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Deformations of a dog heading located in an area of intensive mining operation – case study

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Abstract

The article presents results on the influence range of mining exploitation in a rock mass at the site of dog headings located in an area of intensive mining exploitation. The research is based on geodetic measurements of the subsidence of measurement line points located above the panel of a mined-out longwall. Studies were applied to assess the range of mining influence in a rock mass, which is important for the protection of dog headings against mining damage. If a range of mining influence comprises any protected workings, then the deformations caused by mining operations may result in the loss of their functionality and even in dangerous damage to them. The values of the parameters of the influence theory determined by geodetic measurements of subsidence can be used to determine the permissible length of longwall panels, ensuring the maintenance of the functionality of the protected dog headings and to optimize stress concentration zones in terms of the risk of rock mass tremors.

Introduction

The impact of underground mining of a deposit on objects located in the rock mass has always been the subject of research and experimentation. Yet, despite significant achievements of science in this field, the problem still requires comprehensive research, mainly due to the increased depth of mining exploitation and its intensity. In such conditions, an important mining and technological problem is to maintain the functionality of dog headings, which are indispensable to carry out mining operations and which are placed in the mining fields. Pillars left behind for the protection of dog headings cause many negative effects, such as high concentration of stresses in the rock mass, resulting in the occurrence of tremors, reduction of panel length, difficulties in rational deposit management and deposit loss (Zhu, Jiang & Liu, 2015; Zhu et al., 2022).

Frequently, despite leaving the pillars behind, damage to dog headings is reported, which results in loss of their functionality and rising costs. In the case of the undermining of dog headings, geodetic measurements of deformations occurring in them, even to a small extent, are extremely informative and valuable for scientific purposes. The results of such measurements may also serve as a basis for the application and verification of the protection principles of such workings.

The article presents the results of research on rock mass deformations in Cross-cut I and in Main Entry (i.e., in the excavations located above the panel length of the mined-out longwall C-1 in the seam 505wd) for the assessment of the influence range of this mining operation, which determines the required size of a protective pillar.

Mining conditions in the investigated intensive mining operation area in terms of protection of dog headings

The investigated case of dog heading protection involves a mining area where intensive mining has been conducted for many years. The scope of this mining exploitation in a graphical form with marked longwall contours is presented in Figure 1.

In such mining conditions, the protection of main dog headings is of particular importance, which should ensure their stability and functionality and hence the possibility of effective and planned mining of a coal deposit. The stability of dog headings is understood as their ability to remain fully operational for a specified period of time (i.e., to be technologically usable) (Białek & Mielimąka, 1999).

As to the influence of mining exploitation on dog headings, of prime importance for ensuring their safe exploitation and required functionality is the size and distribution of the deformations, characterized by the so-called deformation indicators. The value of rock mass deformation indices caused by the impact of mining exploitation can be used to assess the effects of deformations that arise in dog headings.

In view of our experience, we can state that the size and intensity of the impact of mining exploitation have a fundamental influence on the possibility to maintain safe and economically justified functionality of a working mine.

The impact of mining exploitation on dog headings depends on a number of natural and mining factors, and above all, on the time and spatial location of such workings in relation to the mining plots (mining longwalls). In terms of time, two cases can be distinguished (Białek, 2003):

- mining of a dog heading in the rock mass disturbed by previous mining operations,
- maintenance of a dog heading within the range of a mining operation.

In terms of the spatial location of a dog heading within the impact range of mining exploitation, the following can be distinguished (Białek, 2003):

- undermining a dog heading,
- overmining a dog heading,
- a mining operation carried out in the area of a dog heading.

