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ANALYSIS OF HORIZONTAL DISPLACEMENTS MEASURED OVER THE MINING OPERATIONS IN LONGWALL NO. 537 AT THE GIRONDELLE 5 SEAM OF THE BW FRIEDRICH HEINRICH-RHEINLAND COAL MINE

ANALIZA PRZEMIESZCZEŃ POZIOMYCH POMIERZONYCH NAD EKSPLOATACJĄ ŚCIANY 537 POKŁADU GIRONDELLE 5 KOPALNI BW FRIEDRICH HEINRICH-RHEINLAND

The article presents an analysis of the horizontal land surface displacements taking place as an effect of coal exploitation on the Girondelle 5 seam in the Friedrich Heinrich-Rheinland mine in Germany. The paper presents changes in displacement vectors measured on the surface following the progress of the exploitation face and an analysis of horizontal displacement measurements assuming that their magnitude is proportional to the profile of subsidence trough slope. Then, the values of horizontal displacement coefficient *B* are assessed for selected longitudinal and transversal calculation cross-sections of longwall No. 537.

Keywords: horizontal displacements, surface deformations, mining exploitation, horizontal displacement coefficient

Artykuł przedstawia analizę przebiegu przemieszczeń poziomych powierzchni terenu powstałych w wyniku eksploatacji górniczej kopalni Niemieckiej Friedrich Heinrich-Rheinland w pokładzie Girondelle 5. Autor przedstawił zarówno zmiany wektorów przemieszczeń powierzchni terenu wraz z postępem frontu eksploatacji, jak również analizę pomiarów przemieszczeń poziomych zakładając, że ich wielkość jest proporcjonalna do nachylenia profilu niecki osiadania. Następnie dla określonych przekrojów obliczeniowych wzdłuż oraz w poprzek analizowanej ściany 537 oszacowano wartości współczynnika przemieszczeń poziomych *B*.

Słowa kluczowe: przemieszczenia poziome, deformacja powierzchni, wpływ eksploatacji na powierzchnię, współczynnik przemieszczeń B

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1. Introduction

Due to the protection of surface constructions, underground mines are carrying out regular measurements of land surface subsidence caused by the mining exploitation. Only some of the mines however do carry out measurements of horizontal displacements due to the significant complexity of this type of observations. Developments in the GPS technology over the last decade allowed larger scale measurement of surface horizontal displacements. These observations demonstrate that horizontal displacement values are low in areas located at the boundary of the exploitation subsidence trough, increasing towards the edge of the exploitation field and decreasing again near the central point of exploitation field. In the centre of the subsidence trough, horizontal displacement of land surface is equal to zero. Comparing the maximum values measured of horizontal displacements u_{max} with the maximum values of subsidence w_{max}, it has been found that their ratio ranges within:

$$0.24 \leq \frac{u_{max}}{w_{max}} \leq 0.58 \tag{1}$$

and depends on a variety of factors, including among other things the geological structure of the overlying rock formations, depth of mining exploitation, number of previously exploited seams and longwalls, exploitation methods, size of the panel field, etc. The majority of these quotients fit a narrower range of 0.3 to 0.35.

Several publications (Popiołek & Ostrowski, 1978; Białek, 2010; Tajduś, 2015, 2013 and others) have presented attempts to determine distribution of surface horizontal displacements caused by underground mining activity based on the Avershin hypothesis, assuming a linear relationship between the value of horizontal displacement and slope. This publication presents further distribution analysis of the surface horizontal displacements. The study was performed in relation with mining exploitation of longwall No. 537 at the Girondelle 5 level (seam) of the Friedrich Heinrich-Rheinland coal mine in Germany.

2. Description of the mining and geological situation of the Friedrich Heinrich-Rheinland mine in the region of longwall panel No. 537

The analysis of horizontal surface displacements and distribution of the *B* coefficient was carried out based on the example of the BW Friedrich Heinrich-Rheinland (DMT) coal mine. In 1998, the mine has initiated exploitation of longwall No. 537 (seam Girondelle 5) located at an average depth of 925 m. The exploitation ended in 1999. The length of the exploited longwall was 430 m with a panel run of 2003 m (Fig. 1). The inclination of the seam was from 3° to 4° in the longwall panel run direction.

