove the major influence of the depth of the workings on the formation of curve dynamics of the Earth surface depression.

Conclusions:

- for analytical description of the curve dynamics of the Earth surface depression over moving broken work-

Table 2

Results of determining coordinates of the distinguished points of the Earth surface depression during its underworking by "Stepnaya" mine

Result of treatment and distinguished points (Fig. 1)	Math functions					
	Logistic dependence		Exponential dependence		Hyperbolic tangent	
	$\eta = \frac{a}{1+b\cdot\exp(-c\cdot L)}$		$\eta = \eta_k(1-\exp[-\beta_2(L+L_0)^2])$		$\eta = n_1[1+\tanh(n_2L+n_3)]$	
Correlation ratio	0.996		0.994		0.986	
Empirical coefficients	$a = \eta_k = 832$; $b = 5.8$; c = 0.064		$\beta_2 = 3.1\cdot10^{-4}$; $L_0 = L_H = -20$; $\eta_k = 835$		$n_1 = 416 = 0.5\eta_k$; $n_2 = 0.029$; $n_3 = -0.95$	
A	$L_A = L_H = -44$ m	$\eta_A = 0$ mm	$L_A = L_H = -20$ m	$\eta_A = 0$ mm	$LA = L_H = -46$ m	$\eta_A = 0$ mm
O	$L_O = 0$ m	$\eta_O = 122$ mm	$L_O = 0$ m	$\eta_O = 97$ mm	$L_O = 0$ m	$\eta_O = 108$ mm
B	$L_B = 7$ m	$\eta_B = 175$ mm	$L_B = 10$ m	$\eta_B = 201$ mm	$L_B = 10$ m	$\eta_B = 175$ mm
C	$L_C = 27$ m	$\eta_C = 416$ mm	$L_C = 20$ m	$\eta_C = 328$ mm	$L_C = 33$ m	$\eta_C = 416$ mm
D	$L_D = 48$ m	$\eta_D = 657$ mm	$L_D = 50$ m	$\eta_D = 649$ mm	$L_D = 55$ m	$\eta_D = 665$ m
F	$L_F = L_k = 88$ m	$\eta_F = 815$ mm	$L_F = L_k = 112$ m	$\eta_F = 818$ mm	$L_F = L_k = 100$ m	$\eta_F = 815$ mm

Table 3

Results of determining empiric coefficients and correlation ratio by the least square method (R) for other objects of observation

The mine, the layer, the literacy source	Math functions											
	Logistic dependence				Exponential dependence				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, [1]	810	4.1	0.016	0.998	2.0	105	810	0.999	405	0.008	–0.70	0.997
No. 22 Kommunarskaya, K_3, [2]	900	9.3	0.010	0.998	1.0	70	900	0.976	450	0.005	–1.11	0.998
Gramoteinskaya-Sychevskyi-III, [6]	2375	13.0	0.028	0.999	5.0	30	2420	0.987	1180	0.015	–1.28	0.995
the mine of Appalachian basin [7]	980	26.0	0.040	0.995	6.5	20	1010	0.991	490	0.019	–1.65	0.994
“Yubileinaya”, C_6', [8]	915	12.5	0.050	0.997	1.5	20	910	0.974	458	0.026	–1.27	0.996
A. F. Zasyadko Mine, m_3, [9]	400	7.0	0.006	0.997	3.0	70	400	0.974	200	0.003	–1.20	0.996
Stashits, 352, [9]	480	4.1	0.020	0.999	5.0	60	980	0.984	490	0.010	–0.70	0.999
The mine of the Ruhr basin, Grimberg 2/3, [9]	1420	5.8	0.010	0.998	5.5	200	1420	0.979	710	0.005	–0.87	0.998
S. M. Kirov mine of “Leninskuhol” manufacturing group, Boldyrevskyi, (S. G. Avershin, D. A. Kazakovskii, M. V. Korotkov etc.)	1300	7.1	0,070	0.996	3.3	21	1310	0.997	638	0.041	–0.98	0.994

Table 4

Results of determining the average coordinates of the distinguished points of the Earth surface depression on the verticals

The mine, the layer, the literacy source	The power of working layer, m, m	The depth of the broken workings, H, m	The average distance between the projecting of the broken workings and distinguished points of the Earth surface depression				
			$\bar{L}_A$	$\bar{L}_B$	$\bar{L}_C$	$\bar{L}_D$	$\bar{L}_F$
Belozerskaya, [1]	1.30	420	–169	8	76	171	361
No. 22 Kommunarskaya, K_3, [2]	1.47	652	–178	91	200	337	595
“Stepnaya” mine, C_6, [5]	0.91	106	–37	9	27	51	103
Gramoteinskaya-Sychevskyi-III, [6]	4.50	220	–57	43	82	137	237
the mine of Appalachian basin, [7]	1.65	220	–28	49	79	122	201
“Yubileinaya”, C_6', [8]	1.00	150	–34	24	46	77	135
A. F. Zasyadko Mine, m_3, [9]	2.10	1195	–292	129	356	547	1010
Stashits, 352, [9]	2.10	480	–126	8	60	128	263
The mine of the Ruhr basin, Grimberg 2/3, [9]	2.20	920	–253	36	151	308	636
S. M. Kirov mine of “Leninskuhol” manufacturing group, Boldyrevskyi, (S. G. Avershin, D. A. Kazakovskii, M. V. Korotkov etc.)	1.70	205	–30	8	23	44	86