Description of the measurement line

The aim of the presented studies of rock mass deformations at the place of dog headings located in

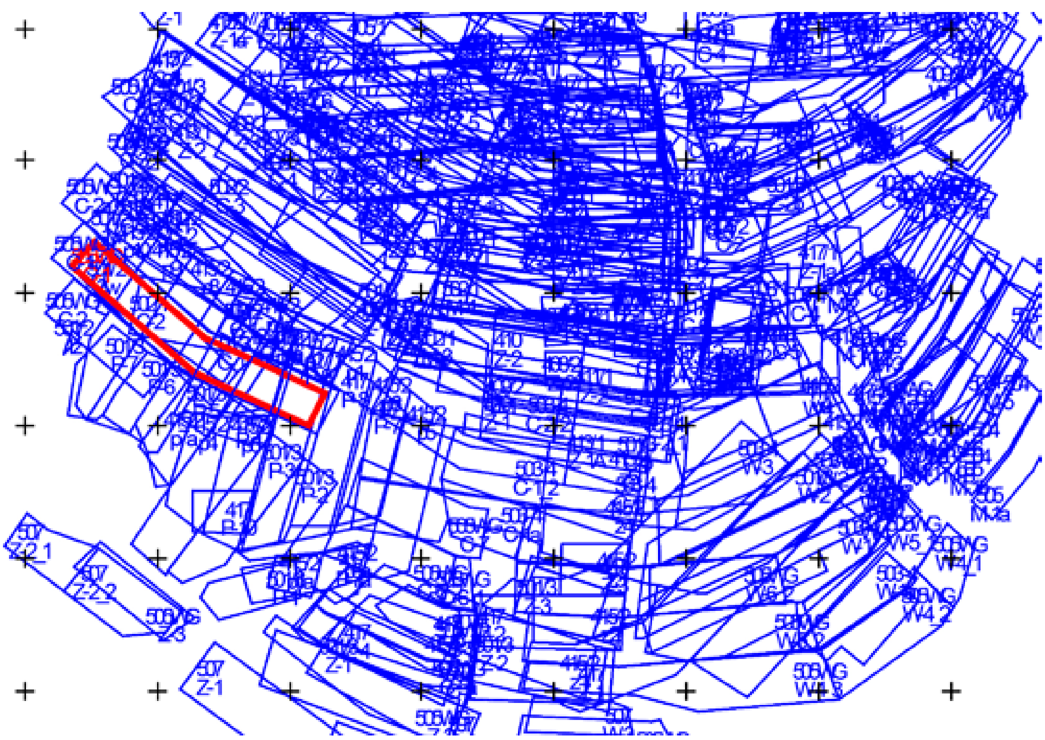

Figure 1. Contours of longwalls in the discussed area (longwall C-1 in the seam 505wg is marked in red)

an area of intensive mining exploitation was to verify the data on the range of mining influence in the rock mass in this area. The range of mining exploitation impact determined by the results of geodetic measurements of deformations is the basis for determining the permissible planned panel length, ensuring the maintenance of the functionality of the protected dog headings and the optimization of stress concentration zones in terms of the risk of rock mass tremors (Mielimąka & Kleta, 2020; Mielimąka et al., 2021).

The study of rock mass deformations was based on the results of displacement measurements carried out in Cross-cut I and in Main Entry located above the panel length of the mined longwall C-1 in seam 505wd (Figure 2). Longwall C-1 is located in the bottom layer of seam 505. The total thickness of seam 505 in this area ranges from about 6.50 m to 8.50 m. Seam 505 was mined in layers, and the upper layer was mined in the years 2010–2017. The exploitation of the bottom layer was carried out, leaving behind a rashing in the roof with a thickness of about 1.0 m, which made it possible to maintain the roof which had a high tendency to subside. This allowed for safe exploitation under the goaf of the first layer of seam 505.

The roof of seam 505 consists of clay shale and sand shale layers. At the initial part of the panel length, the roof of the seam is made of clay shale, above which there is sand shale and a layer of medium and fine sandstone, while further along the panel length of longwall C-1, the sandstone turns into sand shale. At the further and final part of the panel length in the roof of the seam, there is a layer of clay shale covered with sand shale. In the floor of seam 505 there is sand shale and, locally, clay shale.