Longwall No. 537 was designed as a high yield wall generating approximately 1300-1400 tons of coal per meter of extraction progress. Thickness of longwall No. 537 was not constant, in first phase of the exploitation it ranged from 2.5 m to 2.7 m and increased to 3.1 m in phase second (Fig. 2). The average thickness was 2.77 m.

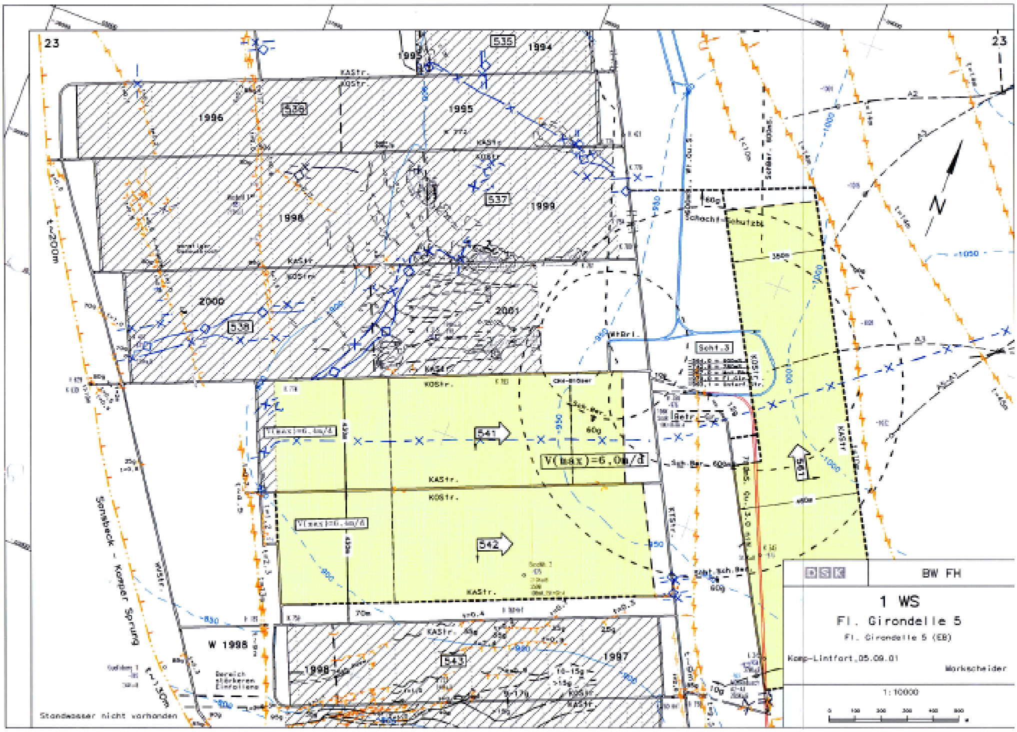


Fig. 1. Mining situation of the Girondelle 5 mining level

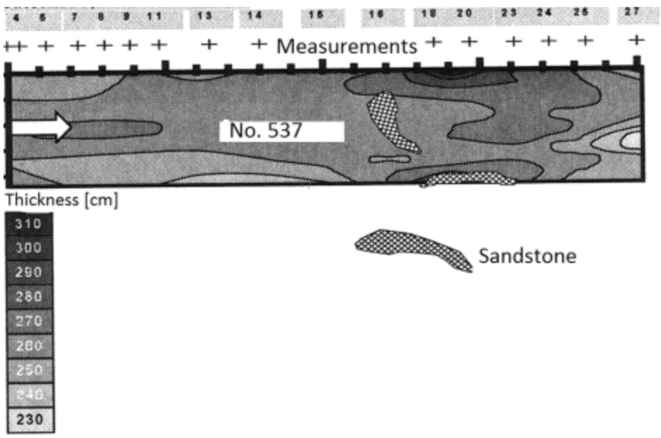


Fig. 2. Changes in longwall No. 537 thickness

The exploitation rate in longwall No. 537 varied, decreasing with increasing thickness of the coal seam and occurrence of sandstone veins (Fig. 3). The average exploitation rate was v = 4.60 m/day, yielding 6 000 to 6 500 Mg/day exploitation from the longwall.

