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

Filatieve Elvira1
Olha Fursova2
Filatieve Mikhail3

Department of Fire Safety, Lugansk State University named after Vladimir Dahl, Lugansk Region, Ukraine.

Email: elfilatyeva@gmail.com
Email: elvira_2022@gmail.com
Email: Mikhail@gmail.com

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 function. 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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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. Voiko, 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 (\( \eta \)) is approximately 0.97 - 0.99 of the final (\( \eta_n \)) at the end of the processes of rock compaction [9].

![Figure 1. Scheme of subsidence of the earth's surface relative to the projection of the production face.](image)

**Note:** 1 - curve of the trajectory of the points of subsidence of the earth's surface; 2 - reservoir under development; \( \delta \) - 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 \( A \); \( \eta_0 \), \( \eta_n \) - respectively, the initial and final subsidence of the earth's surface; \( \eta_0 \) - depth of the flat bottom of the shear trough to the compaction of the rocks; \( L_0 \), \( L_n \) - the distance between the projection of the stope and points \( A \) and \( F \), respectively, at the beginning and end of the displacement; \( \delta \), \( \gamma \), \( \beta \) - 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), \( \vec{L} \) - 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 (\( \delta \) - when mining seams along strike, \( \gamma \) - along rise, \( \beta \) - along dip), as well as \( L_0 \) - 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 \[\eta(L) = \eta_k \left( 1 - \exp^{-\beta_1 |L + L_n|^2} \right) \] (1)

Where \( \eta \) 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, \( \text{mm} \);
\( \beta_1 \) - 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 [5].

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 [6]:

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

Where \( n, n, n \) 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 \( n \) is numerically equal to half of the final subsidence \( n_1 = \eta_k / 2 \).

The distance \( L \) Figure 1 is determined from the condition \( \eta_L = 0 \). 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 \( \eta_L = d_1 \cdot \eta_k = 0.01 \cdot \eta_k \). The parameter \( L \) for this case is determined from Equation 2:

\[ L_n = \frac{\arctan h(2 \cdot d_2 - 1) - n_3}{n_2} = 1.946 - n_3. \] (3)

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

\[ \eta'(L) = n_1 - n_2 \frac{1}{1 + \tan h^2(n_2 \cdot L + n_3)} \] (4)

\[ \eta''(L) = -2n_1 \cdot n_2^2 \tan h(n_2 \cdot L + n_3) \cdot \frac{1}{1 + \tan h^2(n_2 \cdot L + n_3)} \] (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]:

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

Where \( a \) is an empirical coefficient corresponding to the final subsidence of the earth's surface \( \eta_k \);
\( b, c \) - 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:

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

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

The second derivative of the original Equation 6:

\[ \eta''(L) = \frac{-a \cdot b \cdot c^2 \cdot \exp(-c \cdot L) \cdot [1 + b \cdot \exp(-c \cdot L)]}{1 + b \cdot \exp(-c \cdot L)^3}. \] (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 \( L \) for the logistic curve (6) was determined from the conditions \( \eta_n = d_1 \cdot \eta_k = 0.01 \cdot \eta_k \) and \( a = \eta_k \):

\[ L_n = -\frac{\ln(1/d_1 - 1)}{b \cdot c} = -4.595 - \ln b. \] (9)

Parameter \( L \) found from the condition \( \eta = d_2 \cdot \eta_k = (0.97 + 0.99)\eta_k \):

\[ L = -\frac{\ln(1/d_2 - 1)}{b} = -3.892 - \ln b. \] (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.

<table>
<thead>
<tr>
<th>Characteristic points of the curve of the dynamics of subsidence of the earth’s surface</th>
<th>Exponential equation</th>
<th>Hyperbolic tangent equation</th>
<th>Logistic equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Figure 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>$L_m$, m</td>
<td>Ordinate $\eta$, mm</td>
<td>$-2 \cdot \ln 2 + n_3 - \frac{n_1}{n_2}$</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>$0.5246 \cdot \left[\frac{1}{b} - L_m\right]$</td>
<td>$0.241 \eta_k$</td>
<td>$-0.658 + n_3 - \frac{n_1}{n_2}$</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>$0.7071 \cdot \left[\frac{1}{b} - L_m\right]$</td>
<td>$0.395 \eta_k$</td>
<td>$-\frac{n_2}{n_1}$</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>$1.2247 \cdot \left[\frac{1}{b} - L_m\right]$</td>
<td>$0.777 \eta_k$</td>
<td>$0.658 - \frac{n_3}{n_2}$</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>$\left[\frac{\ln(-d) - \frac{1}{b^2}}{\beta^2} - \frac{1}{b} \right]$</td>
<td>$0.97 - 0.99 \eta_k$</td>
<td>$1.946 - \frac{n_3}{n_2}$</td>
</tr>
</tbody>
</table>

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 $\eta_k$, $\beta$, $L_m$ for the Equation 2 of the hyperbolic tangent - $v_0$, $a$, $\eta$. and for the logistic dependence (3) - $a$, $b$, $c$.

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.