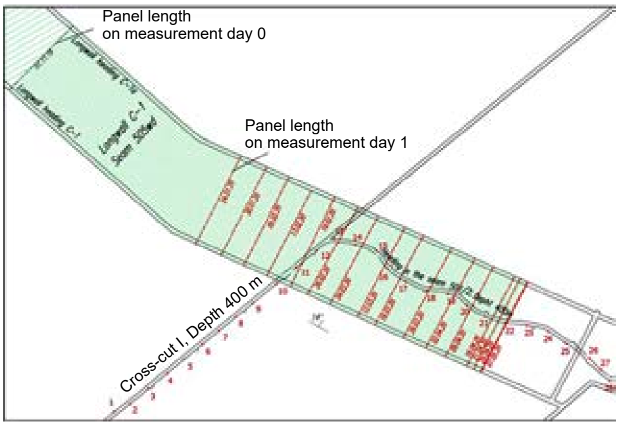

Figure 2. Location of the measurement line (points 1–28) in relation to the plot of longwall C-1 in seam 505wd

The deformations of the cross-cut and heading are characterized by measured deformations in the form of subsidence of the measurement points of the observation line made of 28 points located equally at intervals of approx. 30 m apart. In the period from 07/11/2019 to 27/05/2020, 18 height measurement cycles were performed on the measurement line, which indicated subsidence at the measurement points caused by the realization of subsequent stages of the exploitation of longwall C-1 in seam 505wd, until its completion. The location of the measurement line in relation to the area of longwall C-1 in seam 505wd is shown in Figure 2, and the subsidence of the observation line points in individual measurement cycles in relation to the initial measurement is shown in Figure 3.

As demonstrated in Figure 3, the exploitation of longwall C-1 in seam 505wd resulted in the subsidence of measurement line points in subsequent measurement cycles, and the maximum subsidence (0.816 m) was recorded in the last cycle (18th) at point 15.

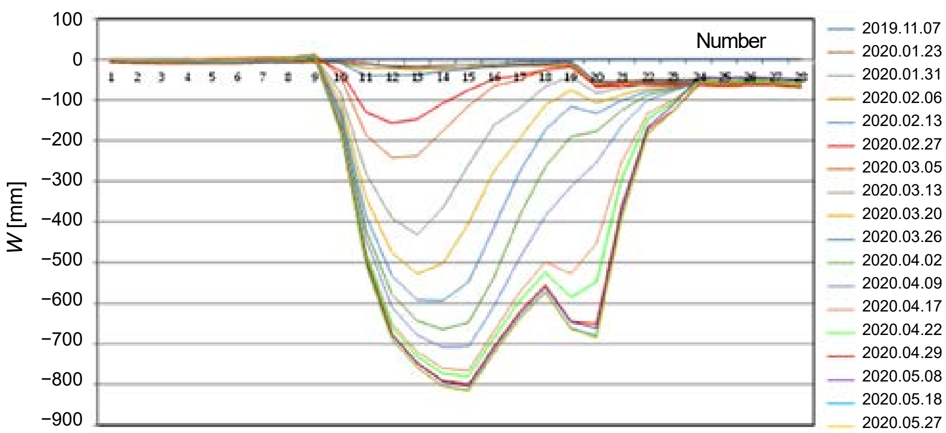

Figure 3. Measured subsidence of the measurement line points in subsequent observation cycles caused by progressive exploitation of longwall C-1 in seam 505wd

Theoretical basis of the applied theory of influence in the conducted research

Research and forecasts involving the impact of mining exploitation on surface ground and rock masses have been performed in Poland mainly by numerical methods using the formulas of S. Knothe's theory (Knothe, 1984), or in line with formulas developed by J. Białek (Białek, 2003), which are modifications of this theory that enable the forecast to include the effect of a mining periphery and the so-called far influences.

In the classic form of S. Knothe's theory, commonly used to describe a deformation, the subsidence caused by the exploitation of a horizontally placed mining plot is described by the following relationship (Knothe, 1984):

$$w(x,y,ag,r,S(t))= =\frac{-ag}{r^2}\iint\limits_{S(t)}\exp\left\{-\pi\left[\frac{(x-\xi)^2+(y-\eta)^2}{r^2}\right]\right\}dS \quad (1)$$

where:

- r – radius of influence scattering determined by measurements or calculated from the formula $r = h\ (\xi, \eta)/\ \mathrm{tg}\beta$,
- x, y – coordinates of the calculation point,
- $S(t)$ – area of the exploited bed, which is generally a function of time t,
- ξ, η – coordinates of the surface element dS,
- $ag = w_{max}$ – maximum subsidence of the so-called full subsidence trough.