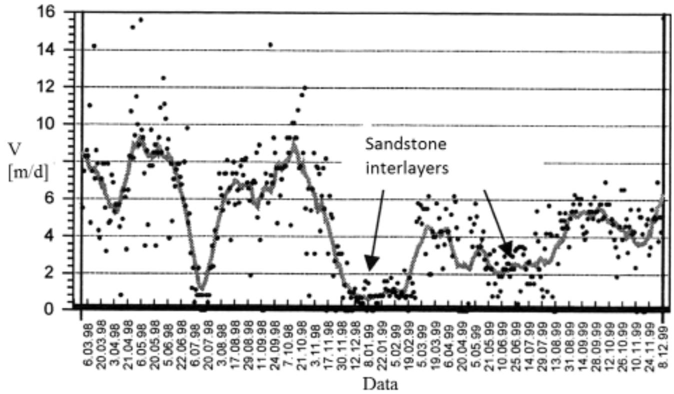


Fig. 3. Daily longwall 537 exploitation velocity

From 1988 to 1997, the seam Girondelle 5 was exploited in 8 longwalls, located in the area of longwall No. 537, using both pneumatic stowing and caving systems. The types of extraction and exploitation parameters are shown in Table 1.

TABLE 1

Characteristics of the longwalls in the extraction area (Hegemann, 2003)

Longwall no.	Date started	Date finished	Thickness [m]	Extraction rate [m/day]	Longwall length [m]	Longwall panel run [m]	Method of filling the void
531	1988	1989	2.38	3.12	252	755	Stowing
532	1989	1991	2.42	3.49	252	1084	
533	1991	1992	2.48	3.90	293	1077	
534	1992	1993	2.62	4.18	237	1087	
553	1993	1995	2.86	3.20	311	1456	Caving
535	1994	1995	2.81	2.45	287	673	
536	1995	1996	2.92	6.95	285	2015	
543	1997	1998	2.72	6.70	313	1440	

Longwalls no. from 531 to 536, and 543, 553 ran in the East-West direction and longwall No. 537 was exploited in the opposite direction. After completion of works in longwall No. 537, exploitation started in adjacent longwall No. 538 with a thickness of 2.6 m, length of 429 m and 943 m run. The longwall equipment and infrastructure systems were installed and exploitation began in 2000 (ending in 2001).

Ten seams were exploited above Girondelle 5 in previous years. In five of them the panels were backfilled (stowed) and the rest were carried out with caving. In general, all these coal seams had an average thickness of 1.2 m and mining works started at the beginning of the 20th century (1914) and ended 15 years before initiation of extraction works in longwall No. 531 on the Girondelle 5 seam (1973). The lowest level exploited in the previous years (Präsident) was located approximately 450 m-550 m above Girondelle 5, and its exploitation ended 19 years before commencement of works in longwall No. 531.

The rock mass structure in the mining operations area is diversified. It includes, among others, quaternary layers (thickness of 20 m) over layers of tertiary and carbonaceous formations characterized by alternating layers of sandstone, shale and sandy schist with veins of coal. The boundary line between the quaternary, tertiary and carbon formations runs at a depth of approximately 180-200 m. In the carbonaceous formations down to a depth of 1320 m the shale with coal veins accounted for about 30%, along with 40% of sandy schist and 30% of sandstone. In general, the carbonaceous deposit layers can be classified as high strength formations. The above structure was determined by borehole drilling (Fig. 5).

3. Measurements of surface deformations caused by exploitation of longwall No. 537

The mine has established a surface measurement network composed of a number of dispersed survey points (Fig. 4). Measurements were performed using the GPS method, guaranteeing an accuracy of less than 5 mm (Sroka et al., 2000). The initial measurement (No. 0) was made on 29.01.1998 and longwall extraction began on 24.02.98. Figure 4 shows a diagram of the longwall with locations of the extraction face for the survey measurements (from p.0 to p.27). The vertical and horizontal displacement measurements were made in in dispersed surface points. Exploitation of the longwall ended on 16.12.1999.