<table>
<thead>
<tr>
<th>Mine, reservoir, literary source</th>
<th>Logarithms</th>
<th>Exponential</th>
<th>Hyperbolic tangent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = \eta_k$</td>
<td>$b$</td>
<td>$c$</td>
<td>$R$</td>
</tr>
<tr>
<td>Belozerskaya, [3]</td>
<td>810</td>
<td>4.1</td>
<td>0.016</td>
</tr>
<tr>
<td>Nez family. &quot;Kommunarka&quot;, K-1-3</td>
<td>900</td>
<td>9.3</td>
<td>0.010</td>
</tr>
<tr>
<td>&quot;Gramoteinskaya&quot;, Syachensky, III, [7]</td>
<td>2375</td>
<td>15.0</td>
<td>0.028</td>
</tr>
<tr>
<td>Appalachian basin mine, [8]</td>
<td>980</td>
<td>20.0</td>
<td>0.040</td>
</tr>
<tr>
<td>&quot;Anniversary&quot;, C-4, [9]</td>
<td>915</td>
<td>12.5</td>
<td>0.050</td>
</tr>
<tr>
<td>Them. A.F. Zasyadko, t. 100, [10]</td>
<td>480</td>
<td>7.0</td>
<td>0.006</td>
</tr>
<tr>
<td>Staniic, 552, [10]</td>
<td>480</td>
<td>4.1</td>
<td>0.020</td>
</tr>
<tr>
<td>Ruhar basin mine, Grimberg, A/3, [10], [11]</td>
<td>1420</td>
<td>5.8</td>
<td>0.010</td>
</tr>
<tr>
<td>Them. CM. Kirov, PO &quot;Leninskugol&quot;, Boldyrevsky, [12]</td>
<td>1300</td>
<td>7.1</td>
<td>0.070</td>
</tr>
<tr>
<td>&quot;Steppe&quot;, [12]</td>
<td>832</td>
<td>5.8</td>
<td>0.064</td>
</tr>
</tbody>
</table>

It should be noted that in most cases the values $\eta_k$, 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 $(L_m)$ 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 ($\delta$, $\gamma$, $\beta$).

<table>
<thead>
<tr>
<th>Mine, reservoir, literary source</th>
<th>Depth of cleaning operation, $H$, m</th>
<th>The thickness of the developed reservoir, $m$, m</th>
<th>$H/m$</th>
<th>Seam dip angle, $\alpha$, degrees</th>
<th>The distance between the projection of the production face and point $A$, $L_A$, m</th>
<th>Boundary angles, $\delta$, $\gamma$, $\beta$, degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Belozerskaya&quot;, [3]</td>
<td>420</td>
<td>1.30</td>
<td>925</td>
<td>12</td>
<td>169</td>
<td>68</td>
</tr>
<tr>
<td>&quot;Granotetskaya&quot;, Sychevsky, III, [7]</td>
<td>220</td>
<td>4.50</td>
<td>49</td>
<td>Four</td>
<td>57</td>
<td>73</td>
</tr>
<tr>
<td>Appalachian Basin Mine, [8]</td>
<td>220</td>
<td>1.65</td>
<td>135</td>
<td>-</td>
<td>28</td>
<td>84</td>
</tr>
<tr>
<td>&quot;Anniversary&quot;, S, [9]</td>
<td>150</td>
<td>1.00</td>
<td>150</td>
<td>3</td>
<td>34</td>
<td>77</td>
</tr>
<tr>
<td>Them. A.P. Zasyadko, m, [10]</td>
<td>1155</td>
<td>2.10</td>
<td>569</td>
<td>10</td>
<td>292</td>
<td>76</td>
</tr>
<tr>
<td>&quot;Stashitz&quot;, 352, [10]</td>
<td>480</td>
<td>2.50</td>
<td>220</td>
<td>-</td>
<td>126</td>
<td>73</td>
</tr>
<tr>
<td>Ruhr mine, Grimberg, 2/3, [10]</td>
<td>920</td>
<td>2.20</td>
<td>418</td>
<td>-</td>
<td>255</td>
<td>75</td>
</tr>
<tr>
<td>&quot;Steppe&quot;, [12]</td>
<td>106</td>
<td>0.91</td>
<td>116</td>
<td>Four</td>
<td>37</td>
<td>71</td>
</tr>
</tbody>
</table>