In the formula of J. Białek implemented in the calculation programs, the theoretical subsidence is determined by the following formula (Białek, 2003):

$$W_k=(1-a_w)w(r_1)+a_w w(r_2)+ -A_1\left(2+\frac{A_3}{2}\right)\frac{w(r_1)[r_1\gamma(r_1)]^2}{A_3[0.5w(r_1)+0.5w(r_2)]^2+[r_1\gamma(r_1)]^2} \quad (2)$$

where:

- $A_1 = A_{obr}$ – parameter capturing the asymmetry of the subsidence trough profile, $A_1 \approx d/r$ (d – periphery),
- $w(r_1)$, $w(r_2)$ – subsidence calculated by Knothe's formula (eq. (1)) using radii r_1, r_2;
- $A_3 = 6.667$,
- $\gamma(r_1)$ – octahedral deformation calculated for $A_2 = 0.25$ with a simplified formula, in which horizontal movements are ignored. To describe its components, Knothe's formula was used, in the following form:

$$\gamma^2\approx\gamma_{oct}^2\approx\frac{4}{3}\varepsilon_z^2+T_x^2+T_y^2\approx$$

$$\approx\left[A_2\cdot r\cdot\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)\right]^2+\left(\frac{\partial w}{\partial x}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2$$

$$a_w=0.4-1.25A_1,\quad r_1=\frac{h}{\mathrm{tg}\beta}F(A_1),\quad r_2=2r_1$$

A_1	0	0.050	0.100	0.150	0.200	0.250	0.300
$F(A_1)$	0.800	0.844	0.916	1.003	1.099	1.200	1.303

The first two components of Formula (2) are a superposition of two subsidence troughs with different radii of influence range, which allows for a description of the so-called far influence. The third component of Formula (2) allows the calculations to take into account the mining periphery, which means that the subsidence over the exploitation edge is much lower than half of the maximum subsidence, and the trough profile is asymmetric with respect to this edge.

The most important feature of the programs EDBJ and EDN-OPN used in the research is the fact that they take into account the development of mining exploitation over time (Białek, 2003). An important consequence of the used description of the exploitation over time is the possibility to obtain forecasts of deformation rates treated as an increment of their values from one specific date to another. Moreover, it is possible to obtain a forecast of the extreme in time values of the deformation indices.

Determination of the values of parameters from the measured subsidence of measuring line points

To determine the parameters of the influence theory of mining exploitation based on geodetic measurements in Cross-cut I and in Main Entry, the TGB.EXE program was used, which determines the parameters a, tgβ, A_{obr} (Formulas (1), (2)) and adopts the residual variance minimum as the criterion for determining the parameters, defined by the formula (Mielimąka, 2009; Białek et al., 2020):

$$B_1(a,\mathrm{tg}\beta,A_{obr})=\sum_{i=1}^{n}\left[aW_{k_i}(\mathrm{tg}\beta,A_{obr})-W_{p_i}\right]^2 \quad (3)$$

where:

- n – number of measurement points,
- a – exploitation coefficient,
- tg$b$, A_{obr} – parameters present in formulas (1) and (2),

$aW_{k_i}\left(\mathrm{tg}\beta, A_{\mathrm{obr}}\right)$ – theoretical value of the subsidence of the i-th measuring point,

W_{p_i} – measured subsidence of the i-th measuring point.

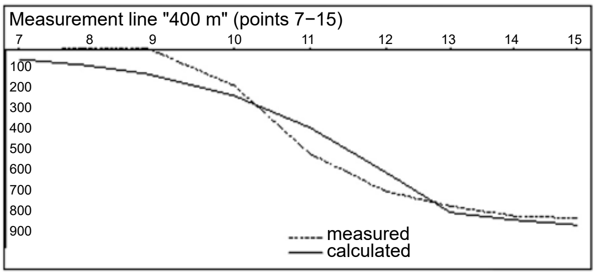

Figure 4. Waveforms of final subsidence of the measured points 7–15 of the “400 m” measuring line and theoretical subsidence adjusted by them