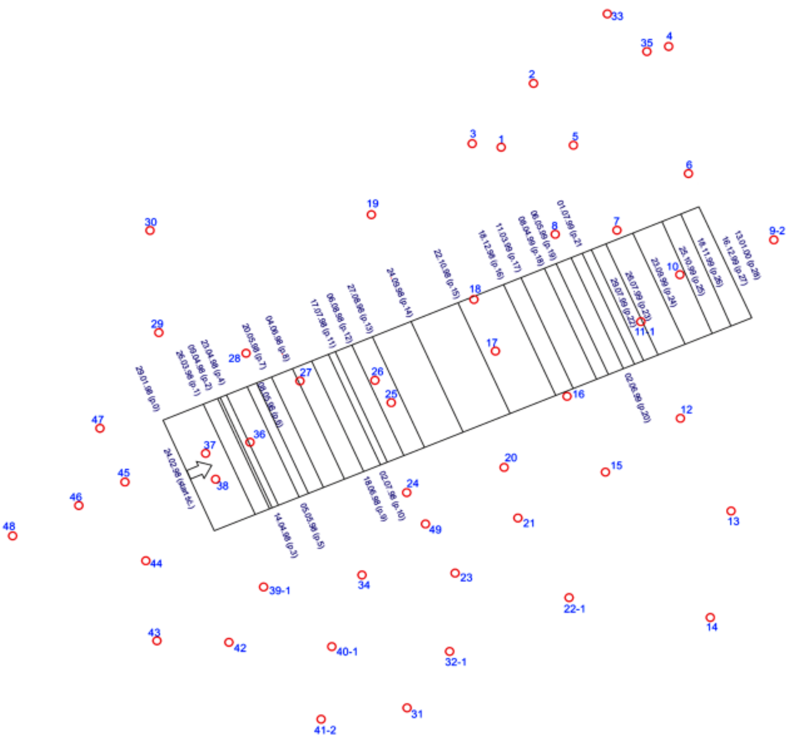


Fig. 4. Diagram of longwall No. 537 exploitation progress with measurement points

Values and distribution of subsidence (Fig. 5) and horizontal displacements in the *x* (Fig. 6a) and *y* (Fig. 6b) coordinates were obtained by measurement. The values presented in the figures correspond to the measurements taken on 04.05.2000, so four and half month after exploitation ends.

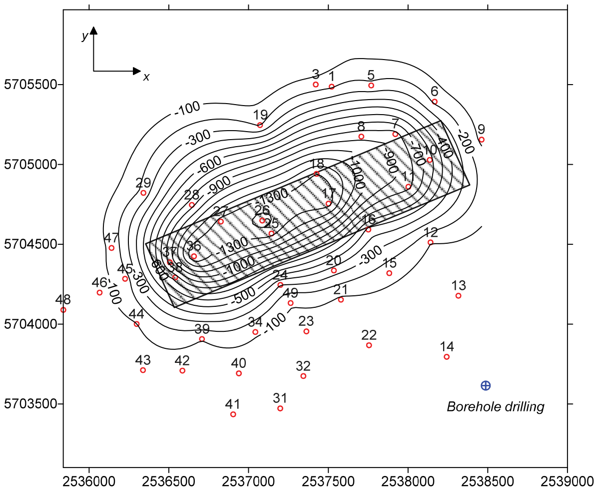
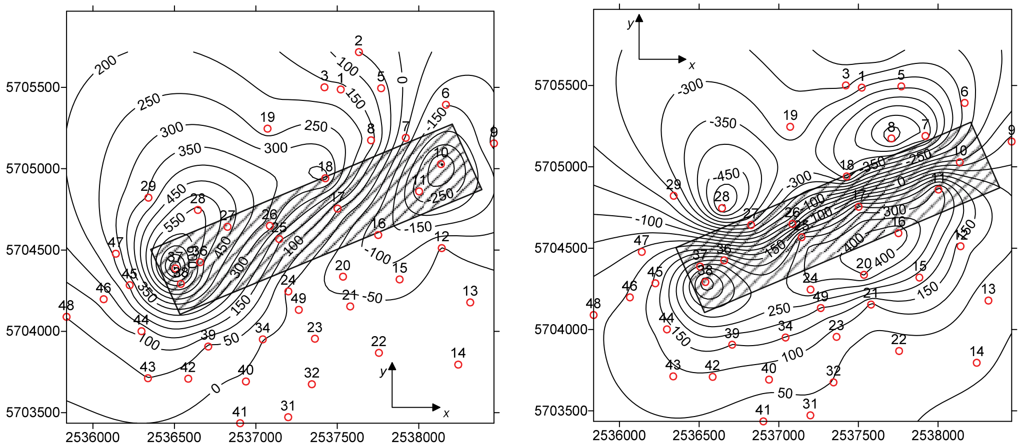


Fig. 5. Maps of geodetic measurement results[1] – surface subsidence *w* [mm]