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 ($\delta$, $\gamma$, $\beta$) with $H$ and $H/m$ has not been established Figure 3. Correlation coefficients were respectively - 0.13 and - 0.25. Boundary angles ($\delta$, $\gamma$, $\beta$) were in the range of 68-83°, with an average value of 76°.
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 \( \text{H}_1 \) from the projection of the stope line onto the earth's surface to the observation points, as well as the distances from the stope \( \text{H}_2 \) and \( \text{H}_3 \) 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: \( A_H \), \( A_K \), \( A_L \) - correspond to the beginning of the shift of soil rocks and the roof of workings and the earth's surface; \( O_H \), \( O_K \), \( O_L \) - are located in the alignment with the stope and serve as the origin of the coordinate axes; \( B_H \), \( B_K \), \( B_L \) - the beginning of the active stage of displacement of soil rocks and the roof of workings and subsidence of the earth's surface; \( C_H \), \( C_K \), \( C_L \) - correspond to the maximum rate of rock displacement and subsidence of the earth's surface and are the inflection points of the curves; \( D_H \), \( D_K \), \( D_L \) - end of active stages and beginning of attenuation stages; \( F_H \), \( F_K \), \( F_L \) - 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 \( F_H \), \( F_K \) and \( F_L \). The subsidence of the earth's surface at a point \( F_1 \) is approximately 0.97 ÷ 0.99 of the final \( \eta^K \) at the end of the rock compaction processes. The end of the processes at the points \( F_H \) 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 \( F_H \) 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 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; \( L_{II}, L_{K}, L_{I} \) - abscissa axes, respectively, for the soil and the roof of the working and the earth’s surface; \( \eta_{II}, \eta_{K}, \eta_{I} \) - y-axis for the soil and the roof of the working and the earth’s surface, respectively; \( A_{II}, B_{II}, C_{II}, D_{II}, F_{II} \) - characteristic points of the soil displacement curve; \( A_{K}, B_{K}, C_{K}, D_{K}, F_{K} \) - characteristic points of the roof displacement curve; \( A_1, B_1, C_1, D_1, F_1 \) - 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 (\( L_{A1}, L_{B1}, L_{C1}, L_{D1}, L_{F1} \)) and the removal of characteristic points of displacement of soil and roof rocks from the production face (\( L_{A2}, L_{B2}, L_{C2}, L_{D2}, L_{F2} \));
- 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:

\[
\eta(L) = \frac{a}{1 + b \cdot \exp(-c \cdot L)},
\]

where \( \eta \) 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 (\( \eta^c \)); \( b, c \) 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 ($\nu_{\text{av}}$) and the length of the lava ($L$):

$$a = \frac{1}{(-2.64 \cdot 10^{-4} \cdot m + 1.54 \cdot 10^{-3})}, \quad (12)$$

$$b = \frac{1}{(-0.14 \cdot \nu_{\text{av}} / H + 0.19)}, \quad (13)$$

$$c = 0.205 + 0.0148 \cdot \ln \left( \frac{1}{m \cdot L \cdot H} \right). \quad (14)$$

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 ($t = 1.04\, \text{m}$, $H = 395\, \text{m}$, $\nu_{\text{av}} = 122\, \text{m/month}$, $L = 300\, \text{m}$). 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](image)

**Figure 5.** Dependence of rock displacement ($\eta$) 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.

<table>
<thead>
<tr>
<th>Characteristic points of the logistic curve</th>
<th>Equations for determining the coordinates of the characteristic points of the logistic curve</th>
<th>Values of empirical coefficients (a, b, c) of logistic dependence and coordinates of characteristic points ( (L, \eta) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abscissa, ( L, ) m</td>
<td>Ordinate, ( \eta, ) mm</td>
<td>Earth surface 159th Drift</td>
</tr>
<tr>
<td>( A )</td>
<td>( 4.595 - \ln b ) ( - c )</td>
<td>0</td>
</tr>
<tr>
<td>( B )</td>
<td>( \ln(3.73/b) ) ( - c )</td>
<td>0.21 ( \eta )</td>
</tr>
<tr>
<td>( C )</td>
<td>( \ln b ) ( - c )</td>
<td>0.50 ( \eta )</td>
</tr>
<tr>
<td>( D )</td>
<td>( \ln(0.286/b) ) ( - c )</td>
<td>0.79 ( \eta )</td>
</tr>
<tr>
<td>( F )</td>
<td>( 3.892 - \ln b ) ( - c )</td>
<td>0.99 ( \eta )</td>
</tr>
</tbody>
</table>

Figure 6. Dependences of the subsidence of points on the earth's surface and the displacement of rocks on the contour of development workings (\( \eta \)) 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; \( A_H, B_H, C_H, D_H, F_H \) - characteristic points of displacement of soil rocks; \( A_K, B_K, C_K, D_K, F_K \) - characteristic points of displacement of roof rocks; \( A_J, B_J, C_J, D_J, F_J \) - 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 \( \pm 151 \pm 261 \) m (Figure 6, Table 4), which is much more than the distance from the projection of a point on the earth's surface \( A_i \) to the stope alignment (\( L_i = 84 \) m).

The beginning of subsidence of the earth's surface corresponds to the beginning of active stages of rock displacement (points \( B_{li} \) and \( B_{ji} \)) 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 \( A_i \) 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 \( C_p \) and \( C_k \). The active stage of subsidence of the earth's surface occurred (points \( A_i \), \( B_{ji} \), \( C_k \)) after the stope passed over the goaf.

Approximately the same distances (152±184 m) from the stope (points \( F_{li} \), \( F_{ki} \), \( F_{ji} \)) 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 on 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 (\( L_i \)) of the dynamic half-trough on the earth's surface in front of the projection of the mining stope is the depth of mining (\( H \)). This dependence is directly proportional \( L_i = 0.203H \);
- Boundary angles (\( \delta \), \( \gamma \), \( \beta \)) 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°.

References


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