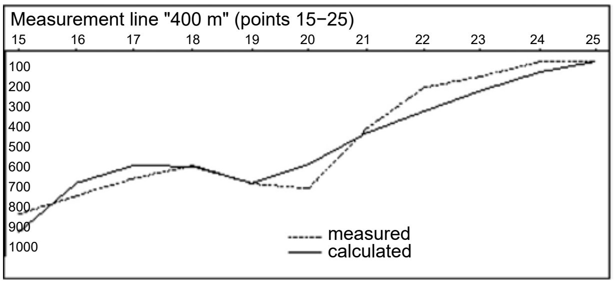

Figure 5. Waveforms of final subsidence of the measured points 15–25 of the “400 m” measuring line and theoretical subsidence adjusted by them

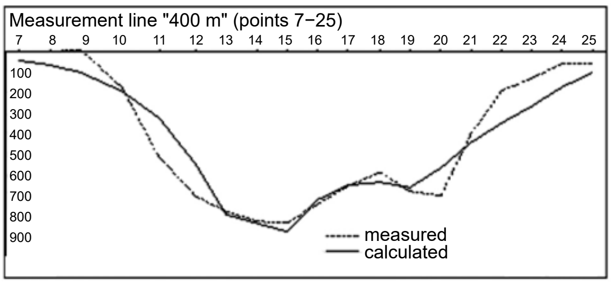

Figure 6. Waveforms of final subsidence of the measured points 7–25 of the “400m” measuring line and theoretical subsidence adjusted by them

Table 1 summarizes the parameters of Knothe’s theory of influence and formulas developed by J. Białek obtained with the program TGB.EXE. Average errors of these parameters were determined with the program BLAD_TGB.EXE.

Relatively large errors in the determined values of the parameters of the influence theory (Table 1) resulted from a relatively low accuracy of geodetic measurements, stabilization of points in the lining of the workings, and the impact of the goaf from the previously exploited upper layer of seam 505wg.

The determined values of parameter tgβ are lower than the value of this parameter accepted in the influence forecasts for surface ground, determined from the subsidence measurements on the observation lines located on the surface ground in this area.

Taking into account the values of the determined parameters of the influence theory (Table 1) and the values of their mean errors, as well as the values of the quantities characterizing the matching accuracy of theoretical subsidence with the measured ones, it can be assumed that the best approach is to describe the deformations that occurred in dog headings using the values of the parameters of the influence theory equal to $a = 0.813$, tg$\beta = 1.368$, $A_0 = 0.084$.

Determination of deformation indicators at measurement line points in Cross-cut I and Main Entry

The values of deformations at the measurement line points were calculated numerically by using the values of parameters of the theory of influence accepted as optimal ($a = 0.813$, tg$\beta = 1.368$, $A_0 = 0.084$).

Figures 7–10 show the distribution of the most important deformation indices calculated numerically at the measurement line points in Cross-cut I and Main Entry.

The performed numerical calculations of selected deformation indices at the measurement line points in Cross-cut I and Main Entry (Figures 7–10) indicate that the workings in question could have been subject to the maximum influences amounting to resultant horizontal displacements – 525 mm and main horizontal deformations – −11.05 mm/m. The deformations to which Cross-cut I and Main Entry

Table 1. Summary of numerically determined parameters of the theory of influence based on subsidence measurements in Cross-cut I and Main Entry

Measurement points	Subsidence coefficient a	Parameter tgβ	Periphery parameter A_0	Standard deviation	Correlation factor
7–15	0.692 ± 0.598	1.224 ± 0.086	0.000 ± 0.194	77.1 mm	0.9753
15–25	0.791 ± 0.282	2.096 ± 0.239	0.129 ± 0.052	69.4 mm	0.9684
7–25	0.813 ± 0.375	1.368 ± 0.098	0.084 ± 0.068	90.7 mm	0.9556