Table 5

The empiric equations for determining the average coordinates of the distinguished points of the Earth surface depression on the verticals according to the depth of the broken workings

The distinguished points of the Earth surface depression	Dependencies of distances of the distinguished points (L_A, L_B, L_C, L_D, L_F) from the depth of the workings (H) for all mine basins		Dependencies of distances of the distinguished points (L_A, L_B, L_C, L_D, L_F) from the depth of the workings (H) for the Donetsk basin	
	Empiric equations	The coefficient of correlation, r	Empiric equations	The coefficient of correlation, r
A	$L_A = -0.231 \cdot H$	–0.89	$L_A = -0.264 \cdot H$	–0.96
B	$L_B = 0.071 \cdot H$	0.50	$L_B = 0.107 \cdot H$	0.92
C	$L_C = 0.208 \cdot H$	0.75	$L_C = 0.290 \cdot H$	0.98
D	$L_D = 0.358 \cdot H$	0.81	$L_D = 0.466 \cdot H$	0.99
F	$L_F = 0.681 \cdot H$	0.84	$L_F = 0.862 \cdot H$	0.99

ings, it is possible to use the exponential, hyperbolic tangent of logistics dependencies. They almost functionally reflect processes of the Earth surface depression (correlation relation were in the range of 0.994 ÷ 0.999);

- each equation contains three empiric coefficients, whose values for particular objects of the investigation are worth defining on basis of the experimental data;

- the determination of coordinates of point *A* (Fig. 1), which distinguish the beginning of the influence of the broking workings on the Earth surface. This determination corresponds to the extremum of the exponential function $\eta''(L)$. The minimal value of functions of hyperbolic tangent and logistic curve asymptotically approach to zero, that is why to determine the beginning of the influence of broken workings on the earth surface it is recommended to follow the task $\eta_H = 0.01\eta_k$;

- the minimal extremum of the exponential function $\eta'''(L)$. corresponds to the beginning of the active stage (point *B*). The positive extremum of the functions of hyperbolic tangent and logistic curve $\eta''(L)$ corresponds to this stage;

- the minimal extremum of the exponential function $\eta''(L)$ corresponds to the ending of active stage (point *D*). The negative extremum of the functions of hyperbolic tangent and logistic curve $\eta''(L)$ corresponds to this stage;

- the usage of exponential, logistic connections and hyperbolic tangent results in equal division of the process of the Earth surface depression into stages according to intensity of their duration;

- the main feature, which distinguishes stages and coordinates of the points of the Earth surface is the depth of broking workings.

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Мета. На підставі експериментальних даних встановити аналітичні рівняння координат характерних точок осідання земної поверхні від глибини ведення очисних робіт.

Методика. Складається з теоретичної та експериментальної частин. У теоретичній частині, залежно від виду вживаних рівнянь, розглянуті принципові підходи до визначення координат характерних точок осідання земної поверхні. У другій частині, на підставі результатів спостережень, встановлені положення цих точок відносно очисних вибоїв і здійснена їх статистична обробка.

Результати. Використання експоненціальної, логістичної або гіперболічного тангенса залежностей призводить приблизно до однакового ділення процесу осідання земної поверхні на стадії по інтенсивності їх протікання. Удосконалена методика обробки експериментальних даних для математичного опису цих процесів. Підтверджена гіпотеза про основний вплив на параметри мульд сдвиження земної поверхні глибини ведення очисних робіт при відпрацьовуванні пологих вугільних пластів.

Наукова новизна. Абсциси координат характерних точок осідання земної поверхні прямо пропорційно залежать від глибини ведення очисних робіт.

Практична значимість. Отримані залежності значно спрощують інженерні розрахунки при розробці заходів щодо раціонального захисту об'єктів на земній поверхні.

Ключові слова: *осідання, земна поверхня, характерні точки, очисні роботи, вугільні пласти*

Цель. Установить координаты характерных точек оседания земной поверхности над очистным забоем в зависимости от глубины горных работ.

Методика. Состоит из теоретической и экспериментальной частей. В теоретической части, в зависимости от вида применяемых уравнений, рассмотрены принципиальные подходы к определению координат характерных точек оседания земной поверхности. Во второй части на основании результатов наблюдений установлены положения этих точек относительно очистных забоев и произведена статистическая обработка.

Результаты. Использование экспоненциальной, логистической или гиперболического тангенса зависимостей приводит примерно к одинаковому делению процесса оседания земной поверхности на стадии по интенсивности их протекания. Усовершенствована методика обработки экспериментальных данных для математического описания этих процессов. Подтверждена гипотеза об основном влиянии на параметры мульд сдвижения земной поверхности глубины ведения очистных работ при отработке пологих угольных пластов.

Научная новизна. Абсциссы координат характерных точек оседания земной поверхности прямо пропорционально зависят от глубины ведения очистных работ.

Практическая значимость. Полученные зависимости значительно упрощают инженерные расчеты при разработке мероприятий по рациональной защите объектов на земной поверхности.

Ключевые слова: *оседание, земная поверхность, характерные точки, очистные работы, угольные пласты*

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