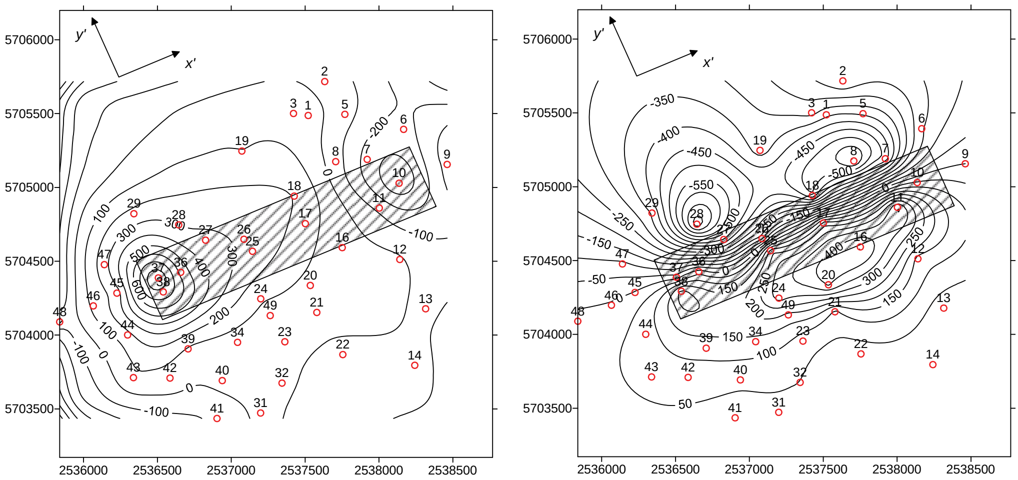


(a) (b)

Fig. 6. Maps of geodetic measurement results[1]: (a) horizontal displacements in the *x* axis [mm], (b) horizontal displacements in the *y* axis [mm]

[1] The matching was done using the Kriging method in which appropriate weights are allocated to points located inside the estimation area (sample selection area). These weights are referred to as kriging coefficients (weights) and they are allocated in a way to minimise the average square estimation error (kriging variance) based on the linear behaviour of the variograph.

Horizontal displacement $u(\alpha)$ distribution in directions parallel and perpendicular to the axis of longwall No. 537 are shown in Fig. 7.



(a) (b)

Fig. 7. Horizontal displacement isolines along the local coordinates system for the *x*' (a) and *y*' (b) axis, over the exploitation area of longwall No. 537.

Subsequently, the distribution was analysed for the ratios of maximum horizontal displacements to maximum subsidence u_{max}/w_{max} in particular points. Distribution of these values is shown in Figure 8.

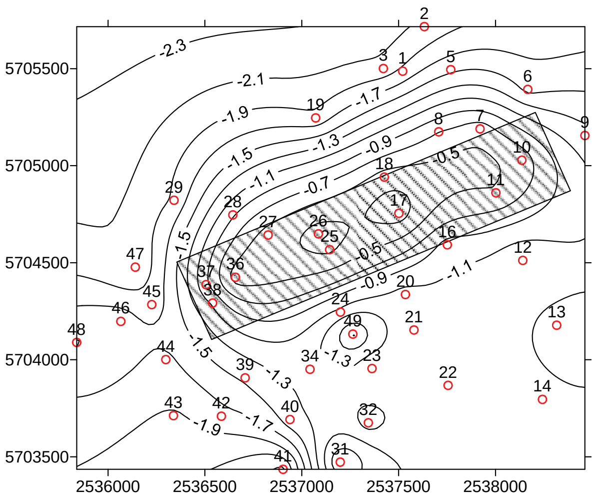


Fig. 8. Isolines of the ratio u_{max}/w_{max} in particular measurement points over the exploitation area of longwall No. 537

As demonstrated by the analysis presented in Figure 8, the minimum values of ratio $(|u_{max}|/w_{max}) = 0.2$ for exploitation of longwall No. 537 are reached in the central part of the extraction area (according to previous Soviet studies – $(|u_{max}|/w_{max}) = 0.3$), moving away from the edge, the value of the ratio increases up to values exceeding one. In some distance from the area of extraction, the value of horizontal displacement is more than two times greater than the value of subsidence.

4. Analysis of the value and distribution of the *B* coefficient for the exploited longwall No. 537

Eleven calculation cross-sections, perpendicular to the longwall's panel run, were prepared to support analysis of the *B* coefficient value distribution in the BW Friedrich Heinrich-Rheinland mine (Fig. 9).