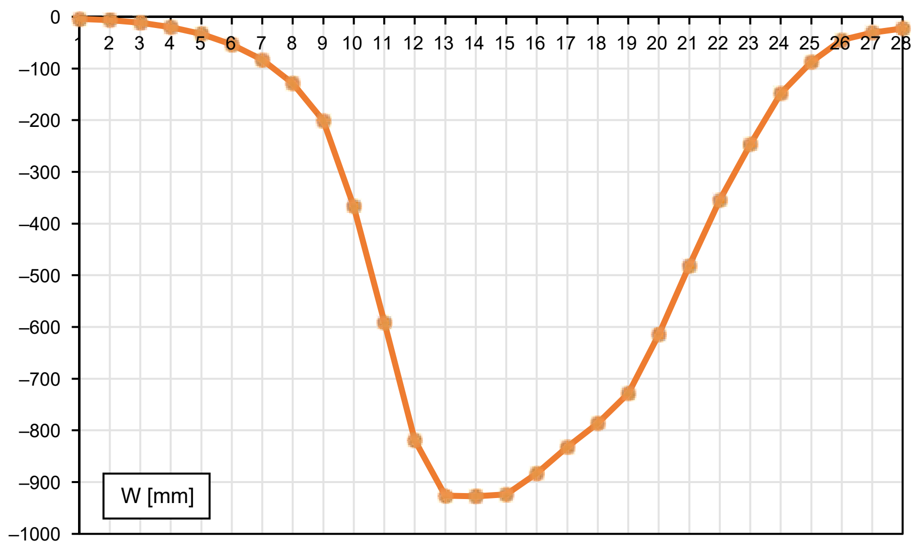

Figure 7. Waveform of the calculated subsidence [mm] of points of the measurement line "400 m"

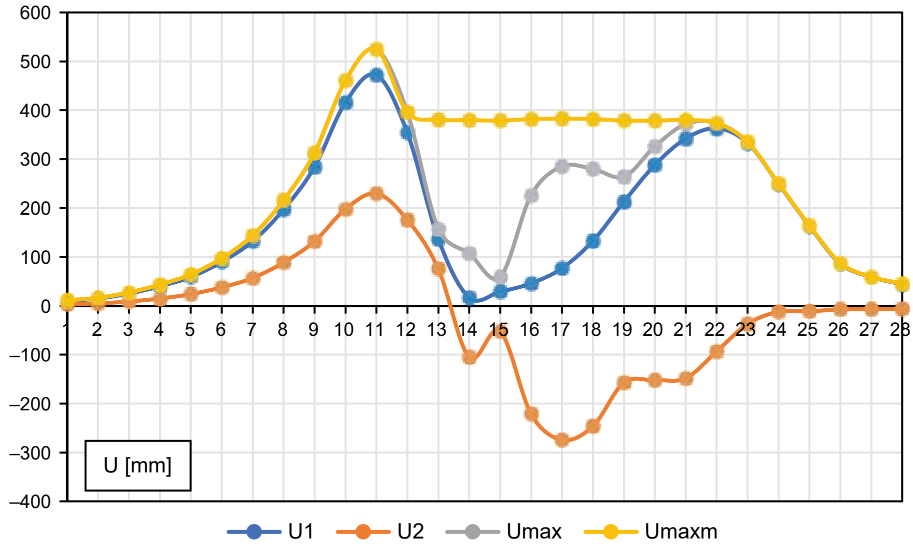

Figure 8. Waveforms of the calculated horizontal displacements [mm] (U1, U2 – horizontal displacement in the directions of the longitudinal and transverse axes of workings, Umax, Umaxm – final resultants and extreme in-time resultants) of points of the measurement line "400 m"

were subjected reached high maximum values in range IV and V of the influence category. However, they did not cause any significant reduction in the functionality of these workings nor, in principle, did they threaten the safety of their use.

Assessment of the influence range of mining exploitation in terms of determining the size of protective pillars for dog headings in the considered mining area

If mine workings are subject to mining influence, then the deformations occurring in them may result in the loss of their functionality or even dangerous damage to them (Duży & Kleta, 1998; Chudek et al., 2011). Therefore, in such conditions, it is necessary to select and apply an optimal protective pillar of a size that ensures the safety and functionality of the workings protected by it. The size of the protective pillar should take into account the predicted size of the radius of influence scattering of the mining exploitation in the individual coal seams planned for exploitation.