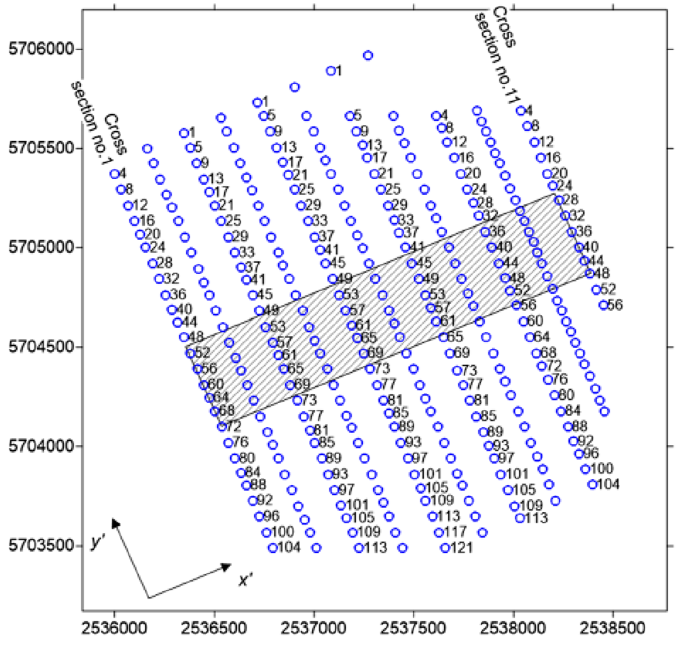
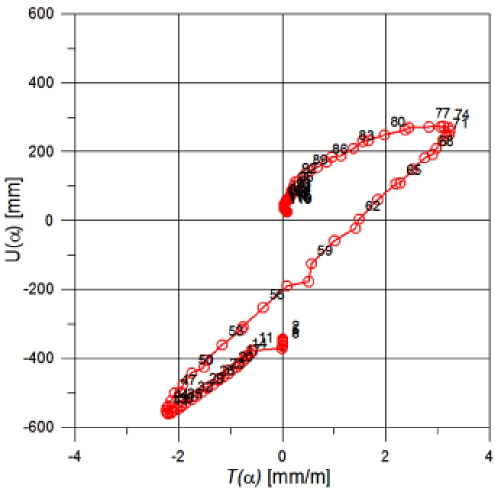


Fig. 9. Cross-sections (from 1 to 11) perpendicular to the panel run of longwall No. 537 with locations of measurement points

Cross-sections from 1 to 11 are composed of over one hundred points, in which the values of horizontal and vertical displacements were estimated using the Kriging interpolation principle. A graph showing the values of horizontal displacements in the cross-section direction $u(\alpha)$ in function of the cross-section slope $T(\alpha)$ (angle α corresponds to axis Y') was also prepared. Figures 10a and 10b show the example of horizontal displacement graphs for the cross-section plane $u(\alpha)$ in function of slope $T(\alpha)$ for cross sections No. 4 (a) and 8 (b).



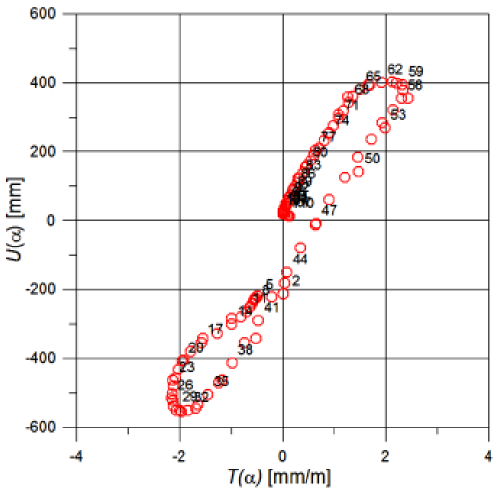


Fig. 10. Graph of horizontal displacements on the cross-section plane $u(\alpha)$ in function of slope inclination $T(\alpha)$ for cross-sections No. 4 (a) and 8 (b)

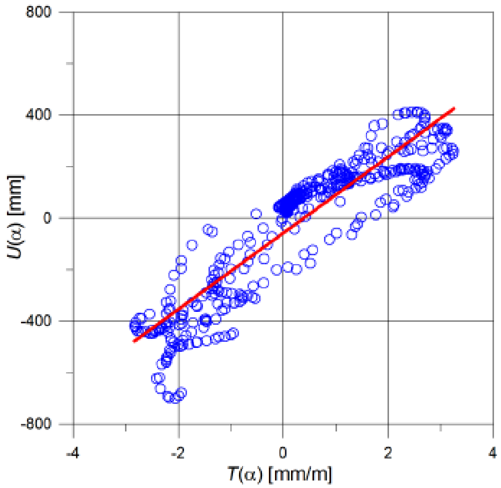
For the analysed cross-sections (1÷11), functional relationships between horizontal displacements and slope were determined using the linear regression method (Table 2). In the formulae presented, the values of horizontal displacements are given in mm and the slope in mm/m, which means that the value of parameter *B* is expressed in metres.