The radius of influence scattering $r(z)$, which is the radius of influence range of mining in the rock mass, can be calculated from the dependence (Drzęźla, 1978):

$$r(z) = \frac{h}{\mathrm{tg}\beta(H)}\left(\frac{z+z_0}{h+z_0}\right)^n \tag{4}$$

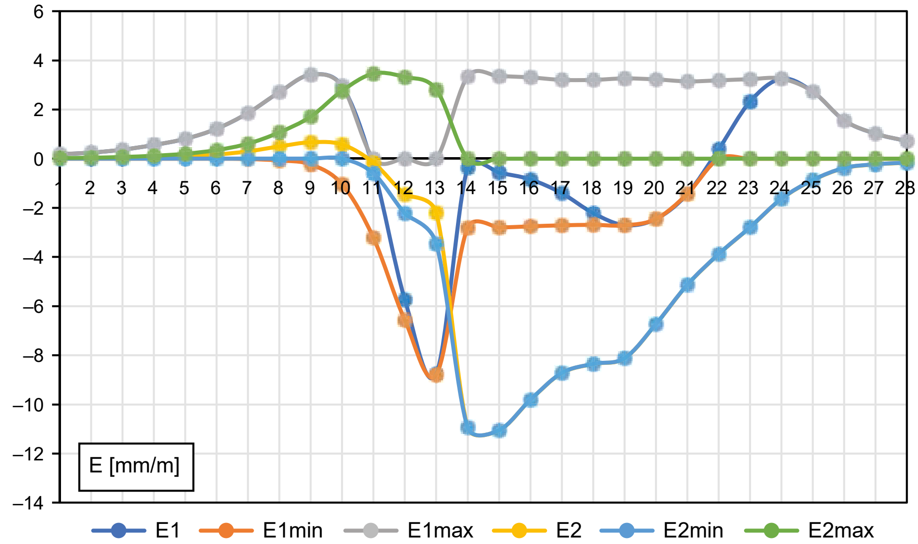

Figure 9. Waveforms of the calculated horizontal directional deformations [mm/m] (E1, E2 – final ones in the directions of the longitudinal and transverse axes of the excavations, E1min, E1max, E2min, E2max – extreme in time, minimum, and maximum in the directions of the longitudinal and transverse axes of the workings) at the points of the measuring line "400 m"

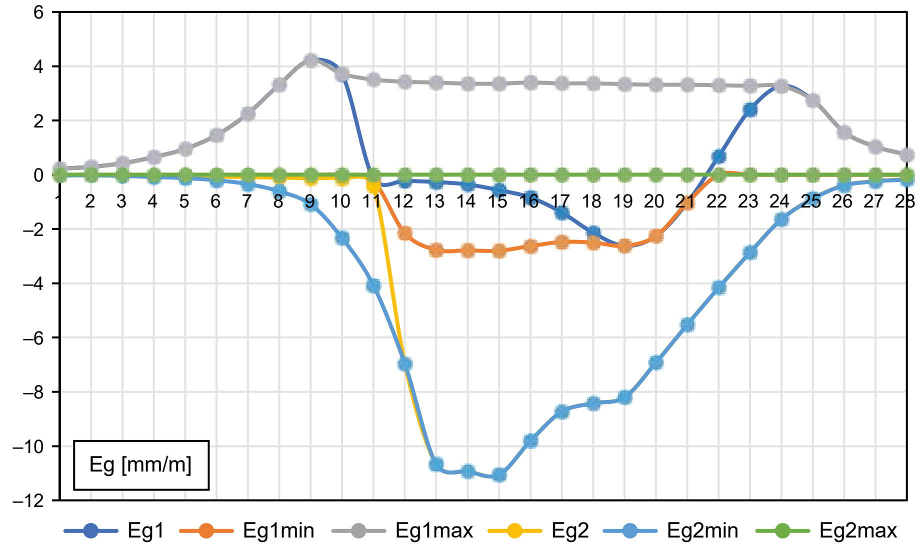

Figure 10. Waveforms of the calculated horizontal main deformations [mm/m] (Eg1, Eg2 – final values of the main deformations, Eg1min, Eg2min – values of extreme in time main minimum deformations, Eg1max, Eg2max – values of extreme in time main maximum deformations) at the points of the measuring line "400 m"

where:

h – depth of the mined element of bed surface dS,

tg$\beta(H)$ – parameter of Knothe's theory for surface ground, tg$\beta(H) = 2.0$,

z – distance of the calculation point over the element ds,

z_0 – parameter proposed by B. Drzęźla (Drzęźla, 1978),

n – exponent, where:

$n = 1$, $z_0 = 0$, by S. Knothe (Knothe, 1984),

$n = 0.5$, $z_0 = 0$, by J. Litwiniszyn (Litwiniszyn, 1954),

$n = 0.665$, $z_0 = 5ag$, by B. Drzęźla (Drzęźla, 1978).

The radius of mining exploitation influence range at vertical distance $z = 160$ m, calculated from Formula (4), corresponding to the location of Cross-cut I and Main Entry above longwall C-1 in seam 505wd, for the considered assumptions, is presented in Table 2.

Figure 11 shows graphically the size of the protective pillar for Cross-cut I and Main Entry, at which there would be no impacts of mining operations carried out in seam 505wd. To determine the required size of this protective pillar (Figure 11), we applied the range of mining exploitation influence effected by the exploitation of longwall C-1 in seam 505wd, determined by Formula (4).

Table 2. Calculated radius *r*(*z*) of the influence range of mining in the rock mass at vertical distance *z* = 160 m above longwall C-1 in seam 505wd

By assumptions of S. Knothe (Knothe, 1984)	By assumptions of J. Litwiniszyn (Litwiniszyn, 1954)	By assumptions of B. Drzęźla (Drzęźla, 1978; Białek, 2003)
$r(z = 160\text{ m}) = 84$ m	$r(z = 160\text{ m}) = 157$ m	$r(z = 160\text{ m}) = 124$ m

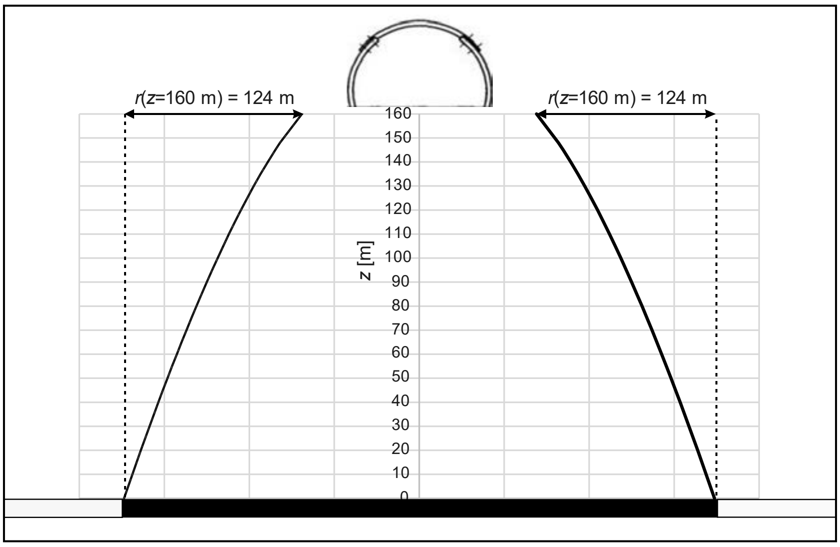

Figure 11. Protective pillar for dog headings located above seam 505wd

Conclusions

The objective of the presented results was to verify data on the range of mining influence in a rock mass in an area of intensive mining operation on the basis of research on rock mass deformations at the location of dog headings. The determination of the values of the parameters of Knothe's influence theory the extensions proposed by J. Białek, on the basis of deformation measurements in the rock mass, taking into account the exploitation periphery and so-called far influences, can be used to determine the permissible range of panel length, thus ensuring the functionality of the protected dog headings and the optimization of stress concentration zones in terms of the risk of rock mass tremors.

The determination of the values of the parameters of the theory of influence and their mean errors was performed three times: for the entire measuring line and for its stabilized parts in Cross-cut I and Main Entry (i.e., in workings located at a vertical distance of approx. 160 m above longwall C-1 in seam 505wd).

The range of mining exploitation influence in the rock mass at the site of Cross-cut I and Main Entry is of particular importance for their functionality. If the influence range comprises these workings, then deformations caused by mining exploitation may result in a loss of functionality of the workings or even in dangerous damage to them. The optimal size of the protective pillar for these workings should take into account the forecasted size of the radius of influence scattering of mining exploitation in the individual coal seams planned for mining operations.

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