TABLE 2

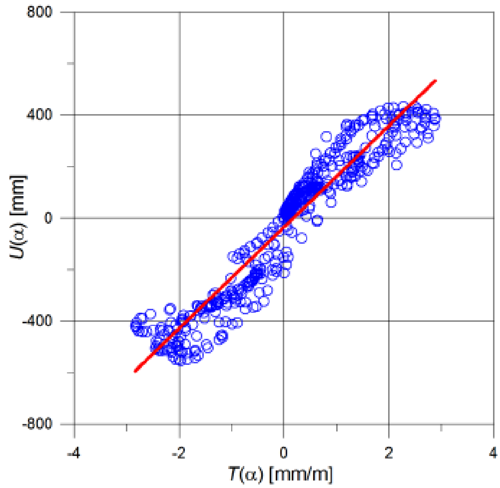
Linear regression matching formulae for cross sections perpendicular to the panel run of longwall No. 537

Number of section	Formula of linear regression	Matching
Cross Section no.1	$U(\alpha) = 175.7T - 19.2$	$R^2 = 0.87$
Cross Section no.2	$U(\alpha) = 132.6T - 74.0$	$R^2 = 0.76$
Cross Section no.3	$U(\alpha) = 158.7T - 123.9$	$R^2 = 0.74$
Cross Section no.4	$U(\alpha) = 170.3T - 150.2$	$R^2 = 0.78$
Cross Section no.5	$U(\alpha) = 152.8T - 42.2$	$R^2 = 0.95$
Cross Section no.6	$U(\alpha) = 161.6T - 18.8$	$R^2 = 0.96$
Cross Section no.7	$U(\alpha) = 192.0T - 3.0$	$R^2 = 0.93$
Cross Section no.8	$U(\alpha) = 227.3T - 45.0$	$R^2 = 0.90$
Cross Section no.9	$U(\alpha) = 226.2T - 49.3$	$R^2 = 0.91$
Cross Section no.10	$U(\alpha) = 221.7T - 46.5$	$R^2 = 0.96$
Cross Section no.11	$U(\alpha) = 186.6T - 8.3$	$R^2 = 0.99$

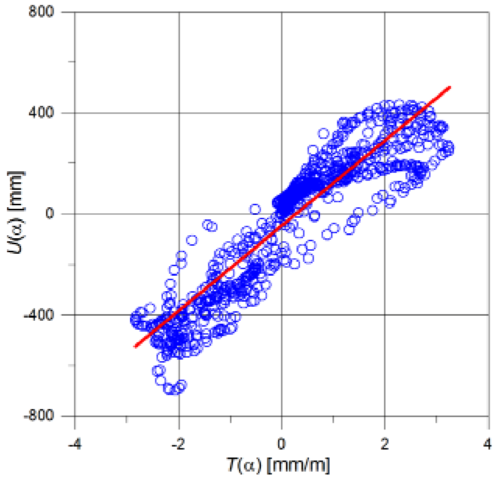
Analysis of the linear regression results for the eleven cross-sections (Table 2) indicates that in the first four cases, the matching is less than $R^2 = 0.9$, and in the other cross-sections the linear regression matching is more accurate. These conclusions are further confirmed by summary analysing values for cross-sections from 1 to 5 (Fig. 11a) (to the mid-point of the longwall panel run) and for cross-sections from 6 to 11 (Fig. 11b).



(a)



(b)



(c)

Fig. 11. Linear regression matching graph for cumulative values of *B* in sections: (a) from 1 to 5 and (b) from 6 to 11 and (c) from 1 to 11

The following matching values were obtained for the above-mentioned summary cross-sections:

- for cross-sections 1 to 6: $U(\alpha) = 148.5T - 58.0$, with $R^2 = 0.83$,
- for cross-sections 6 to 11: $U(\alpha) = 197.1T - 35.4$, with $R^2 = 0.91$.

The following formula was obtained for all summary cross-sections, i.e. from 1 to 11:

$$U(\alpha) = 167.9T - 52.9, \text{ with } R^2 = 0.86.$$

The above formulae for matching linear regressions to the measurement results differ from the Avershin hypothesis by the value of the absolute term. In order to approximate these values to the solution presented by Avershin it has been assumed that the regression lines cross in the centre of the coordinate system (Table 3).

TABLE 3

Matching formulae for linear regressions crossing in the centre of the coordinate system in cross-sections perpendicular to panel run of longwall No. 537

Number of section	**Formula of linear regression**	**Matching**
Cross Section no.1	$U(\alpha) = 174.1 \cdot T$	$R^2 = 0.86$
Cross Section no.2	$U(\alpha) = 129.0 \cdot T$	$R^2 = 0.67$
Cross Section no.3	$U(\alpha) = 138.6 \cdot T$	$R^2 = 0.57$
Cross Section no.4	$U(\alpha) = 171.0 \cdot T$	$R^2 = 0.55$
Cross Section no.5	$U(\alpha) = 151.3 \cdot T$	$R^2 = 0.92$
Cross Section no.6	$U(\alpha) = 161.2 \cdot T$	$R^2 = 0.96$
Cross Section no.7	$U(\alpha) = 191.4 \cdot T$	$R^2 = 0.92$
Cross Section no.8	$U(\alpha) = 227.4 \cdot T$	$R^2 = 0.88$
Cross Section no.9	$U(\alpha) = 225.1 \cdot T$	$R^2 = 0.88$
Cross Section no.10	$U(\alpha) = 219.7 \cdot T$	$R^2 = 0.91$
Cross Section no.11	$U(\alpha) = 188.8 \cdot T$	$R^2 = 0.98$

The results of this matching are also presented for summary cross-sections:

– for summary cross-sections from 1 to 5: $U(\alpha) = 143.6 \cdot T$, where: $R^2 = 0.78$,
– for summary cross-sections from 6 to 11: $U(\alpha) = 196.4 \cdot T$, where: $R^2 = 0.89$,
– for summary cross-sections from 1 to 11: $U(\alpha) = 165.7 \cdot T$, where: $R^2 = 0.82$.

A standard deviation of the sample equal to $S = 34.2$ m was determined for the estimated values of the horizontal displacement coefficient B. This means that individual values of B were determined with an accuracy of 19%.

The value of horizontal displacement coefficient can be also present as a function of depth (H) or radius of main influence (r) where:

– for summary cross-sections 1-5: $B = 0{,}16H$ or $B = 0{,}22r$,
– for summary cross-sections 6-11: $B = 0{,}21H$ or $B = 0{,}30r$,
– for summary cross-sections 1-11: $B = 0{,}18H$ or $B = 0{,}26r$.

5. Conclusions

Distribution analysis of the horizontal displacement coefficient B, carried out for the exploitation of longwall No. 537 on the Girondelle 5 seam of the Friedrich Heinrich-Rheinland coal mine has demonstrated that there is a proportional relation between the horizontal displacement vector and the slope of subsidence trough. This proportionality is noticeable in the case of cross-sections perpendicular to the excavation face. They indicate that the average displacement coefficient is $B = 0.26r$ (where r is the radius of main influence range) or $B = 0.18H$. This value was obtained assuming that $\tan\beta = 1.43$, (β – angle of main influences) as determined for the above-mentioned longwall in the publication by Ballhaus et al. (2000). The intermediate values of coefficient B for different cross-sections range between $0.20r$ and $0.35r$ (in the case of data meeting the $R^2 > 0.85$ condition).

The rock mass in the region of seam Girondelle 5 are consisting of mostly high strength formations (strong sandstones and sandy schist are almost 70% of whole overburden thickness). As a result of such rock mass conditions the value of angle of main influence β ($\tan\beta = 1.43$) is low. The value of horizontal coefficient B is describe as a function of depth (H) or radius of main influence (r) (so the value of $\tan\beta$). The coefficient μ presented in formula $B = \mu \cdot H$ is strongly dependent on rock mass overburden properties. It is recommended to determine the value (μ) from GSI rock mass classifications.

The approximate value of coefficient $B = 166$ is close to the value of the boundary line between the quaternary, tertiary and carbonaceous layers.

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